Robotics as a Future and Emerging Technology

Biomimetics, Cybernetics, and Neuro-Robotics in European Projects

BY PAOLO DARIO, MARIA CHIARA CARROZZA,
EUGENIO GUGLIELMELLI, CECILIA LASCHI,
ARIANNA MENCIASSI, SILVESTRO MICERA,
AND FABRIZIO VECCHI

The first machines in history were basically composed of mechanical parts, mechanisms, and some form of actuators supplied by an energy source. For a few centuries, this has been the paradigm for machines like windmills, textile frames, steam trains, and ships. What really changed in modern times was the incorporation of electronics into this basic scheme, allowing the integration of sensors and control, and the evolution of human-machine interfaces. This gave origin to mechatronics as the modern paradigm of machine design and the baseline for the development of robotics. This paradigm is today adopted in most products, from appliances to vehicles, aircrafts, robots, and biomedical devices.

The new complete scheme, as depicted in Figure 1, can be seen in an analogy with biological systems, integrating a musculo-skeletal apparatus with a nervous system and a circulatory apparatus. When machine design takes inspiration from biology, as in this analogy, then it can be referred to as *biomechatronics*. Robotics, especially, is now following this direction, with a stronger emphasis on biorobotics and biomedical applications.

The evolution of the paradigm of modern biomechatronics and robotics can be seen in two main directions, standing as two extremities of a range of future biomechatronics systems:

- increasing the performance and miniaturization of the hardware platform
- increasing the intelligence of the integrated system.

Regarding the first direction, the current challenge is to develop sophisticated machines with a higher level of miniaturization and performance, as they can be inspired by insects. Towards the other extremity, there is research on intelligent and autonomous robots, like humanoids. At intermediate levels, we can envisage the development of machines with a good degree of sophistication and performance and with a moderate degree of intelligence and that are more prone to human supervision and control or even to integration with natural bodies as bionic components.

In this article, three projects funded by the European Commission in the 5th Framework Programme, in the Information Society Technology-Future and Emerging Technologies (IST-FET) program, are presented as implementing three levels of this evolution of the biomechatronic paradigm: from the biomimetic wormlike microrobot for endoscopic exploration to a cybernetic hand prosthesis to an anthropomorphic robotic platform implementing learning schemes for sensory-motor coordination in manipulation.

The IST-FET Biomimetic Structures for Locomotion in the Human Body Project

The objectives of the biomimetic structures for locomotion in the human body (BIOLOCH) project are to understand motion and perception systems of lower animal forms, such as parasites, worms, insects, and even snakes and eels, and to design, model, and fabricate bioinspired mini- and micromachines able to navigate in tortuous and hostile cavities and, in particular, in the human body. This idea comes from the medical need to make more powerful tools for microendoscopy, which is one of the most challenging frontiers of modern medicine.

The most significant objectives that represent parallel and complementary results are:

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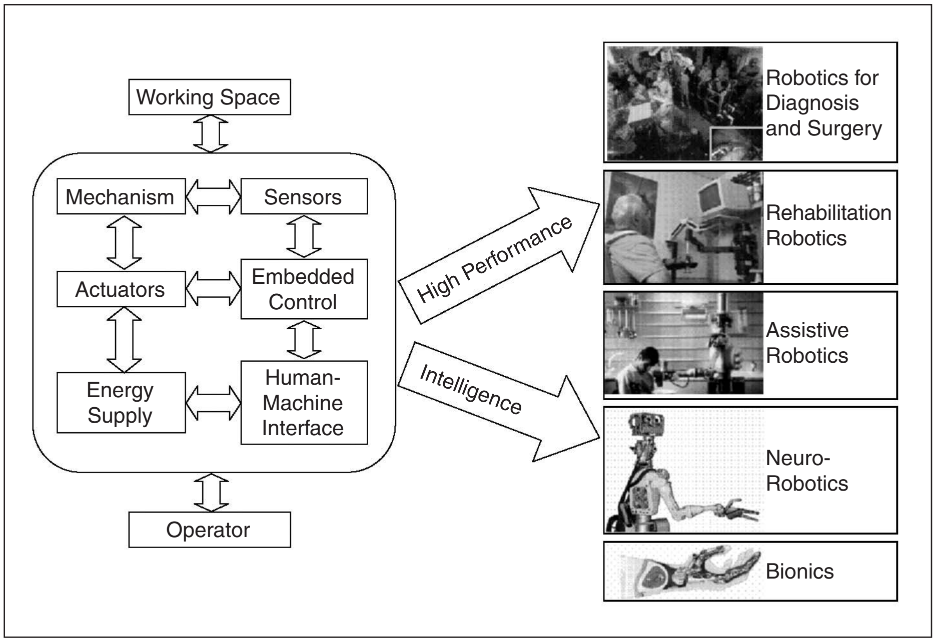


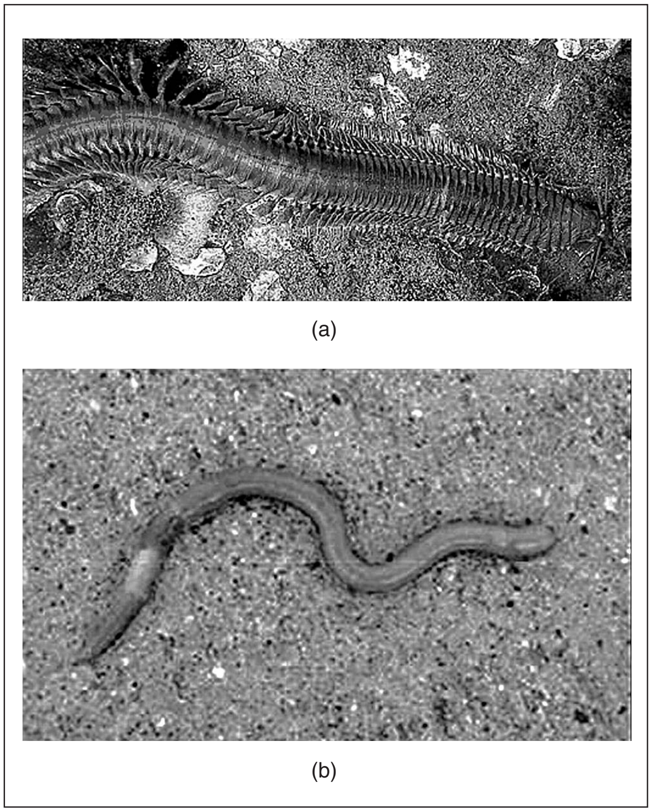
Figure 1. *A scheme of the mechatronic paradigm for machine design with an illustration of development lines. The blocks of mechanism, actuators, and energy supply are common to the design of virtually all machines since the first historical examples. The inclusion of sensors, embedded control, and a human-machine interface led to the modern paradigm of mechatronics and, when inspired by biological systems, biomechatronics. The current lines of development range from a full focus on the robotic platform performance (from a hardware point of view) to the focus on the machine intelligence and robot behavior.*

- the increase of knowledge in the field of biomechanics and neural control
- the definition of biologically inspired design paradigms
- the development and introduction of innovative hybrid manufacturing technologies.

The first step in the project is the study of the locomotion mechanisms used by animals that move in a wet environment containing large amounts of solid and semisolid materials. In order to understand better how to gain net advancement on this soft tissue, the mechanisms of attachment used by parasites, both internal and external, have been investigated. The interaction between a biomimetic worm and the gut wall has been analyzed, and objective parameters, like fracture and tear resistance of such tissue, have been estimated.

The second step of the project consists of the development of a biomimetic control module. The unit action-perception reaction of insects, worms, and parasites has been studied in order to define a strategy of replication and implementation in an artificial, bio-inspired, adaptable system. Finally, the third step consists of the biomechatronic design of the previously identified systems and of their implementation by innovative technologies integrating and merging different functions.

In this article, we illustrate the selection of the most promising locomotion architectures, and we present some preliminary platforms, developed both for mimicking the selected models and for creating a better understanding of the interaction between the platforms and the locomotion environment.


(a)

(b)

Figure 2. *Examples of (a) polychaete and (b) oligochaete worms.*

Biomimetic Undulatory Mechanisms

The taxonomy of biological propulsion systems has been performed by dividing them between adhesion (or differential friction) systems and locomotion systems. This classification has been pursued in order to analyze the problem of locomotion in the human cavities from an engineering point of view. In fact, even the simplest biological creatures exploit quite complex and sophisticated motion mechanisms, which are hard to understand and replicate without a sort of a priori systematization. This approach has been implemented extensively by studying locomotion issues in the human colon for more application driven robotic projects [1]. These studies have demonstrated that the peculiar anatomy, tribology [2], and mechanics of the human gut and of other human cavities pose many problems in terms of adhesion and stopping rather than in terms of propulsion, which is often a physiological process (in the intestine, blood vessels, and other such organs).

In this context, locomotion often indicates the displacement of adhesive or high friction contact points. On the basis of this analysis, the authors studied, designed, and

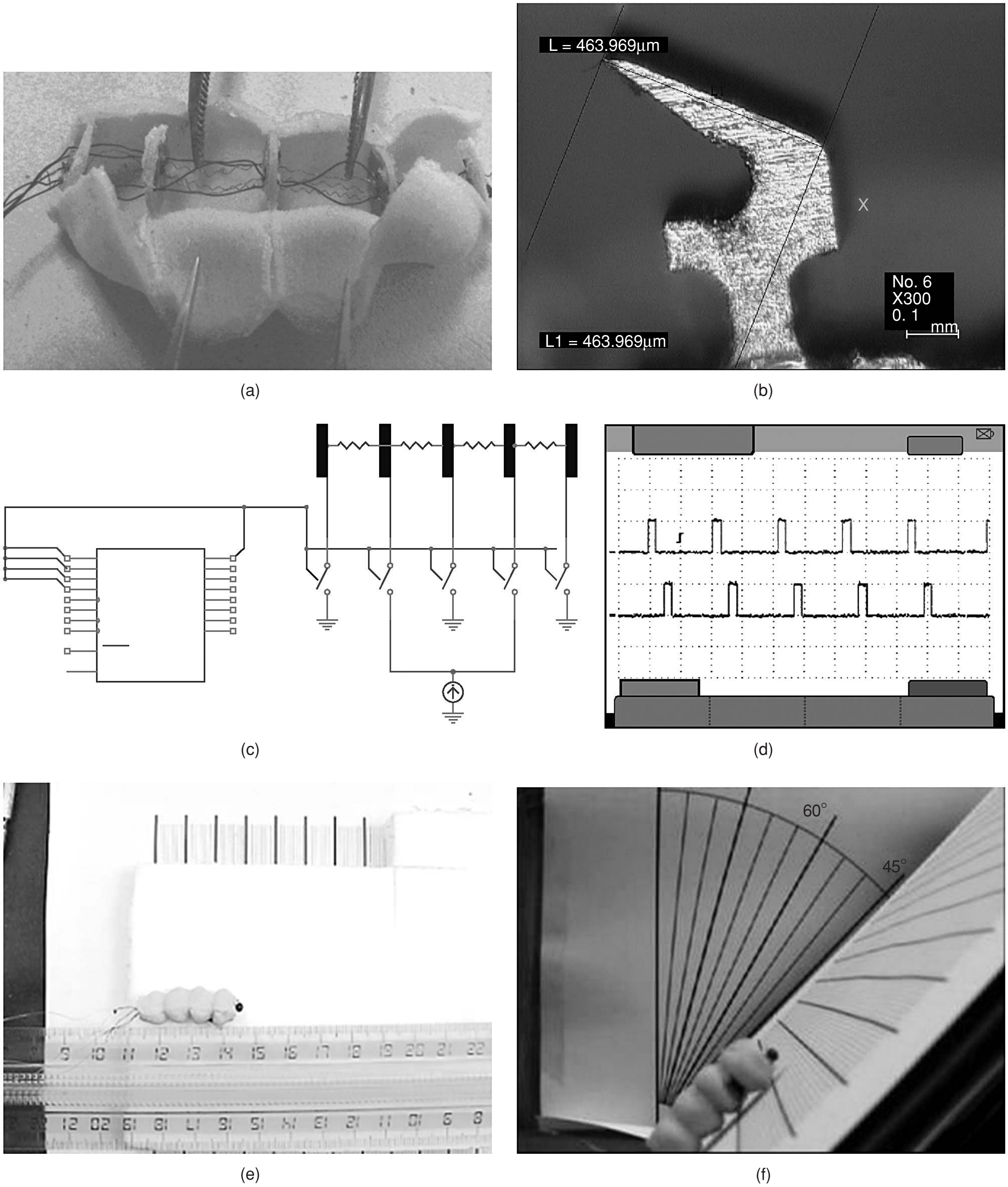


__Figure 3.__ (a) An earthworm skeleton during assembly. (b) The directional microleg. (c) An earthworm control scheme. (d) The activation sequence of two contiguous modules (A and B) where the delay is shown. (e) Locomotion on a Teflon substrate. (f) Locomotion on a sloped surface.

