A future of living machines? International trends and prospects in biomimetic and biohybrid systems

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ABSTRACT

Research in the fields of biomimetic and biohybrid systems is developing at an accelerating rate. Biomimetics can be understood as the development of new technologies using principles abstracted from the study of biological systems, however, biomimetics can also be viewed from an alternate perspective as an important methodology for improving our understanding of the world we live in and of ourselves as biological organisms. A biohybrid entity comprises at least one artificial (engineered) component combined with a biological one. With technologies such as microscale mobile computing, prosthetics and implants, humankind is moving towards a more biohybrid future in which biomimetics helps us to engineer biocompatible technologies. This paper reviews recent progress in the development of biomimetic and biohybrid systems focusing particularly on technologies that emulate living organisms—living machines. Based on our recent bibliographic analysis [1] we examine how biomimetics is already creating life-like robots and identify some key unresolved challenges that constitute bottlenecks for the field. Drawing on our recent research in biomimetic mammalian robots, including humanoids, we review the future prospects for such machines and consider some of their likely impacts on society, including the existential risk of creating artifacts with significant autonomy that could come to match or exceed humankind in intelligence. We conclude that living machines are more likely to be a benefit than a threat but that we should also ensure that progress in biomimetics and biohybrid systems is made with broad societal consent.

Keywords: biomimetic, biohybrid, living machines, mammalian robots, social robotics, neuroprosthetics, societal impacts.

1. INTRODUCTION

The development of future real-world technologies will depend strongly on our understanding and harnessing of the principles underlying living systems and the flow of communication signals between living and artificial systems.

Biomimetics is the development of novel technologies through the distillation of principles from the study of biological systems [2]. Biomimetic research operates in three directions. First, by promoting a flow of ideas from the biological sciences into engineering the latter can benefit from the millions of years of design effort performed by natural selection. Second, biomimetic artifacts can provide excellent models of their biological counterparts, allowing us to ask and answer questions about the biological system that cannot be addressed through experiment alone. Biomimetic systems thus provide a test-bed for theoretical ideas in biology and a means for generating new hypotheses for empirical research. This approach becomes particularly important when considering interactions among many elements across different levels of organization. Third, the construction of artifacts as models, to address scientific aims, can lead to the availability of a new class of technologies that can then be advanced towards innovation and direct application.

Biomimetics can, in principle, extend to all fields of biological research from, physiology and molecular biology to ecology, and from zoology to botany. Promising research areas include system design and structure, self-organization and co-operativity, new biologically-active materials, self-assembly and self-repair, learning, memory, control architectures and self-regulation, movement and locomotion, sensory systems, perception, and communication. Biomimetic research, particularly at the nano-scale, should also lead to important advances in component miniaturization, self-configuration, and energy-efficiency.

Biohybrid systems are formed by combining at least one biological component—an existing living system—and at least one artificial, newly-engineered component. By passing information in one or both directions, such a system forms a new hybrid bio-artificial entity. Biomimetic and biohybrid technologies, from nano- to macro-scale, are expected to produce

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major societal and economical impacts in quality of life and health, information and communication technologies, robotics, prosthetics, brain-machine interfacing and nanotechnology. Such systems should also lead to significant advances in the biological sciences that will help us to better understand ourselves and the natural world.

In the first decade of this century there has been an explosive growth in biomimetic research, with the number of published papers each annum doubling every two to three years [1]. From a relatively small field in the mid-1990s of just ten or so papers per year, biomimetics has expanded exponentially thereafter to reach critical mass of several hundred papers per year by 2003-2005. More than 1000 papers are now being published every year in biomimetic engineering and technology. Furthermore, this growth does not appear to be saturating, so this expansion of the area of biomimetics can be expected to continue into the near future.

