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Nanotechnology for Humans and Humanoids

A vision of the use of nanotechnology in future robotics

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Abstract**—**Humanoids will soon co-exist with humans, helping us at home and at work, assisting elder people, replacing us in dangerous environments and somewhat adding to our personal communication devices the capability to actuate motion. In order for humanoids to be compatible with our everyday tools and our lifestyle it is however mandatory to reproduce (at least partially) the body-mind nexus that makes humans so superior to machines. This requires a totally new approach to humanoid technologies, combining new responsive and soft materials, bioinspired sensors, high efficiency power sources and cognition/intelligence of low computational cost: in other words, an unprecedented merge of nanotechnology, cognition and mechatronics.

Keywords—robotics; nanotechnlogy;

Introduction

When a goal keeper takes the ball, he ignores gravity, initial forces, spin, air friction etc. He does not perform any variational calculation to be at the right instant with his hand at the right place. He simply knows how to do it. A computer would take too much time to compute the trajectory of the ball and to control the actuation of the movement of a robotic goal-keeper. The human body exploits the multiple inputs of senses and processes them in a smart way to decide actions. The effectiveness of such an evolution-improved process relies on the fact that the same part of the brain that controls grasping controls the vision of the object to be manipulated (the visuo-motor neurons). The same happens, for instance, with another brain area which controls both speech and language interpretation. The human brain is a three dimensional, water-based, strongly interconnected circuit (each synapses is connected to some 10000 other neurons) performing the equivalent of 10^{16} binary operation per second with less than 40W. The central processing unit of a robot is a two-dimensional Silicon based circuit (no water) where each transistor is interconnected to the nearest neighbors (about a dozen) able to perform some 10^8 operations per second with about 200 W. Approaching the computational capability of a human brain would requires a Hexa-flop supercomputer whose power consumption exceed tens of MW. In addition, humans have actuation systems that are designed to optimize the brain functionality: muscles, nerves and senses have evolved to be perfectly synergistic to the neural plasticity and learning capability of the brain, resulting in the so called "orchestration" between body and mind. Mechanical motors and actuator do not work in the same way. This is why humanoid technology is much more than a combination of computer, sensors and actuators. In this paper we will shortly review the state of the art and the perspective of this research field, starting from the open source humanoid platform iCub developed by the Italian Institute of Technology.

I. BIOINPIRED ROBOTICS: NEW MATERIALS, SENSORS AND ARCHITECTURES

Our main integration effort happens on a humanoid robotic platform called iCub which we aim at evolving towards a future design incorporating new materials and advanced solutions both in the body (actuators, sensors, power, structure) and the mind (computation). The iCub project functions as a test-bed where researchers with a variety of backgrounds can prove their solutions in a challenging scenario: that is, a robotic assistant working in close contact with humans.

The current version of the iCub (see Fig. 1) is still a traditional robot shaped as a 5 year old child; about 1m tall, 27kg in weight. The robot has 53 degrees of freedom (DoF) distributed mainly in the upper part of the body allowing for instance fine manipulation as well as fast movement of the cameras towards stimuli of interest. The robot is equipped with inertial sensors (providing the sense of balance), microphones (for sound and speech), encoders (body posture), and quite unique in the current panorama of robotics, tactile sensors distributed across the whole body (4000 sensing points at the moment of writing). In the latest implementation the iCub supports compliant joints in the knees and ankles that favor impact absorption during walking [1].

To favor integration of research the robot has been created with a standard software interface and a set of development tools contained in open source repositories (GitHub) available to researchers worldwide. More than 30 iCub's have been built for research institutes as far as Japan, Korea, USA and, to a large extent, Europe.

As mentioned earlier, the iCub is evolving. New releases are starting to be designed with polymer based skeletons, joints and gears. Although current polymers are not up to the performance of metals (by a factor of 4 to 10), research into graphene inks [2] may provide a solution for hard coatings, whereas reinforced polymer nanocomposites may replace metal (jointly with a redesign of the mechanics of the robot). In addition new fully biodegradable plastic materials have been

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recently obtained by recycling the waste of the vegetable-food industries (rice, cacao, coffee, spinach, etc.). The mechanical properties of these plastics can be tuned (ultimate tensile strength and Young modulus) plastics spanning from the soft stretchable PDMS to the hard and stiff PET, and can be further modified by nanofillers to increase strength. Nanocomposites for flexible circuits and contacts have also been developed recently. Graphene-polymer nanocomposites have achieved sheet resistance in the range of 10 Ohm/cm^2, which is enough to replace metallic wiring in the robot [3].