implemented some solutions for the realization of bioinspired mechanisms for friction enhancement. Adhesion modules can possess very different configurations and structures; they can consist of extremely tiny structures interacting by atomic force with the substrate [3]; they can be based on bio-glues, as used in surgery; or they can be based on mini- and microstructures, which generate high friction in one direction and low friction in the opposite direction, thus giving a preferred direction to the motion [4].

Concerning the displacement of adhesive points (i.e., the propulsion), the undulatory locomotion has been considered the most appropriate for locomoting robotic devices in solid, semisolid, and dirty environments, after an overall analysis of biological locomotion mechanisms (e.g., legged or polypedal locomotion and serpentine locomotion). Undulatory locomotion has been modeled for two different cases: waves longitudinal and waves transversal, regarding the motion direction (Figure 2) [5], [6].

Locomotion with longitudinal waves (i.e., peristaltic locomotion) consists of waves that propel in parallel with the direction of motion. This motion is exploited by earthworms (oligochaeta) and leeches. The difference between the earthworm locomotion and the leech locomotion (also called inchworm locomotion) is that the first consists of continuous waves and the second of discrete waves. Peristaltic locomotion is generated by the alternation of longitudinal and circular muscle contraction waves flowing from the head to the tail. The sites of longitudinal contraction are the anchor points; body extension is by circular contraction. The pattern of movement is initiated by anchoring the anterior end. As the longitudinal contraction wave moves posteriorly, it is slowly replaced by the circular contraction wave. The anterior end slowly and forcefully elongates, driving the tip farther over the surface. The tip then begins to dilate and anchor the anterior end as another longitudinal contraction wave develops. This sequence is repeated, and the worm moves forward. Reversing the direction of the contraction waves enables the worm to back up.

Locomotion with transversal waves consists of waves that are transversal to the motion direction, and it is typical of paddleworms (errant and sedentary polychaete). The large range of locomotion modes employed by errant polychaete is related to the diversity and structural complexity of their habitat environment. One species that is generalized locomotion-wise and has been extensively studied in the literature is *nereis diversicolor*, a common intertidal polychaete. It inhabits muddy substrata, and it possesses the ability to efficiently burrow. Its

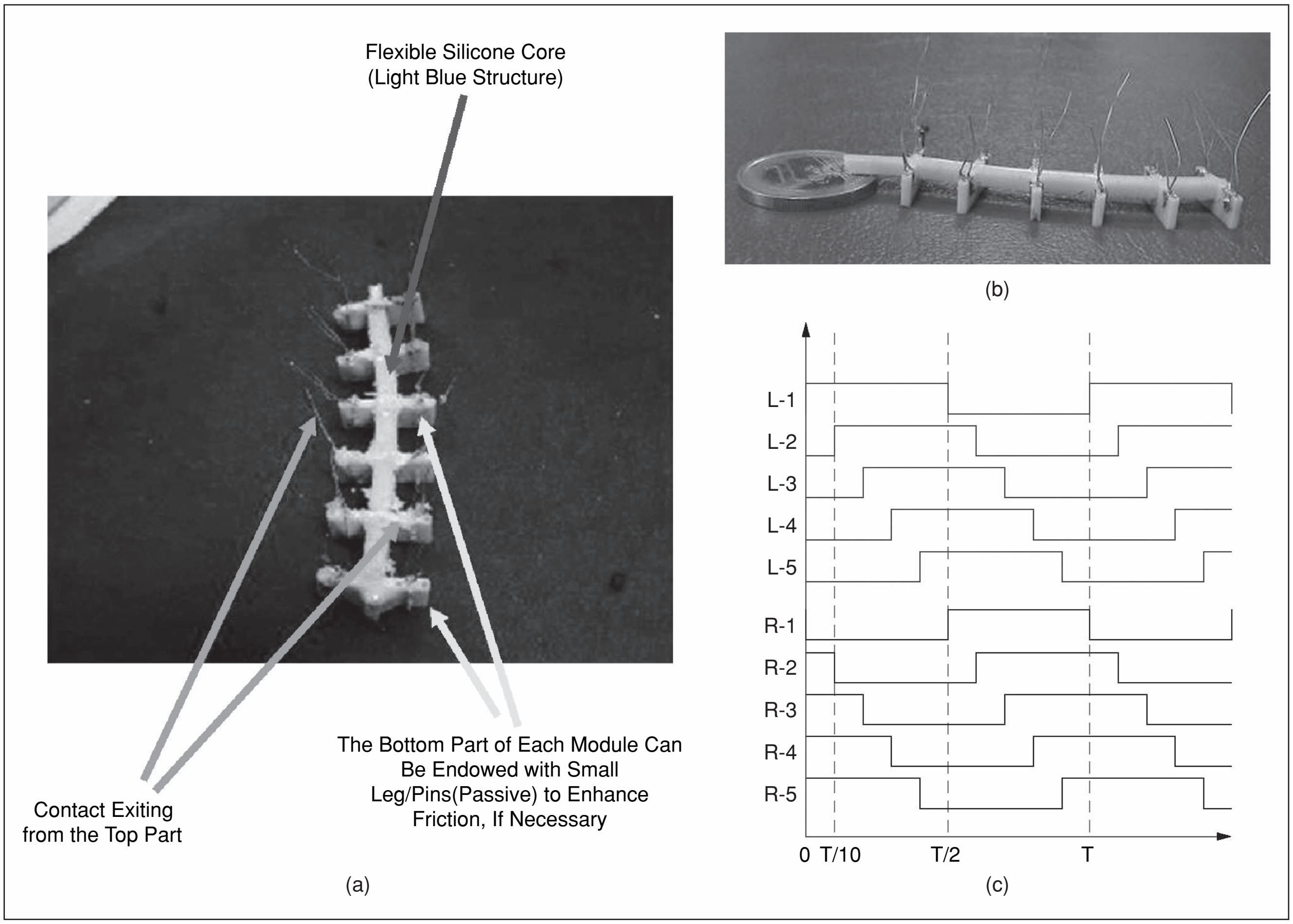


Figure 4. *A preliminary prototype of polychaete shown from the (a) top and (b) side. (c) A reasonable approximation for the traveling body wave is obtained by activating the SMA springs with a (constant) time offset between them.*

motion is very active, and it is also able to swim. Its body can reach 60–120 mm and consists of approximately 200 segments, each bearing a pair of parapodia.

The authors have developed several locomotion prototypes of oligochaeta and polychaete with the aim of studying the interaction of these platforms with different environments [7] and of testing the computational models of locomotion and evaluating the effect of friction on the motion [8]. With respect to pioneer activity on snakelike robots [9], the main feature of the current research consists of the ability to generate propulsion without exploiting wheels but understanding and exploiting the same mechanisms used by worms (e.g., legs, parapodia, and differential friction surfaces).

Figure 3 shows a four-module artificial oligochaeta with shape memory alloy (SMA) actuators. It consists of four silicone shells embedding SMA springs, which contract when activated. The robot possesses an external controller that activates each module sequentially. The robot locomotion is enabled by small metal legs that produce a differential friction, thus generating the net advancement of the device on flat surfaces, slippery surfaces (e.g., TEFLON), and sloped surfaces (Table 1).

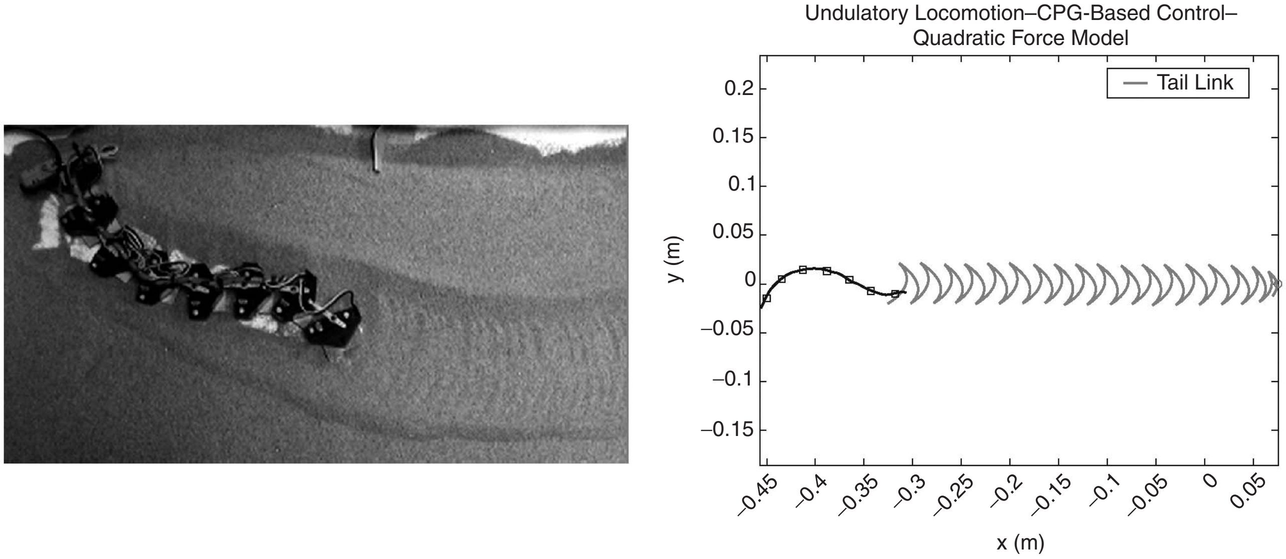
A five-module artificial polychaete, developed by exploiting the same principles used for the four-module worm, is illustrated in Figure 4. In this case, the traveling body wave is generated by the alternative contraction of two sets of SMA springs, which bend sequentially the left and the right

Table 1. Summary of the performance of the robot by using different activation frequencies of the shape memory alloy (SMA) actuators.

Frequency (mHz)	Current Peak Duration (ms)	Current (mA)	Energy for Module (J)	Velocity on Flat Surface (mm/s)	Velocity on Sloped Surface (40^0) (mm/s)
330	320	400	0.15	0.7	0.45
530	260	350	0.096	2	1.43
600	130	350	0.05	2.5	1.25

Table 2. Summary of the performance of the robot without and with hooked minilegs.