Other possibilities include integrated electronics, wiring and tactile or temperature sensors embedded directly into the robot structure. Further into analyzing the typical robot mechanical structure, polymers designed for strength can provide 83% weight reduction in the transmission components (levers, gears, etc.) of the robot joints. Similarly a 50% weight reduction could be achieved by replacing e.g. aluminum by reinforced plastic in the robot frame (skeleton). Electric motors may also be modified by using graphene based polymers to replace the rare earth magnets currently employed.

These are just a few relevant examples of novel nanotech and nanocomposite technologies being developed specifically for robotic applications. The expected improvement is enormous, both in performance and cost reduction, as till now robotic research has been mainly employing technologies from the consumer electronics, multimedia, telecommunication or car industries.

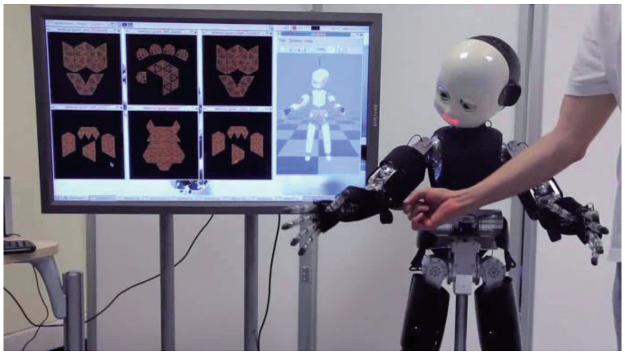

Fig. 1: the iCub robot showing interaction with a human experimenter.

Bio-inspired mechanics is an important ingredient of morphological computation which, in the spirit of “orchestrating” body and mind, states that controllers can be made simpler by relying on the correct behavior being generated automatically by the dynamics of the robot structure. Research in robotics is heading towards the design of controllers that take into account the body dynamics of the robot aided by the use of whole body tactile sensors, by verstibular signals (inertial sensors) and proprioception (joint encoders). Besides the generation of fast and accurate movements this allows the estimation of contact forces that in turn enable safe human-robot interaction, a kind of robot sociality and overall physical compliance. These robots will therefore sport the ability to learn from interaction with humans through actual physical contact.

All sensing modalities mentioned above rely on recent progress in MEMS and design of silicon-based micro-chips as well as on new materials for compliance (in the robot structure). Often the state of the art in robotics is yet to incorporate these solutions. For example one of the most reliable tactile sensing technologies is at the moment capacitive – derived from existing smart phone solutions. A ten-fold increase in accuracy is available at the prototypical stage [4].

We have incorporated a whole body capacitive skin system in the iCub humanoid robot. This research adapted the smart phone common solution to robotics by making the “capacitors” compliant employing flexible PCBs, flexible conductors and by making sure the sensors are activated by any non-electrically conductive object. The same circuitry – see Fig. 2 – performs capacitance to digital conversion, filtering and temperature drift compensation. The resulting resolution and sensitivity are good enough for typical laboratory applications, though still far from human sensitivity in terms of texture detection, shear force and incipient slip detection, e.g. during manipulation of objects.

Alternative solutions may be feasible with focused research combining MEMS, system engineering, electronics, etc. to make the existing benchtop sensors into proper industry-grade solutions. Flexible Mo/AlN heterostructures covered with Parilene have been recently developed for biomimetic multifunctional touch sensors for static/dynamic and normal/shear forces [5], as well as to reproduce Hair Cells-like sensors mimicking the internal ear of living systems or the proximity sensors of fishes moving in swarm [6].

Fig. 2: the iCub skin solution; flexible PCB structure showing the sensor allocation (left) and connection routing (right).

Another important component of measuring the body state to estimate dynamics is given by strain gauges. Recently the solutions based on semiconductor gauges have made considerable progress providing an increase in the sensitivity per unit of strain. Part of the robot body can be equipped with sensors the measure the interaction forces with the environment causing an infinitesimal deformation of the robot structure. Similarly, semiconductor-based solutions have made inertial measurements very compact and cheap. These can be incorporated into any link of the body thus providing redundant measures of acceleration (including gravity) or angular velocity. Sensory fusion techniques can be then used to estimate the body state (position, velocity, acceleration), the external forces and the body dynamics.

Additional computational techniques are employed to subtract the measured forces (internal and external) from the body dynamics (up to the points of contact measured by the distributed whole body skin sensors) finally leading to an estimation of the external forces only and their locations. Controllers can take into consideration the ensuing interaction with the environment and exploit the ability to foresee disturbing external stimuli to achieve their control targets as e.g. in balancing, walking, etc.

In recent experiments, the iCub has been shown to be able to balance, minimize angular momentum in spite of severe disturbances from the environment. These are thought to be the first steps towards human-like walking: the holy grail of humanoid robotics.

II. ARTIFICIAL INTELLIGENCE

Although the mind-body nexus cannot be truly divided into body and mind (or hardware and software), for reasons of presentation, here we discuss about the goals of intelligence in the context of future humanoid robots. We keep in mind though that often (and surprisingly) AI solutions in robotics have to necessarily take into account the body of the robot. Our wish list in AI include a few very important concepts: (i) *learning by doing* , a capability of paramount importance for advanced robotics which is typical of living systems; (ii) the ability to imitate somebody else's action (in itself a part of learning by doing); (iii) the three-dimensional vision and recognition; (iv) speech recognition is another hot topic (especially to be applied in everyday conditions) leading to social behaviors. All these capabilities are to be imagined in the context of machine learning (adaptation).

A. Learning by doing

The main difference between generic AI and learning in robotics is that a robot takes action. Data do not need to be parsed and labeled by human hands. The robot can explore the world, collect data and self-label them based on its experience: e.g. temporal continuity, motion, manipulation of objects, internal control goals, self-preservation (as in minimizing impacts), etc. All these "innate skills" can in fact contribute to learn about objects, people, effects of actions and so forth.

On the iCub, for instance, we studied the problem of learning that certain objects have functions as tools [7]. This is paradigmatic of the approach because object affordances can only be discovered by effectively trying them. We showed that indeed this is possible and machine learning techniques can select visual features on the object that map directly into the behavior of the object being manipulated: e.g. a stick for pushing rather than a rake for pulling. Learning itself is a vast subject of study. Research in machine learning algorithms spans the domain of modern statistics, optimization, function approximation, etc. the goal being that of predicting the algorithm performance beforehand. Recently, we started to employ multi-layer artificial neural network (ANN) following a resurgence of methods to train them effectively. Unexpected performance has been achieved as for example memorization of large number of objects and their recognition with high-fidelity (>90%).

As a complement to learning by doing techniques, we investigate the possibility of learning by imitation. This can take the form of a direct teaching by physical guidance – moving the robot to the correct configuration to complete a given task – or conversely by observing a human experimenter carrying out the task. Also in this case, machine learning has been used on the iCub to recognize actions and gestures performed by the human fellows. Imitation can guide a robot through complex tasks – e.g. assembly of a piece of machinery – without the need of programming it step by step on a computer.

Yet another application of the "learning by doing" paradigm is the ability to grasp objects in order to move and carry them as well as to use the hands in assembly tasks, to grasp tools and anywhere physical action is needed with a certain level of accuracy: e.g. compare grasping with pushing or other less sophisticated actions on objects. The iCub can grasp objects. In its simplest form learning to grasp requires extracting 3D information from images, interpreting it and planning a configuration of the fingers that guarantees stability. All this can be learned from self-interaction of the robot with objects as presented for example in [8].

B. Social awareness and interaction

A paradigmatic case showing the strict connection of body and mind – of action and perception – is speech. Recent results from brain science have highlighted the strict dependency of speech perception from the activation of motoric areas of the brain [9]. We have thus started investigating by means of computational experiments the performance of various cross-learning methods that employ combinations of motor and acoustic information. A database of action-speech recordings has been acquired as part of the studies of cognitive skills within the iCub project. Our goal is to achieve human-like speech recognition rates in noisy (everyday) scenarios whereby today speech recognition works well in high signal to noise ratios.

Our results clearly show that constructing sensory representation (via machine learning) by taking into account the motor structure of the data delivers a better overall performance compared to traditional acoustic features. Also in this case, ANNs seem to be delivering very high quality results. The main take home message of this research is thus – once more – that body and mind are strictly intertwined and therefore that human-like intelligence requires a human-like body. Evolution forged the action-perception connection. Our experiments may simultaneously lead to human-like performance in AI and to explaining why the brain possesses certain special action-perception neural networks [10].