	Frequency (Hz)	Current Peak Duration (s)	Current (mA)	Energy for Module (J)	Velocity on Flat Surface (mm/s)
Without hooked minilegs	0.5	0.2	170	0.06	1
With hooked minilegs	0.5	0.2	170	0.06	1.3



(a) (b)

Figure 5. *(a) An artificial polychaete moving on sand. It consists of eight modules and 7 DOF. Each module is activated by a dc motor. The locomotion gait is obtained by replicating the gait of living creatures. (b) The computational simulation of the polychaete motion.*

modules of the polychaete. In this case, locomotion is obtained also without introducing differential friction structures (e.g., small hooked legs); the slight mounting asymmetries of the robot body contribute to generate a preferential direction of advancement (Table 2).

Finally, a robotic polychaete endowed with traditional actuators (servos dc minimotors) has been developed for testing the computational models of locomotion and evaluating the effect of friction onto the motion. The robotic platform, whose joints are driven by a sinusoidal wave while moving on sand, and a typical computational model for forward locomotion are shown in Figure 5 [8].

Sensory System and Low-Level Control: Work in Progress

Polychaete and oligochaete have developed a rich variety of sensors well adapted to their lifestyle and habitat.

Polychaete are highly touch sensitive; touch receptors are distributed over much of their body surface, in particular on the head and in parts of the parapodia; setae also function as such receptors. These touch receptors are used in the worm's interaction with its immediate surroundings. Many polychaete possess photoreceptors of varying complexity, ranging from simple pit eye-spots to eyes with sophisticated lenses and compound eyes. Annelids are one of the six phyla (out of the 33 metazoan phyla), where a competent optical system has evolved. Eyes usually occur in pairs on the dorsal surface of the head [10]. Nearly all polychaete possess chemoreceptors, which are specialized cells, sensitive to chemicals dissolved in the environment. They are scattered over much of their body surface. Statocysts also occur, mainly in burrowing and tube-dwelling polychaete; they function as georeceptors and help the animal maintain proper orientation in its burrow.

The sensor integration into the robotic platform is still in progress; many issues have to be addressed both from the theoretical and from the technological point of view in order to obtain a perceptive and reactive behavior. A possible concept of the devised final biomimetic system is illustrated in Figure 6.

The current activity on this topic is twofold. From the technological point of view, the authors are going to integrate simple contact sensors (PVDF foil) into the silicone skin of the artificial earthworm illustrated in Figure 3. The PVDF sensor should distinguish the sinusoidal deformation of the shell from any external contacts produced by obstacles on the pattern (Figure 7). This signal could be used for the reactive control at the module level. Concerning the overall architecture, the authors are investigating a control structure allowing the integration of up to 64 locomotion units (such as the one illustrated in Figure 6), each one embedding a microcontroller, the module actuator, and two contact sensors. One of these modules (i.e., the head module or master module) would consist of the same hardware but of a different controller able to generate the gait pattern for the overall prototype (i.e., for the slave modules). This architecture would allow overcoming the wiring problems that pose dramatic limitations to the current prototypes.

The Development of a Cybernetic Hand Prosthesis

Imitating the capabilities of the human manipulation systems has been the dream of scientists and engineers for centuries. In fact, developing a truly humanlike artificial hand is probably one of the most widely known paradigms of bionics [11]. The IST-FET CYBERHAND Project aims at combining recent advances in various fields of neuroscience, medicine, and technology in order to investigate the concept of a truly bionic hand, i.e., an artificial hand whose shape, functions, and, above all, perception, are so advanced that it is interchangeable with the natural hand. Within the framework of CYBERHAND, the consortium aims to achieve a number of important and tangible results, both in terms of enhanced basic knowledge and in terms of technological implementations. The main result of the CYBERHAND Project will be the development of a new kind of hand prosthesis (i.e., a cybernetic prosthesis) able to recreate the natural link that exists between the hand and the central nervous system

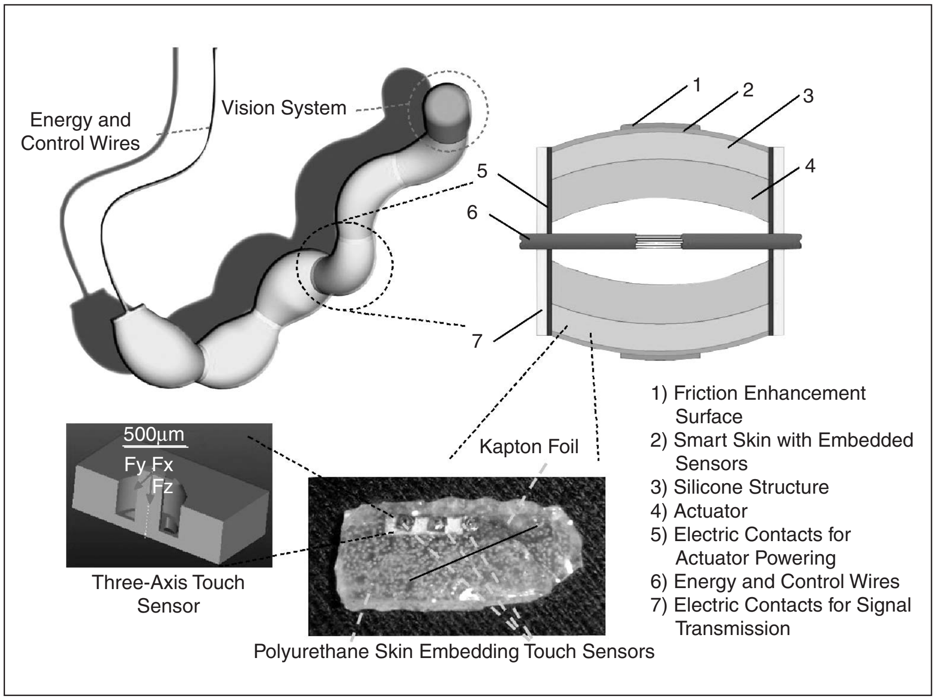


Figure 6. The concept of the BIOLOCH robot integrating force/contact sensors into each module.

(CNS) by exploiting the potentialities of implantable interfaces with the peripheral nervous system.

The natural hand is controlled by using the neural commands (i.e., the efferent neural signals) going from the CNS to the peripheral nervous system (to recruit the different muscles). At the same time, the information (concerning the position of the fingers, the force produced during grasp, and the slippage of the objects) obtained from the natural sensors (mechanoreceptors and muscle spindles) are brought to the CNS by activation of the afferent peripheral nerves. The hand prosthesis, which is being developed in the framework of the CYBERHAND Project, aims to implement the above described structure (see Figure 8).

The possibility of restoring the perception of the natural hand (i.e., the possibility of delivering a natural sensory feedback to the user) will increase the acceptability of the artificial device. This result will be achieved also by developing biomimetic sensors replicating the natural sensors of the hand, and specific neural electrodes will allow selective stimulation (to deliver the sensory feedback) and recording (to extract the user's intentions).

The following presents, in brief, the main results and the current works on the neural interfaces and the biomechatronic hand topics.

Results and Current Work on Noninvasive and Invasive Neural Interfaces

Two different steps are under investigation: 1) the development of a noninvasive neuromechatronic interface based on the processing of the electromyographic (EMG) signal and on the use of external systems to deliver a cognitive feedback to the user and 2) the development of an invasive neuromechatronic interface, achieved by using different kinds of electrodes. The noninvasive approach is being used for investigating

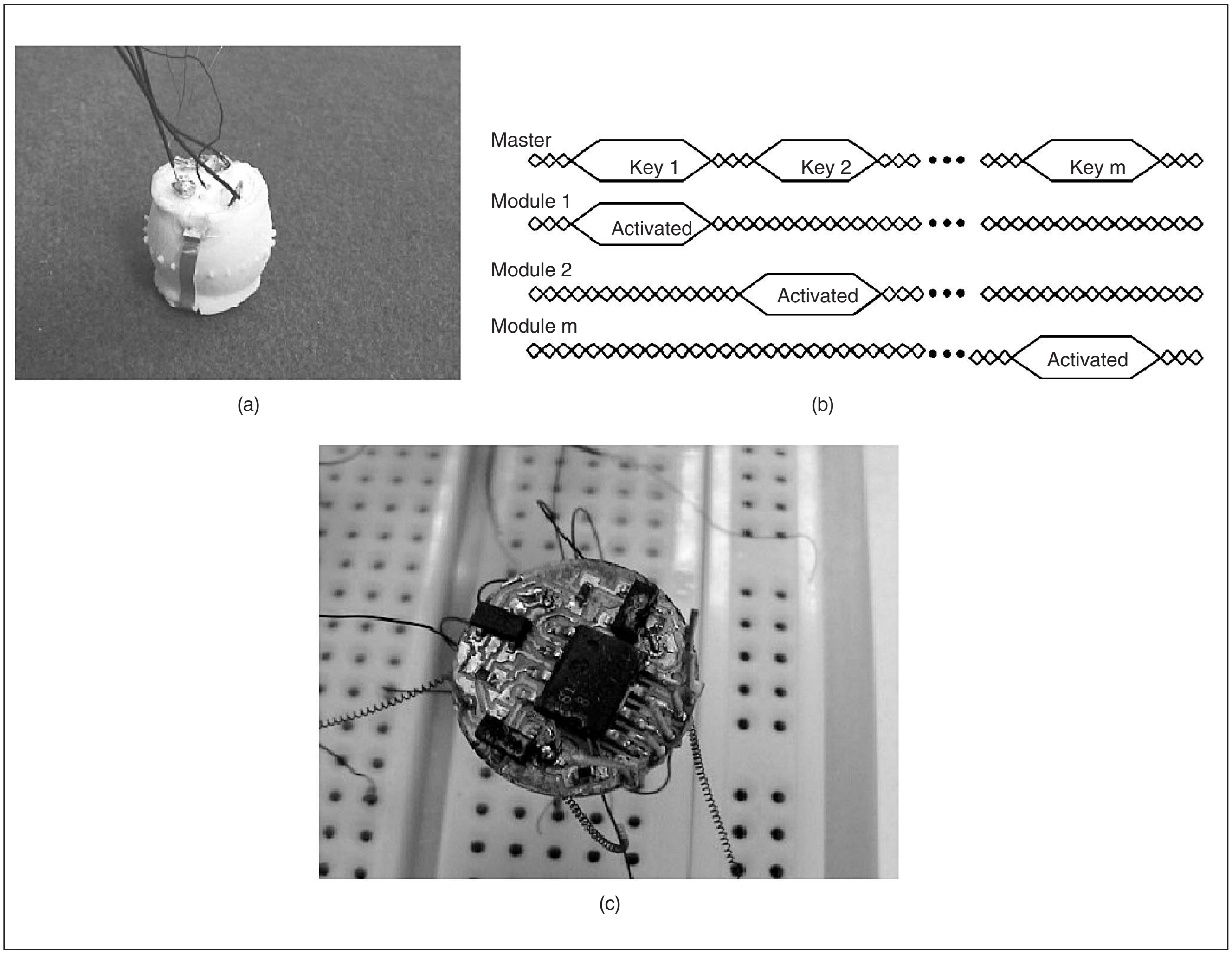


Figure 7*. (a) A locomotion unit embedding PVDF foils into the silicone skin. (b) The master module sends one key code (1 B) every 1.2 ms; the slave modules receive the code and compare it with the known key codes. The memory of each slave module contains three key codes identifying the three SMA wires embedded into the module. When a code corresponding to a spring is received, the spring is activated for about 300 μs. (c) The connecting disk for multimodule architecture. The actuators (three SMA springs) are connected on the back part of the disk; on the front part, the electronics for the low-level control and the connectors for multimodule integration are visible.*

the possibility of controlling the multiple degrees of freedom (DOF) prosthesis by processing the EMG signals [12].

The EMG signal is a simple and easy to obtain source of information on what the user of a prosthesis would like to do with her/his artificial hand. Surface electrodes are easy to use and manage, and they do not require any surgery. Moreover, there is no harness that could limit the movements of the forearm. It is possible to control an active device with just one electrode placed on the residual limb. However, it is important to point out that among the different robotic artifacts (exoskeletons, teleoperated robots, etc.), the EMG-based control of hand prostheses is the more challenging. In fact, in this case it is not possible to use the "homologous" natural muscles to control the artificial movements of the device. For example, the muscles related to the movements of the wrist (extensor and flexor carpi) are in many cases no longer available because of the amputation; for this reason, it is necessary to code this movement with other voluntary movements (e.g., the flexion/extension of the elbow). This situation asks for the development of a complex approach using advanced pattern recognition techniques [12].

During the first phase of the project, the EMG signals from the biceps and triceps of five able-bodied subjects (participating after providing informed consent) have been used to discriminate two different upper-limb movements (elbow flexion-extension and forearm pronation-supination) in order to allow the subjects to control two different kinds of prehension (palmar and lateral grasps [13]). Three levels of force for each grasp were coded. The level of force was extracted from the "intensity" of the activation of the muscles. An algorithm based on statistical (the "generalized likelihood ratio" (GLR) test [14]) and neurofuzzy algorithms has been used. The rate of successful classification was around 95% with the neurofuzzy classifier. This latter performance is quite similar to the state of the art in this field (see [13] and [15] for examples), even if in our case fewer electrodes have been used. Moreover, it is important to point out that this is one of the few examples in literature of the real-time control of a multi-DOF prosthetic hand. In fact, in many cases the papers address the problems of the EMG-based control of a prosthesis "simulating" the existence of the robotic device. After this preliminary phase, the possibility of controlling more DOF is currently under investigation. Ten able-bodied subjects have been enrolled in the experiments. During this phase, the EMG activity of several muscles from the shoulder and the upper arm will be recorded (e.g., deltoid, trapetius, biceps, triceps). The movements of the shoulder will be used to select the different DOF of the hand. Jerky elevation movements of the shoulder will allow locking-unlocking the grasping type selected. At the same time, the performance achieved by delivering a sensory feedback to the subject by means of several approaches that do not require the implant of electrodes (e.g., mechanical stimulation or electrical stimulation) will be analyzed in order to understand the noninvasive approach's potential and its advantages.

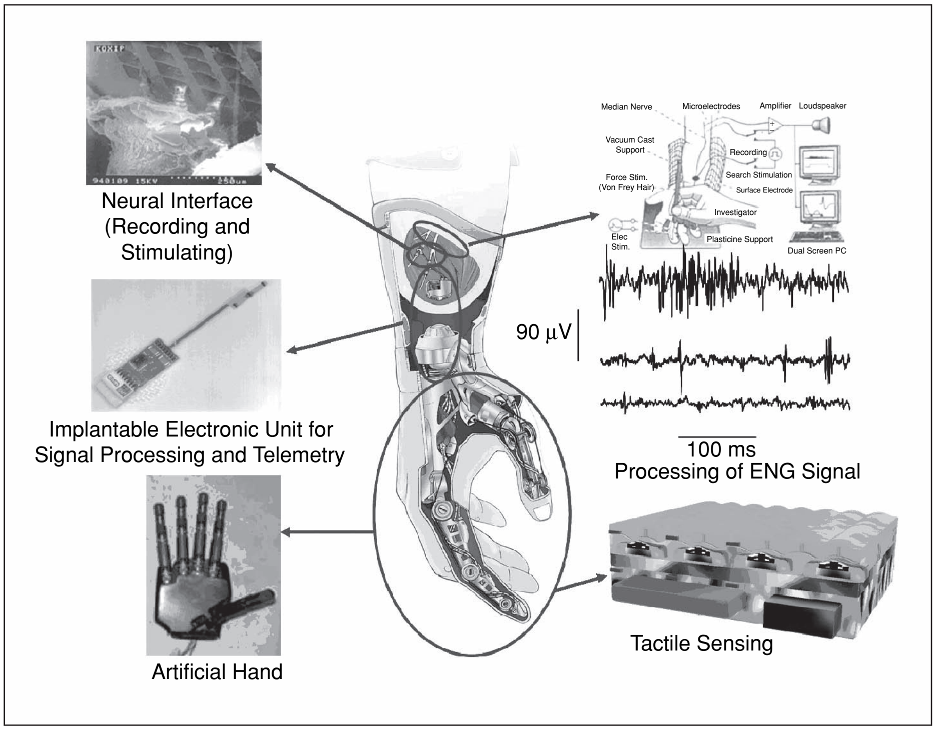


Figure 8. *The CYBERHAND prosthetic hand aims to be controlled by an amputee in a very natural way, by processing the efferent neural signals coming from the central nervous system (CNS) and detected by means of neural interfaces. Moreover, the prosthesis will be felt by the amputee as the lost natural limb since a natural sensory feedback will be delivered to him/her by means of the stimulation of some specific afferent nerves (i.e., the nerves which bring the sensory information to the CNS).*

According to the invasive approach, three different kinds of electrodes—regeneration type [16], cuff type, and longitudinal intrafascicular electrodes (LIFEs) (see Figure 9)—have been developed and implanted in different animal models (rats and rabbits).

These experiments are useful for verifying the bandwidth (i.e., the amount of information that can be extracted from the signals recorded and can be delivered to the user by means of neural stimulation) of these two electrodes. In particular, for the sieve electrodes it is crucial to understand what degree of regeneration is obtainable with the new electrodes, not only from a histological point of view but also in addressing the issues related to the extraction of the information carried in the recorded signals, specifically:

- What is the degree of similarity of the recorded signals to cuff signals and to needle signals (i.e., microneurography)?
- What is the influence of the afferent signals on the efferent signals, and what kind of countermeasures can be envisaged in order to reduce the interference?

Two different experimental trials are under development in order to investigate the possibility of delivering a sensory feedback and to analyze the possibility of extracting information from the neural signals recorded using the electrodes to control the biomechatronic prosthesis.

The experiments on sensory feedback will be carried out in three different phases (in collaboration with the Consortium of the IST-FET ROSANA Project).

- Phase 1: Development of a model to correlate the sensory stimuli delivered to the hindpaw of the rat to the signals recorded from the holes of the sieve electrodes.
- Phase 2: Update of the model developed during Phase 1 by comparing the cortical signals obtained during sensory and electrically induced stimulation.
- Phase 3: Deliver the sensory feedback by using the signals recorded from the artificial sensors developed in the framework of the project.

Efferent signals are commonly elicited in the animal model, provoking some pain in the limb (for example by means of a laser-assisted stimulation). This strategy may have some drawbacks; for example, it could be not easy to obtain a repeatable movement (and thus repeatable efferent signal). Two other protocols are under investigation: 1) a protocol based on the reward concept (the rat moves the hind limb in a specific direction and obtains some food; moving the limb in another directions brings it some water) and 2) a protocol based on the reaction of the rats to movements imposed on its limb. If the experimenter pushes or pulls the limb in a specific direction, the rat is supposed to react, bringing the limb to a rest position and thereby activating different muscles for each specific direction.

Results and Current Work on Biomechatronic Artificial Hand

A new biomechatronic artificial hand is under development. It will interact with the environment according to the patient's intentions and will generate the sensory information for the low-level control and the cognitive feedback systems. A three-dimensional (3-D) CAD model of the hand has been created

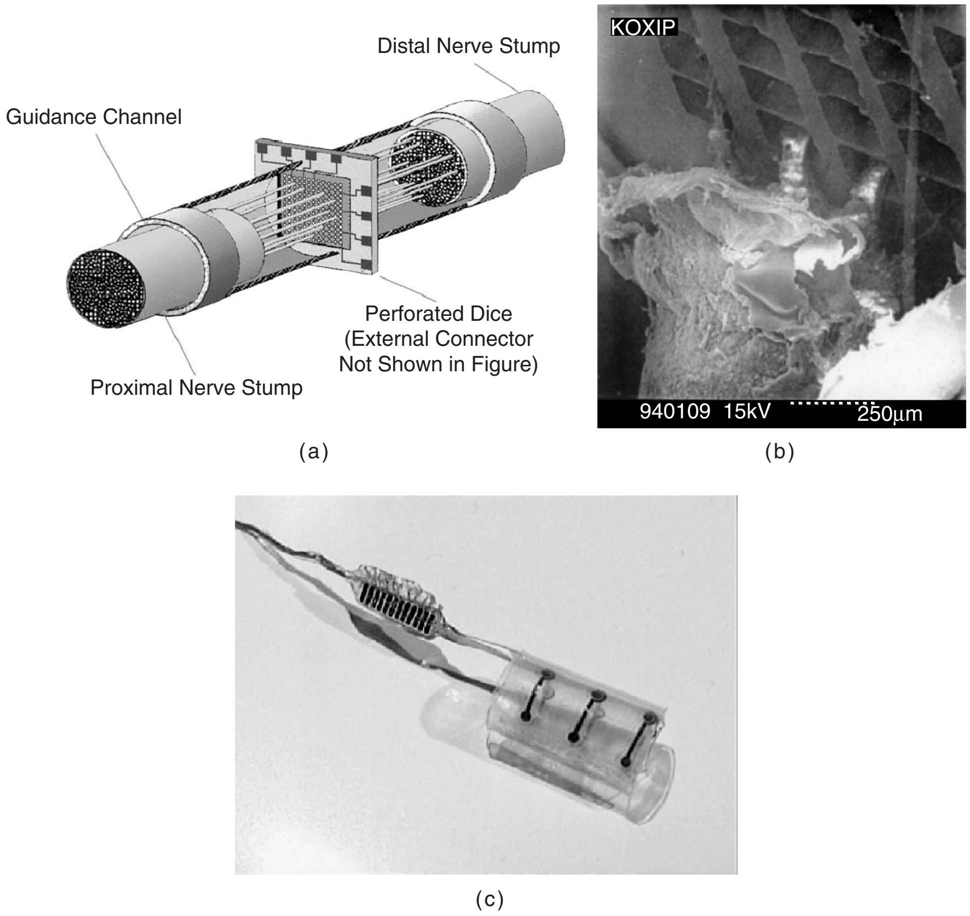


Figure 9. *(a) The regeneration-type electrode and (b) an example of regeneration of the peripheral nerve fibers through the holes. (c) The cuff-type electrode.*

using ProMechanica Motion. This model is useful to evaluate the performance of every underactuated hand based on the RTR2 finger mechanism [17]. It is the result of a design process that can be applied for developing a generic robotic or prosthetic hand with a cable actuation system. The human hand geometric and kinematics characteristics have been studied in order to develop a hand much closer to the anthropomorphic size and movements. In particular, we focused on the fingers' sizes and joints range. Using the model, it has been possible to optimize the thumb position in order to mimic the human grasps and to dimension the electromagnetic motors. The resulting biomechatronic hand is depicted in Figure 10. It is able to perform several functional grasps (e.g., the lateral, the cylindrical, the pinch, and the tridigital grasps) that will be controlled by means of the neural interfaces developed in the CYBERHAND framework or by means of EMG signals (see the previous section "Results and Current Work on Noninvasive and Invasive Neural Interfaces").