As an extension to speech perception, social interaction is made of a plethora of small actions that affect the behavior/perception of the human partner. This has been studied in human-robot interaction [11]. Attention and gaze are important cues to the robot behavior. The iCub has a complex attention system that relies on biological vision and sound localization. Complex behaviors have been shown in recent experiments [12].

C. Neuromorphic hardware

Although most computation can work with traditional sensors, the efficiency of human sensors cannot be mimicked entirely in software. The temporal accuracy and encoding of neural activation requires specialized sensor designs. The neuromorphic technology is a VLSI that mimics in analog hardware the properties of neurons. Artificial receptors for vision, touch, sound can be reproduced with transistors in the exponential regime (under threshold) yielding to low power devices with no central clock. The encoding of signals as variations of the sensed quantities – e.g. light intensity, sound frequency, etc. – is also efficient since only relevant information is transmitted, stored or processed, reducing the requirements for bandwidth, memory or computational power. The output of these devices is encoded in the temporal occurrences of events or artificial neural spikes.

Modified versions of the iCub [13] use neuromorphic visual VLSI chips that provide light variation at unprecedented speed (1kHz) and at a fraction (1/10 typically) of the bandwidth required for standard cameras. In addition, focal plane processing is under development that provides a first layer of computation as for example the estimation of image pixel velocities (optical flow).

This technology promises to be extremely important to lower the power requirements of brain-like computation and ANNs processing as well as higher processing speed in tasks that require a high dynamics as for example in visual based control of movement. Examples of one of a neuromorphic chip and output image is shown in Fig. 3.

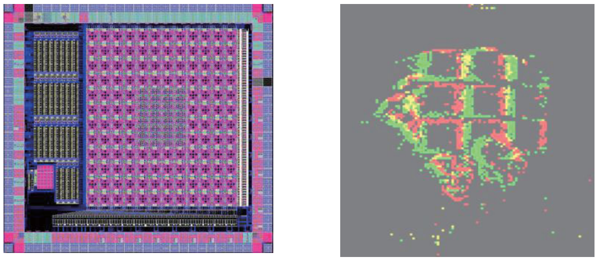

Fig. 3: examples of neuromorphic VLSI chips. Left: a space variant camera with focal plane processing. Right: output image of an event-based camera.

Beyond-silicon vision-devices are also under study, not only for robotics, but also for prostheses in degenerative eye diseases. A fully biocompatible, implantable artificial retina has been recently demonstrated and implanted in animals [14], which might be in the future exploited also for human-like vision sensors. This is based on a photovoltaic soft heterostructure consisting of a silk substrate covered by a Pedot contact a photoconductive P3HT polymer doped with C-fullerenes. The heterostructure is surgically implanted in conformal contact with the retina of the eye and it turns out to be quite effective in activating visual neurons under illumination, with no need of any external power source.

III. CONCLUSIONS

The growing integration of nanotech and robotics paves the way to new bioinspired humanoids, whose functions and behavior become as similar as possible to us. New nanocomposite materials in combination with novel sensors will improve the bodyware substantially. A robot with sensing systems and body closer to humans is ready to accept an increasing level of intelligence, thus becoming a social machine. However brain performances are presently unreachable, so that future robots, though equipped with very advanced body and sensing capabilities will rely on external intelligence: unlike humans, future humanoids will not have a local computer capable of 10^{16} operation/seconds with 40 W. Rather they will be all connected to a Si-based supercomputer through a fast wireless system. We can thus envisage a global repository of the intelligence of humanoids in the Cloud. In order this to be effective in everyday life (e.g. to ensure a response of the humanoids on a time scale comparable to that of humans in typical interacting situations) humanoids should be sub-kW machines powered by batteries, connected to the Cloud by a fast wireless protocol (e.g. 5G or 6G with transmission rate >300 Mbps), whereas the Cloud should operate at Gbps with 300ms bursts. Finally, a robot operating 12 hours per day in the house should undergo technical assistance every 4000 hours (i.e. once a year). This means that reliability should be ten times better than cars (technical assistance every 400 hours on average), with a clear impact in the level of technology to be developed.

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