The sensory system is the core of the CYBERHAND control system, and it should have a twofold function.

- It should provide input signals for the low-level control loop of the grasping phase, thus enabling local and autonomous control of the grasp without requiring the user's attention and reaction to incipient slippage. The low-level control system should increase the grasping force as soon as incipient slippage occurs and the object is going to slip, and thus it should replicate the user's natural reaction without requiring his/her attention and specific effort. The regulation grasping force must be an unconscious process, since humans don't feel muscles when they use them. The ideal control requires a simple starting command to perform a secure grasp, independently of the specific object characteristics in terms of shape, size, and texture.
- The artificial sensory system should generate sensory signals (contacts, slippage, hand posture, and surface texture) to be transmitted to the user through an appropriate neural interface (high-level control loop) and neural algorithms. The transmission of sensory information directly stimulating the nervous system (afferent nerves) by means of the neural interfaces will be exploited during the CYBERHAND Project.

Extensive proprioceptive and exteroceptive sensory systems have been developed in the Progressive and Adaptive Learning for Object Manipulation (PALOMA) Project framework. The CYBERHAND sensory system is the evolution of the PALOMA Hand sensory system in order to achieve the right compromise between the system complexity and the space limitations. Proprioception is included in order to provide the required information on all the phalanges of the hand. The sensory system includes:

- 15 Hall-effect sensors embedded in all the joints of each finger
- an incremental magnetic encoder and two stroke end Hall-effect sensors on each of the six motors
- five tension sensors on the cables.

The Hall-effect sensors and the encoders are used to provide information about the position of all the phalanges during grasping and manipulation tasks. The tensiometers that measure the tension on the cables controlling the fingers flexion are meant to mimic the function of the Golgi tendon organs that give information about the tendon stretches.

The exteroceptive sensory system currently includes:

- flexible contact sensors
- three-axial strain gauge force sensors.

Contact sensors provide on-off information to the tactile sensing system. Efforts have been made in order to confer a high contact sensitivity (about 10 mN) to emulate the mechanoreceptors of the human hand in an engineering implementation, according to neurophysiology studies [18]. The three-axial strain gauge sensors will be mounted on the thumb, index, and middle fingertips for detecting the three components of an applied force.

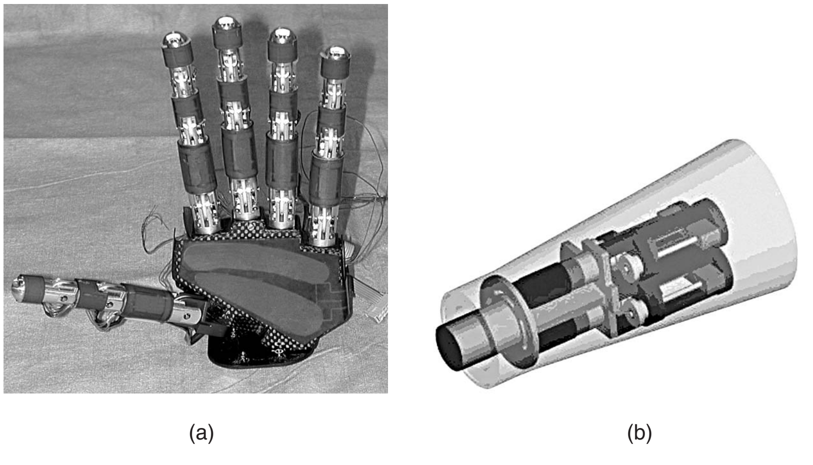

(a) (b)

Figure 10. (a) The five-fingered hand is underactuated:16 DOF are actuated by six motors. Five motors [(b) integrated in the socket] control the fingers' flexion, and one motor (integrated in the palm) controls the thumb abduction/adduction. The estimated grasping force is 45 N. The estimated total weight (including the actuation system) of the CYBERHAND biomechatronic hand is about 700 g, and the dimensions are: 191 mm (total length), 92.2 mm (length of fingers), 14 mm (diameter of fingers), 95 mm (palm width), and 40 mm (palm thickness).

The IST-FET PALOMA Project, a Biologically Inspired Multinetwork Architecture

In robotics, biology has been a source of inspiration for the development of biomimetic components as well as new control models for biomorphic robotic platforms. But the advances of robotics technology in the development of humanlike components, i.e., sensors and actuators, is improving the opportunities of its application in the study of humans, as a tool for neurophysiologists, physiologists, neuroscientists, and psychologists to validate biological models and to carry out experiments that may be difficult or impossible with human beings.

Therefore, the interaction between biological science and robotics becomes twofold [19], [20] (see Figure 11): on one hand, biology provides the knowledge of the human system needed to build humanoid robots (or humanlike components) [21], and, on the other hand, anthropomorphic robots represent a helpful platform for experimental validation of theories and hypotheses formulated by scientists [22].

The PALOMA (a biologically inspired multinetwork architecture) Project is aimed at developing an anthropomorphic robotic manipulation platform, which mimics human mechanisms of perception and action, and can implement neurophysiological models of sensory-motor coordination through a strict interaction between the roboticist and the neuroscientist partners.

The system developed in the PALOMA Project is composed of sensors and actuators replicating some level of anthropomorphism in the physical structure and/or in the functionality. It is worth noting that their specifications are defined together by roboticists and neuroscientists: on the neuroscientific side, the sensory-motor functionality that the robotic platform should possess and, on the robotic side, the best available robotics technology.

Neurophysiologic Requirements

Addressing sensory-motor coordination control schemes for grasping and manipulation, the anthropomorphic model considered as reference in PALOMA is the human upper torso, including an arm, one hand, a head, and the corresponding sensory apparatuses.

The human arm can be modeled with a shoulder with at least 3 DOF, an elbow with 1 DOF, and a wrist with 3 DOF. The shoulder and elbow allow positioning the hand in the workspace, while the wrist allows defining the orientation of the hand. The biological motor control for the arm requires proprioceptive information of the arm as provided by the muscle spindles and the Golgi tendon organs. No special requirements have been formulated for the arm speed and acceleration, in consideration of the addressed task of grasping.

For the hand, studies on the human hand and its functionality show that at least three fingers are necessary to perform most human grasps [23]; hence, the human model of the hand has to include at least the thumb, the index finger, and the middle finger, with 3 DOF for the index and middle fingers and 4 DOF for the thumb, and the proprioceptive and somatosensory apparatus.

The main human eye movements considered are saccades (rapid eye movements that change fixation from one target to another) and smooth pursuit (slow, smooth eye movements that enable one to follow a steadily moving target). Even though eye muscles allow small rotations of the eyeballs, we can approximate the eye model with a common tilt movement and independent pan movements allowing eye vergence. To approximate the human eye range of motion, 120° should be achieved for the tilt and 60° for the pan movements. Especially for saccades, eye speed is an important requirement; in humans it is, on average, around 300°/s, but can reach as high a speed as 900°/s [24]. The intraocular distance in humans is approximately 70 mm. The accuracy of the head and eye movements should be enough to guarantee that a point of interest is never put outside the fovea by positioning errors. This depends on a number of factors, including the sensor size, the focal length, and the distance of the point of interest. By considering likely values for such parameters, a maximum error of 2° has been calculated.

For the neck, the ventral/dorsal flexion, lateral flexion, and rotation are considered [25], [26]; according to [26], ventral and dorsal flexions occur around different axes; therefore, a total of 4 DOF are required. The reference

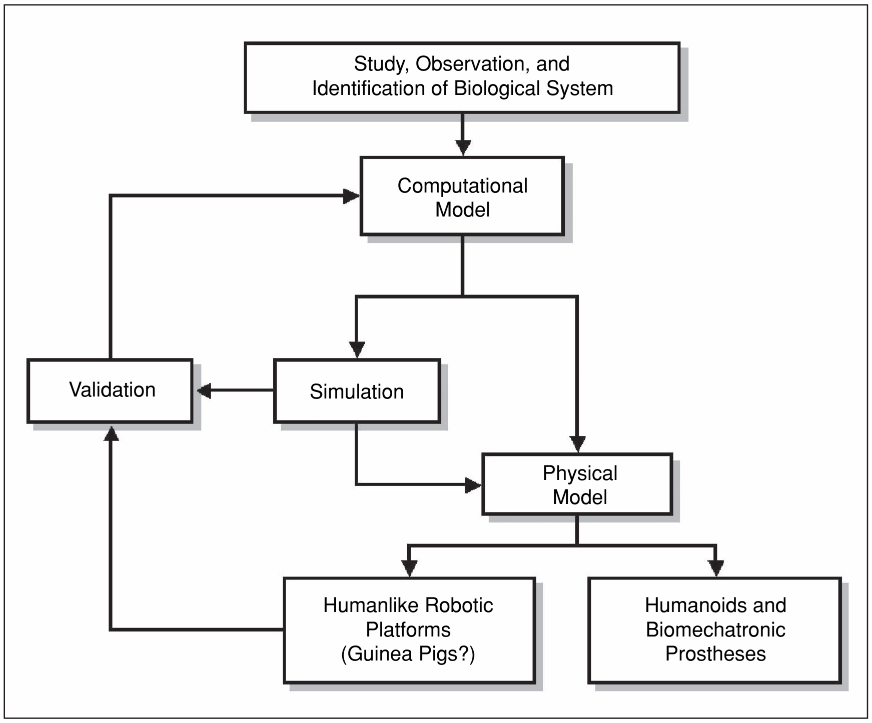


Figure 11. *The relation between biological science and robotics. In the more traditional interpretation of biological inspiration, the study, observation, and identification of a biological system is used to formulate a computational model and to derive a physical model, with or without a previous simulation, based on which humanoids or biomechatronic components can be built. In the neurorobotic interpretation, the physical model is used to build a humanlike robotic platform for experimental validation of the starting model, like a robotic guinea pig.*

ranges of motion are 45°–60° for the ventral flexion, 55°–60° for the dorsal flexion, 40° for the lateral flexion, and 70°–80° for the rotation.

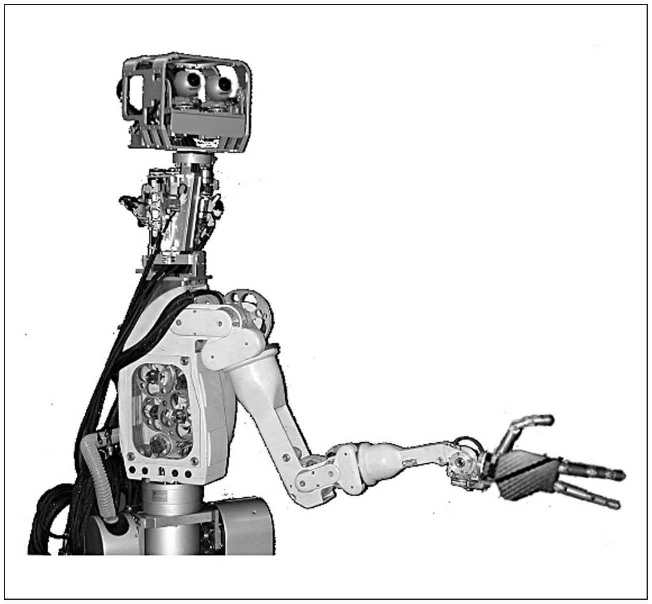


Figure 12. The PALOMA robotic artifact.

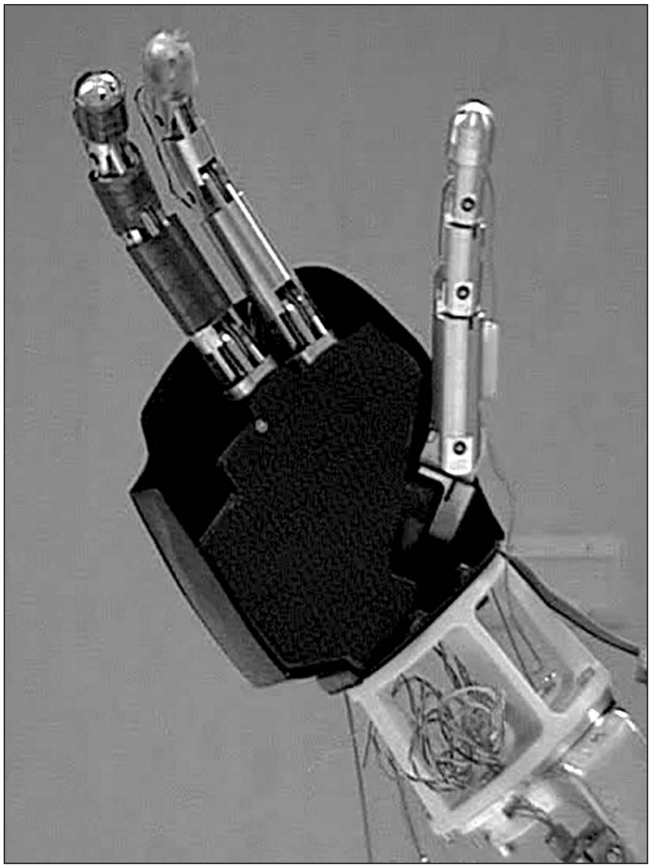


Figure 13. The three-fingered PALOMA hand. The thumb has three phalanges and a trapezometacarpal (TM) joint with 2 DOF for the movement of the thumb along the flexion plane in order to enable several grasping configurations.

Regarding the perception system, two basic apparatuses were indicated as important for the addressed applications:

- a somesthetic perception system, providing sensory information on the actual status of arm and hand, usually related via proprioceptive and somatosensory signals. The classifications adopted in neuroscience are fast adapting (FA) and slowly adapting (SA) receptors of different types, related to their presence in the superficial (I) or deep (II) skin layers. The physiological model of the somatosensory system consists of tactile FAI, FAII, SAI, and SAII afferent signals [27], while the proprioception is analogous to the arm (i.e., information from muscle spindles and Golgi tendon organs). The artificial sensory system should provide information on contact making and breaking, slip friction between object and fingertips, object shape, and force vector at the contact points
- a visual apparatus, to give information about the hand configuration during the reaching and grasping task and about the object to be grasped, with specific reference to shape, orientation of grip axis with respect to gravity, size (for size-weight association), and position.

Development of the PALOMA Humanlike Robotic Platform

The overall PALOMA robotic platform (shown in Figure 12) consists of

- a three-fingered robotic hand, with a somatosensory system, which includes proprioceptive and tactile systems
- a robotic head equipped with a stereoscopic vision system
- an anthropomorphic 8-DOF robot arm, with a proprioceptive sensory system.

The basic characteristics of all the components are described in the following.

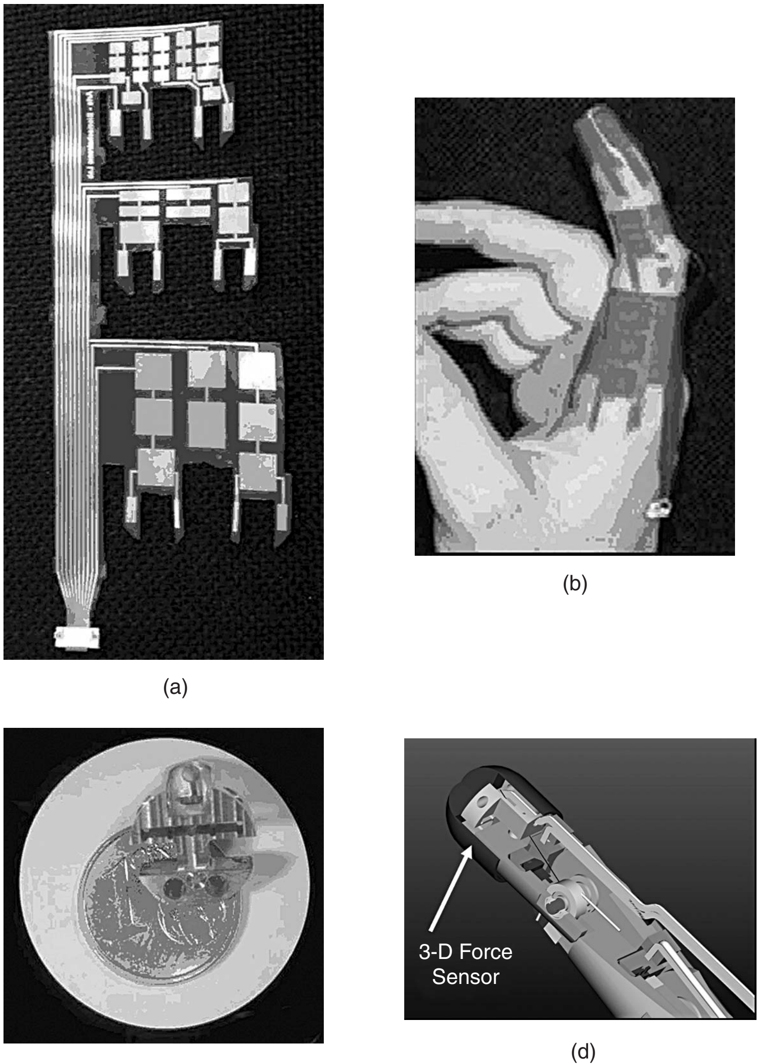
The Robotic Hand

A three-fingered anthropomorphic hand has been developed, starting from the biomechatronic three-fingered RTR2 hand [17], [28], [29]. The PALOMA hand has been designed for grasping at least the set of experimental objects identified by the neuroscientists, for generating bioinspired sensory information, and for having anthropomorphic dimensions and weight. Other advanced technical solutions have been analyzed, but they do not respect the PALOMA size and weight requirements [30], [31]. The grasping kinematics and dynamics have been analyzed by means of a specific 3-D CAD model of the hand created using ProMechanica Motion. The number of grasping configurations has been improved by changing the thumb mechanism and position and designing a new palm (see Figure 13).

Regarding the mechanical structure, four dc motors (three are extrinsic and control the flexion/extension movements of the three fingers independently, and the last one is integrated in the palm and used for the adduction/abduction movement of the thumb) have been used for actuating 10 DOF, so each finger is underactuated, and the mechanism is the same as the RTR2 and CYBERHAND hands. The total weight (including the actuators) is about 500 g.

The perception system includes proprioceptive and exteroceptive sensory systems in order to achieve the neurophysiologic requirements. Each finger is provided with a number of sensory signals: 1) a high density matrix of on-off tactile sensitive areas for each finger, distributed on the volar and lateral sides of the phalanges [see Figure 14(a)]; 2) one 3-D force sensor embedded in the fingertip, providing the three force components of the contact [see Figure 14(b) and (c)]; 3) three Hall-effect sensors (one for each joint) mounted as angle joint sensors; 4) one tension sensor mounted at the base of the finger; and 5) one encoder. In addition, an accelerometer is mounted within the palm for detecting the contact of the hand with the environment.

In addition to the sensors currently integrated onto the robotic hand, a micro 3-D force sensor (2300 μm × 2300 μm × 1300 μm) is under development at Scuola Superiore Sant'Anna. Together with the neuroscientific partners, the possible distribution of a number of such sensors in the artificial hand skin that is under development has been studied and defined. At present, the missing steps of the fabrication process of the sensor's back side have been successfully completed. Also, the process for the front side (the silicon substrate, i.e., support wafer, with aluminum metallizations and gold pads) has been studied, the related masks have been designed, the process has been completed, and the sides have been assembled (see Figure 15).



(a) (b) (c) (d)

Figure 14. *(a) A matrix of on-off contact sensors has been developed for localizing the contact points on the fingers surfaces during the implementation of grasping tasks. The activation threshold of each sensor is less than 50 g, and their receptive fields are in the range of 3–15 mm^2. (b) A specific mechanical structure hosting six strain gauges has been developed and (c) integrated in the fingertips for measuring the components of the 3-D force vector during the implementation of grasping tasks.*

The Robotic Head and Vision System

With respect to the vision system, in order to focus the anthropomorphism requirements, a retinalike vision system is simulated on the robotic head. It is based on space variant images whose resolution is higher in the center (fovea) and degrades towards the periphery, as an imitation of images generated onto the human retina (see Figure 16). In particular, the arrangement of pixels is based on a circular structure: a constant number of pixels (252) is arranged along 110 concentric circles, with decreasing width from the periphery to the center; in the central area of 42 rings, named fovea, the number of pixels is decreased by six in each ring. Therefore, these images have a total of 33,193 pixels: 110 rings with 252

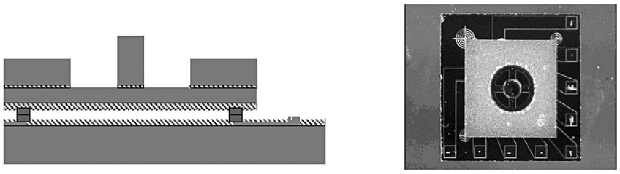
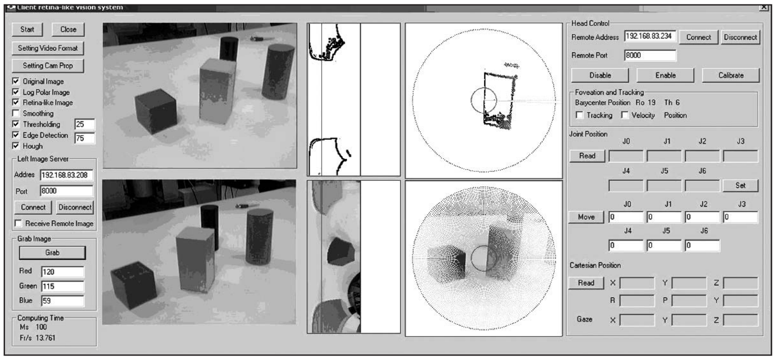


Figure 15. *A section and top view of the assembled micro 3-D force sensor. Electrical connections have been ensured via polymer flip-chip bonding technique. After assembling, the final silicon chip dimensions are 2300 μm x 2300 μm x 1300 μm.*

pixels in the periphery and 42 rings with a number of pixels decreasing toward the center in the fovea, corresponding to a standard image of 1,090 × 1,090 pixels [32].

The main advantage of this kind of sensor is that the amount of data is drastically reduced and faster processing can be achieved, provided that the eyes are moved in a continuous tracking of the points of interest (it happens in humans). This allows inclusion of visual processing in the control loop of the head and eye movements. On the other hand, retinalike cameras need very fast and accurate movements in order to focus the points of interest and have good vision. Therefore, it is crucial that they are mounted on a robotic head that is able to quickly and precisely move them.



☑ Original Image
☑ Log Polar Image
☑ Retina-like Image
☐ Smoothing
☑ Thresholding 25
☑ Edge Detection 75
☑ Hough
Addres 192.168.83.208
Port 8000
☐ Receive Remote Image
Red 120
Green 115
Blue 59
Ms 100
Fr/s 13.761
Remote Address 192.168.83.234
Remote Port 8000
Barycenter Position Ro 19 Th 6
☐ Tracking ☐ Velocity Position
J0 0 J1 0 J2 0 J3 0
J4 0 J5 0 J6 0

Figure 16. *An example of a retinalike image with the corresponding log-polar projection and of a step of visual processing (edge detection).*

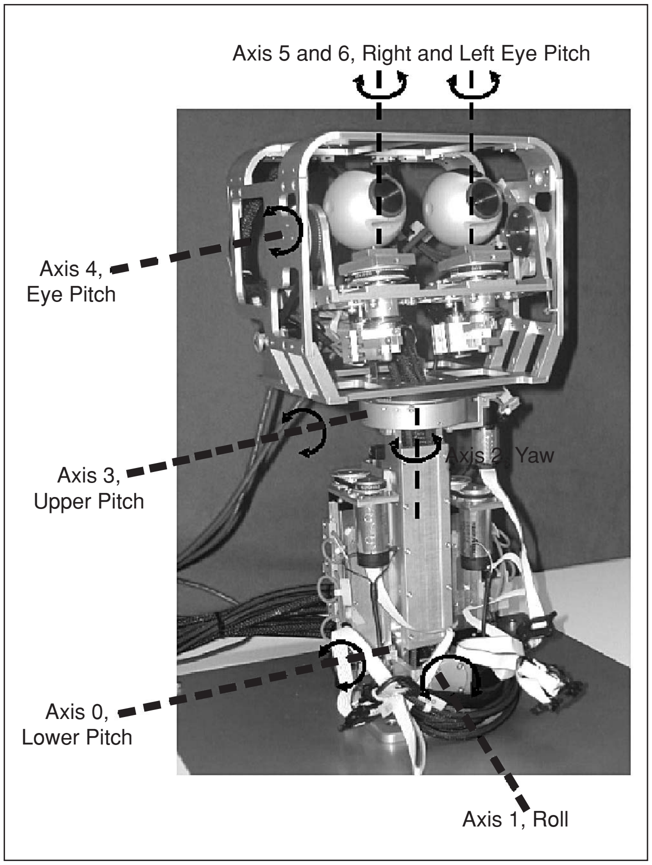


Figure 17. *Picture of the anthropomorphic robotic head and DOF configuration.*

The mechanical structure and the performance of the robotic head (Figure 17) have been designed based on the model and performance of the human head in terms of DOF, ranges of motion, speeds, and accelerations. The resulting head has a total of 7 DOF: 4 DOF on the neck (one yaw, two pitches at different heights, and one roll), 1 DOF for a common eye tilt movement, and 2 DOF for independent eye pan movements. The performances of the robotic head in terms of ranges of motion, speeds, and accelerations are reported in Table 3. The 2-DOF performing pan movement of the eye permits vergence of the two cameras, thus allowing foveation of targets. The performance of the head allows performance of the human eye movements of smooth pursuit and saccades, as well. The head is equipped with incremental encoders for measuring the positions of all the joints as proprioceptive information. The direction of gaze is calculated from the geometrical specifications of the robotic head and from the configuration of the eyes in the joint space. For the smooth pursuit movements, a simplified vestibulo-ocular reflex (VOR) has been implemented to counterbalance the eye movements with respect to the head movements.

The Robot Arm

The robotic arm integrated in the platform is an 8-DOF robot arm named Dexter and developed by S.M. Scienzia Machinale, Pisa, Italy, as an assistive robot.

Its physical structure is highly anthropomorphic (see Figure 12), with the link arrangement reproducing the human body from trunk to wrist. A trunk, a shoulder, an elbow, and a wrist can be identified in the Dexter kinematic structure and, as a consequence, human movements in the interaction with the environment can be easily mimicked.

The mechanical transmission system is realized through steel cables (which allow the six distal motors to be located on the first link, representing the trunk) by achieving low weight and low inertia for the distal joints. The first two proximal joints are aimed at prepositioning the distal 6-DOF manipulator to increase the overall workspace. They also help compensate the difference in the number of DOF between the human shoulder (3 DOF) and the Dexter shoulder (2 DOF). The proprioceptive information on the position of all the joints are provided by incremental encoders located on each motor.

The arm can be controlled through a standard stiff proportional-integral differential (PID) controller and through interaction controls with self-adjusting compliance [33]. Furthermore, original control schemes have been developed, aimed at implementing biomorphic control mechanisms based on the combination of a feedforward control loop with a feedback control loop [34].

Conclusions

Considering the current evolution of biomechatronics and biorobotics research towards parallel directions, privileging

Table 3. Main features of the robotic head.

Axis	Range of Motion (°)	Maximum Velocity (°/s)	Maximum Acceleration (°/s^2)
Lower pitch	±25	20	200
Roll	±30	25	200
Yaw axis	±100	170	750
Upper pitch	±30	120	750
Eye pitch	±47	600	4,500
Right eye yaw	±45	1,000	10,000
Left eye yaw	±45	1,000	10,000

either the improvement of biomimetic hardware performances, or the improvement of humanlike behavior, the 5th Framework Programme of the European Commission provides the authors with the opportunity to explore innovative biorobotic systems at three different levels: a biomimetic wormlike robot to be applied in endoscopy; a highly anthropomorphic robotic hand to be used as a cybernetic prosthesis connected with the human body; and a humanlike robotic platform for manipulation, to be used for conducting experiments on sensory-motor coordination models.

The ongoing experience of the BIOLOCH Project shows that a sophisticated hardware imitating the mechanisms of low-level animals can reach a high degree of effectiveness by overcoming the limitations of control problems. The main issues behind this activity are essentially related to miniaturization and merging technologies able to go beyond the limits of traditional robot design.

The CYBERHAND Project explores the application of bionic systems with a moderate level of intelligence to be integrated in humans. The authors propose the development of a cybernetic hand prosthesis connected to the nervous system by means of specific interfaces implementing a lifelike perception and control of a specific biomechatronic hand prosthesis.

The PALOMA Project explores the application of robotics in the study of man, by providing artificial platforms for validating neuroscientific models. The authors propose a work on the development of an anthropomorphic robotic platform for sensory-motor coordination in human grasping and inspired by the analysis of neurophysiologic specifications for the human actuators and sensory systems. The integrated platform is being used for implementing a multinetwork architecture that correlates sensory and motor signals and for validating a five-step model of progressive learning of grasping and manipulation skills [35] mimicked from human babies.

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Keywords

Biorobotics, neuro-robotics, cybernetic hand, bioinspired sensors, underactuated hand, biomimetic robot.

References

[1] L. Phee, D. Accoto, A. Menciassi, C. Stefanini, M.C. Carrozza, and P. Dario, "Analysis and development of locomotion devices for the gastrointestinal tract," *IEEE Trans. Biomed. Eng.*, vol. 49, no. 6, pp. 613–616, June 2002.

[2] D. Accoto, C. Stefanini, L. Phee, A. Arena, G. Pernorio, A. Menciassi, M.C. Carrozza, and P. Dario, "Measurements of the frictional properties of the gastrointestinal tract," in *Proc. 2nd AIMETA Int. Tribology Conf.*, Vienna, Austria, 2001.

[3] K. Autumn, Y. Liang, T. Hsieh, W. Zesch, W.-P. Chan, T. Kenny, R. Fearing, and R.J. Full, "Adhesive force of a single gecko foot-hair," *Nature*, vol. 405, no. 6787, pp. 681–685, 2000.

[4] A. Menciassi and P. Dario, "Bio-inspired solutions for locomotion in the gastrointestinal tract: background and perspectives," *Philos. Trans. R. Soc. London A, Math. Phys. Sci.*, vol. 361, no. 1811, pp. 2287–2298, 2003.

[5] R.C. Brusca and G.J. Brusca, *Invertebrates*. Sunderland, MA: Sinauer Associates, 1990.

[6] K.J. Quillin, "Kinematic scaling of locomotion by hydrostatic animals: ontogeny of peristaltic crawling by the earthworm lumbricus terrestris," *J. Experimental Biol.,* vol. 202, no. 6, pp. 661–674, 1999.

[7] A. Menciassi, S. Gorini, G. Pernorio, and P. Dario, "A SMA actuated artificial earthworm," in *Proc. IEEE Int. Conf. Robotics Automation*, New Orleans, LA, 2004, pp. 3282–3287.

[8] D.P. Tsakiris, A. Menciassi, M. Sfakiotakis, G. La Spina, and P. Dario, "Undulatory locomotion of polychaete annelids mechanics, neural control and robotic prototypes," in *Proc. Computational Neurosciences CNS 2004 Meeting*, Baltimore, MD, 2004.

[9] S. Hirose, *Biologically Inspired Robots: Snake-Like Locomotors and Manipulators*. New York: Oxford Univ. Press, 1993.

[10] M.F. Land, "Optics and vision in invertebrates," in *Handbook of Sensory Physiology*, VII/6B, H.-J. Austrum, Ed. Berlin, Germany: Springer-Verlag, 1981, pp. 471–592.

[11] NATO ASI Series, *Robots and Biological Systems: Towards a New Bionics?*,vol. F102, P. Dario, G. Sandini, P. Aebischer, Eds. New York: Springer-Verlag, 1993.

[12] M. Zecca, S. Micera, M.C. Carrozza, and P. Dario, "On the control of multi-functional hand prostheses by using the EMG signal," *Crit. Rev. Biomed. Eng.*, vol. 30, no. 6, pp. 419–416, 2002.

[13] K. Englehart and B. Hudgins, "A robust, real-time control scheme for multifunction myoelectric control," *IEEE Trans. Biomed. Eng.*, vol. 50, no. 7, pp. 848–854, 2003.

[14] S. Micera, G. Vannozzi, A.M. Sabatini, and P. Dario, "Improving detection of muscle activation intervals," *IEEE Eng. Med. Biol. Mag.*, vol. 20, no. 6, pp. 38–46, 2001.

[15] K. Englehart, B. Hudgins, and P.A. Parker, "A wavelet-based continuous classification scheme for multifunction myoelectric control," *IEEE Trans. Biomed. Eng*. vol. 3, no. 3, pp. 302–311, 2001.

[16] P. Dario, P. Garzella, M. Toro, S. Micera, M. Alavi, J.-U. Meyer, E. Valderrama, L. Sebastiani, B. Ghelarducci, C. Mazzoni, and P. Pastacaldi, "Neural interfaces for regenerated nerve stimulation and recording," *IEEE Trans. Rehab. Eng.*, vol. 6, no. 4, pp. 353–363, 1998.

[17] B. Massa, S. Roccella, M.C. Carrozza, and P. Dario, "Design and development of an underactuated prosthetic hand," in *Proc. IEEE Int. Conf. Robotics Automation*, Washington, DC, 2002, pp. 3374–3379.

[18] R.S. Johansson and A.B. Vallbo, "Spatial properties of the population of mechanoreceptive units in the glabrous skin of the human hand,"

Brain Res., vol. 184, no. 2, pp. 353–366, 1980.
[19] P. Dario, E. Guglielmelli, and C. Laschi, "Humanoids and personal robots: Design and experiments," *J. Robot. Syst.*, vol. 18, no. 12, pp. 673–690, Dec. 2001.
[20] B. Adams, C. Breazeal, R. Brooks, and B. Scassellati, "Humanoid robots: A new kind of tool," *IEEE Intell. Syst.*, vol. 15, no. 4, pp. 25–31, July-Aug. 2000.
[21] R.A. Brooks, *Cambrian Intelligence*. Cambridge, MA: MIT Press, 1999.
[22] M. Kawato, "Robotics as a tool for neuroscience: Cerebellar internal models for robotics and cognition," in *Robotics Res., 9th Int. Symp.*, M.H. Holerbach and D.E. Koditschek, Eds. London: Springer-Verlag, 2000, pp. 321–328.
[23] A. Kapandji, *The Physiology of the Joints, Vol.1, Upper Limb*. Edinburgh, U.K.: Churchill Livingstone, 1982.
[24] E.R. Kandel, J.H. Schwartz, and T.M. Jessell, *Principles of Neural Science*, 4th ed. New York: McGraw-Hill, 2000.
[25] G. Westling and R.S. Johansson, "Responses in glabrous skin mechanoreceptors during precision grip in humans," *Exp. Brain Res.*, vol. 66, no. 1, pp. 128–140, 1987.
[26] J. Hamill and K.M. Knutzen, *Biomechanical Basis of Human Movement.* Baltimore, MD: Williams & Wilkins, 1995.
[27] G.A. Thibodeau and K.T. Patton, *Anatomy and Physiology*, 3rd ed. St. Louis, MO: Mosby, 1996.
[28] M.C. Carrozza, F. Vecchi, F. Sebastiani, G. Cappiello, S. Roccella, M. Zecca, R. Lazzarini, and P. Dario, "Experimental analysis of an innovative prosthetic hand with proprioceptive sensors," in *Proc. IEEE Int. Conf. Robotics Automation*, Taipei, Taiwan, 2003, pp. 2230–2235.
[29] M. Zecca, G. Cappiello, F. Sebastiani, S. Roccella, F. Vecchi, M.C. Carrozza, and P. Dario, "Experimental analysis of the proprioceptive and exteroceptive sensors of an underactuated prosthetic hand," *Int. J. Human-Friendly Welfare Robot. Syst.*, vol. 4, no. 4, pp. 2–6, 2003.
[30] J. Butterfass, G., Hirzinger, S. Knoch, and H. Liu, "DLR-Hand II: Next generation of a dextrous robot hand," in *Proc. IEEE Int. Conf. Robotics Automation*, Seoul, Korea, 2001, pp. 109–114.
[31] C.S. Lovchik and M.A. Diftler, "The Robonaut hand: A dexterous robot hand for space," in *Proc. IEEE Int. Conf. Robotics Automation,* Detroit, MI, 1999, pp. 907–912.
[32] G. Sandini, P. Questa, D. Scheffer, and A. Mannucci, "A Retina-like CMOS sensor and its applications," in *Proc. IEEE Sensor Array Multichannel Signal Processing Workshop*, Cambridge, MA, 2000, pp. 514–519.
[33] L. Zollo, B. Siciliano, C. Laschi, G. Teti, and P. Dario, "An experimental study on compliance control for a redundant personal robot arm," *Robot. Autom. Syst.*, vol. 44, no. 2, pp. 101–129, 2003.
[34] L. Zollo, B. Siciliano, E. Guglielmelli, and P. Dario, "A bio-inspired approach for regulating visco-elastic properties of a robot arm," in *Proc. IEEE Int. Conf. Robotics Automation*, Taipei, Taiwan, 2003, pp. 3576–3581.
[35] L. Zollo, E. Guglielmelli, G. Teti, C. Laschi, S. Eskiizmirliler, F. Carenzi, P. Bendahan, M.A. Maier, Y. Burnod, and P. Dario, "Abio-inspired neuro-controller for an anthropomorphic head-arm robotic system," in *Proc. IEEE Conf. Robot. Automat.*, Barcelona, Spain, 2005, pp. 12–17.

Paolo Dario received the Dr. Eng. degree in mechanical engineering from the University of Pisa, Italy, in 1977. Currently, he is a full professor of biomedical robotics at the Scuola Superiore Sant'Anna, Pisa, Italy. He teaches the course on mechatronics and biomedical robotics at the School of Engineering, University of Pisa. He has been a visiting professor at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, and at Waseda University, Tokyo, Japan. He is the founder of the Advanced Robotics Technologies and Systems (ARTS) Laboratory and Director of the Center for Research in Microengineering (CRIM) Laboratory of the Scuola Superiore Sant'Anna, where he supervises a team of approximately 95 researchers and Ph.D. students. His main research interests are in the fields of biomedical robotics, mechatronics, and microengineering, specifically in sensors and actuators for biomedical applications. He is the coordinator of many national and European projects, the editor of two books on the subject of robotics, and the author of more than 200 scientific papers. Dario is a member of the Board of the International Foundation of Robotics Research. He is the coeditor of the *Journal of Micro-Mechatronics*, a member of the steering committee of the *Journal of Microelectromechanical Systems*, the guest editor of the special issue on medical robotics of *IEEE Transactions on Robotics and Automation,* and an editorial committee member of the following journals: *Journal of Robotic Systems, Journal of Robotics and Mechatronics, Advanced Robotics, Autonomous Robots,* and *Biomedical Microdevices.* He served as president of the IEEE Robotics and Automation Society in 2002–2003 and as cochair of the Technical Committee on Medical Robotics of the Society. He currently serves as cochair of the technical committees on Biorobotics and on Robo-Ethics.

Maria Chiara Carrozza received the Laurea degree in physics from the University of Pisa, Italy, in 1990 and the Ph.D. in mechanical engineering at Scuola Superiore Sant'Anna, Pisa, in 1994. She is an associate professor of biomedical robotics at Scuola Sant'Anna and is the coordinator of the Advanced Robotic Technology and System (ARTS) Laboratory. She is the author of several papers published in international scientific journals on different issues related to the design, fabrication, and assessment of micromechatronic and biomechatronic systems, with a specific focus on biomedical microengineering, micromanipulation, artificial hands, and systems for functional augmentation and substitution. She is coauthor of international patents, and she is cofounder of two spin-off companies of Scuola Sant'Anna in the areas of microengineering and technology assessment. She serves as a reviewer of *IEEE Transactions of Robotics*, and she has been guest coeditor for the "Special Issue on Rehabilitation Robotics" of the international journal *Autonomous Robots*. She has been appointed a visiting professor at the Technical University of Vienna for a course called *Biomechatronics*. She serves as director of the research division of the Scuola Superiore Sant'Anna, and she is an elected member of the executive board of the Italian National Group of Bioengineering. She is a Member of the IEEE Engineering in Medicine and Biology and the IEEE Robotics and Automation Societies.

Eugenio Guglielmelli received the Laurea degree and the Ph.D. in electronic engineering from the University of Pisa, Italy, in 1991 and in 1995, respectively. He is currently associate professor of bioengineering at Campus Bio-Medico University in Rome, Italy, where he teaches the courses of biomechatronics and of rehabilitation bioengineering and where he also cofounded the new Research Laboratory of Biomedical Robotics and EMC.

For the last 15 years, he has been working in the field of biomedical robotics at the Scuola Superiore Sant'Anna (Pisa, Italy) where he also served (2002–2004) as the head of the Advanced Robotics Technology & Systems Laboratory (ARTS Lab). His main current research interests are in the fields of novel theoretical and experimental approaches to human-centered robotics and to biomorphic control of mechatronic systems and in their application to robot-mediated motor therapy, assistive robotics, and neuro-developmental engineering. He has been a coauthor and workpackage leader of several research and development projects in the III, IV, V, and VI Framework Programmes of the European Commission.

He was a guest coeditor of the "Special Issue on Rehabilitation Robotics" of the international journal *Autonomous Robots*. He served (1999–2004) as a founding member of the Scientific Management Board of the Italian INAIL Research Centre on Rehabilitation Engineering and as principal investigator on assistive technology.

He is a Member of the IEEE Robotics and Automation and IEEE Engineering in Medicine and Biology Societies and is a member of the Association for the Advancement of Assistive Technology in Europe (AAATE). He served (2002–2003) as secretary of the IEEE Robotics and Automation Society, and he is currently cochair of the RAS Technical Committee on Rehabilitation Robotics. He serves on the program committees of several international conferences and was a general cochair of the 1998 International Conference on Humanoid Robotics (HURO).

Cecilia Laschi is an assistant professor of biomedical engineering at the Scuola Superiore Sant'Anna in Pisa, Italy. She graduated with a degree in computer science from the University of Pisa, Italy, in 1993 and received the Ph.D. in robotics from the University of Genoa, Italy, in 1998.

Since 1992 she has been with the ARTS Lab (Advanced Robotics Technology and Systems Laboratory) of the Scuola Superiore Sant'Anna in Pisa, Italy.

Her research interests are in the fields of biomedical robotics, artificial robotic perception (robot vision and artificial tactile perception), and multisensory integration for robotic manipulation. The main application areas are neurorobotics and personal robotics. She has been involved in many national and EU-funded projects in the field of robotics and assistive technologies.

She is a Member of the IEEE, the IEEE Engineering in Medicine and Biology Society, and the Robotics and Automation Society (for which she cochairs the Technical Committee on Human-Robot Interaction and Coordination). From July 2001–June 2002 she was a visiting researcher at the Humanoid Robotics Institute of the Waseda University in Tokyo, as a Japan Society for the Promotion of Science (JSPS) Fellow.

She has authored/coauthored more than 80 papers that have appeared in international journals and conference proceedings.

Arianna Menciassi received her Laurea degree in physics (with honors) from the University of Pisa in 1995. In the same year, she joined the MiTech (now CRIM) Lab of the Scuola Superiore Sant'Anna (SSSA) in Pisa as a Ph.D. student in bioengineering, with a research program on the micromanipulation of mechanical and biological microobjects. In 1999, she received her Ph.D. degree by giving the dissertation "Microfabricated grippers for micromanipulation of biological and mechanical objects." Then, she became an assistant professor in bioengineering at SSSA. Her main research interests are in the field of biomedical microrobotics and microfabrication technologies. She is working on several European projects and international projects for the development of minimally invasive instrumentation for medical applications. She is a Member of the IEEE Engineering in Medicine and Biology and the IEEE Robotics and Automation Societies. Moreover, she servers as cochair of the Technical Committee on Surgical Robotics.

Silvestro Micera received the Laurea degree in electrical engineering from the University of Pisa, Italy, in 1996 and the Ph.D. degree in biomedical engineering from Scuola Superiore Sant'Anna (SSSA), Pisa, in 2000.

From 1998–2001, he was the project manager of the European Union GRIP Project (an integrated system for the neuroelectric control of grasp in disabled persons). He is an assistant professor of biomechanical engineering at SSSA. His research interests include the development of neurorobotic systems for function restoration in disabled persons and the analysis of the biomechanics of the musculo-skeletal system.

He is an associate editor of the *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. He is a Member of the IEEE Engineering in Medicine and Biology Society, the IEEE Systems, Man, and Cybernetics Society, the IEEE Robotics and Automation Society, and the International Functional Electrical Stimulation Society.

Fabrizio Vecchi received the Laurea degree in electrical engineering from the University of Pisa, Italy, in 1999 and the Ph.D. in robotics at the University of Genova, Italy, in 2003. He is a postdoctoral research assistant at Scuola Superiore Sant'Anna, where he is member of the Advanced Robotic Technology and System (ARTS) Laboratory. He is the project manager of the Neurorobotics Integrated Project. His research interests are in the fields of rehabilitation engineering and neuro-robotics and in the design and development of human/machine interfaces, biomechatronic prostheses, and orthoses.

Address for Correspondence: Paolo Dario, Scuola Superiore Sant'Anna, Piazza Martiri della Liberta, 33, 56127 Pisa, Italy. E-mail: dario@sssup.it.