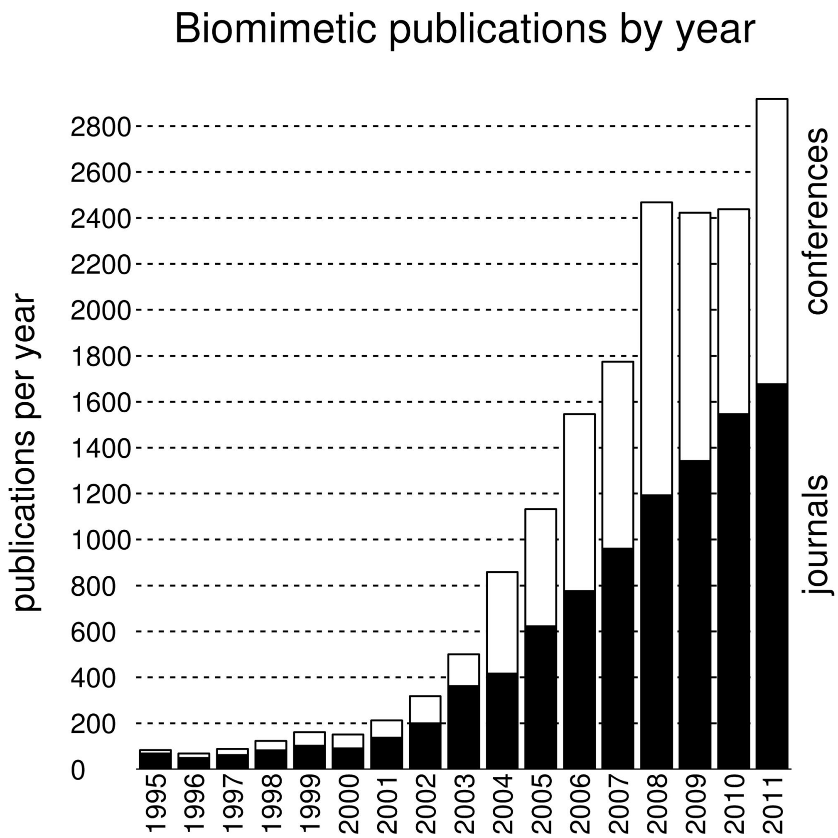

Figure 1. Growth in publications in biomimetics 1995–2011. Reproduced from Lepora et al. (2013) with permission.

Biomimetics also encompasses an expanding range of research areas, as indicated by the published research analyzed by Lepora et al. [1]. Using several synonyms for biomimetics as search terms for resources such as IEEE Xplore and the Thomson-Reuters Web of Science we were able to construct a comprehensive database of publications relating to biomimetics. We then used information analysis techniques to infer the general breakdown of the field (see, for instance, the word cloud in Figure 2). The results of this analysis showed that biomimetics now spans a diverse range of domains. Leading concepts in our analysis include 'robot', followed by 'biomimetic' and then 'control', indicating that much of contemporary biomimetic research in engineering and ICT is focused towards applications in robotics. The word cloud also shows a wide variety of research interests. For example biomedical research is a key domain as evinced by the popularity of terms such as 'tissue', 'cell' and 'bone'. Also evident are the capabilities of biological organisms, such sensing ('vision') and locomotion ('walking'), as being important foci for research efforts. These findings indicate that biomimetics is becoming a major paradigm for research in robotics and also in wider fields of engineering (note the presence of many key engineering terms in Figure 2).

In Europe, the Convergence Science Network (CSN, http://csnetwork.eu), a European Union-funded partnership across several EU countries, has taken a key role in promoting and integrating research in biomimetic and biohybrid systems. Network activities include organizing workshops, summer schools and meetings; assembling databases, video/podcast libraries, and code repositories; and, for the last three years, organizing "Living Machines" and a new international conference on biomimetic and biohybrid systems.

The concept of "Living Machines" is intended to bridge across both biomimetic and biohybrid approaches emphasizing not only the goal of creating new life-like technologies but of furthering our understanding of biology systems including ourselves. Whilst human invention has been inspired by nature throughout history, we see a deeply biomimetic approach as emerging with the work of Leonardo Da Vinci, in the late 15th and early 16th centuries, whose designs for machines were largely based on his own detailed observations of natural systems and mechanisms. By the middle of the 17th century, Descartes was willing to assert that animals are complex machines, however, the extension of this idea to our own species came a further century later with Julien Offray de La Mettrie's book "L'Homme Machine" (1748). At the same time as expanding Descartes notion of the mechanistic nature of life to include humans, La Mettrie also realized that machines—natural or otherwise—can be dynamic, autonomous, and purposive entities. Following in these footsteps, we see our goal, as scientists and technologists, as being to offer a new understanding of the natural world that recognizes the continuity of our species with other animals, as evolved "living machines".

Biomimetics combines the power of the analytical sciences, to investigate and understand complex biological systems, with the synthetic capability of engineering to build (synthesize) new types of physical systems that operate according to derived mechanistic principles. Since analysis and synthesis proceed by different methods [3], they are complementary approaches that can unlock challenges previously seen as beyond our reach. Further, as synthetic approaches result in real-world technologies, they can stand as powerful existence proofs for the validity of the insights, drawn from biology but translated into engineering, that they embody. The concept of organisms as living machines is also strongly aligned with the systems approach in biology (e.g. [4]) that opposes reductionist formulations and advocates an understanding of the organism at multiple interacting levels of organization—cells, organs, bodies, ecosystems and societies. The notion of the animal or person as a "living machine" therefore does not imply the reduction of psychology and the other behavioral and social sciences to physics, or of the usefulness of concepts such as thoughts, feelings, beliefs, goals and motives for understanding human behavior. It also leaves room for a meaningful notion of self-determination (e.g. [5]). Rather, we hope, through biomimetics, to offer a richer scientific understanding of these notions, compatible with concepts of human rights, and offering people the prospect of better self-understanding and compassion for others.

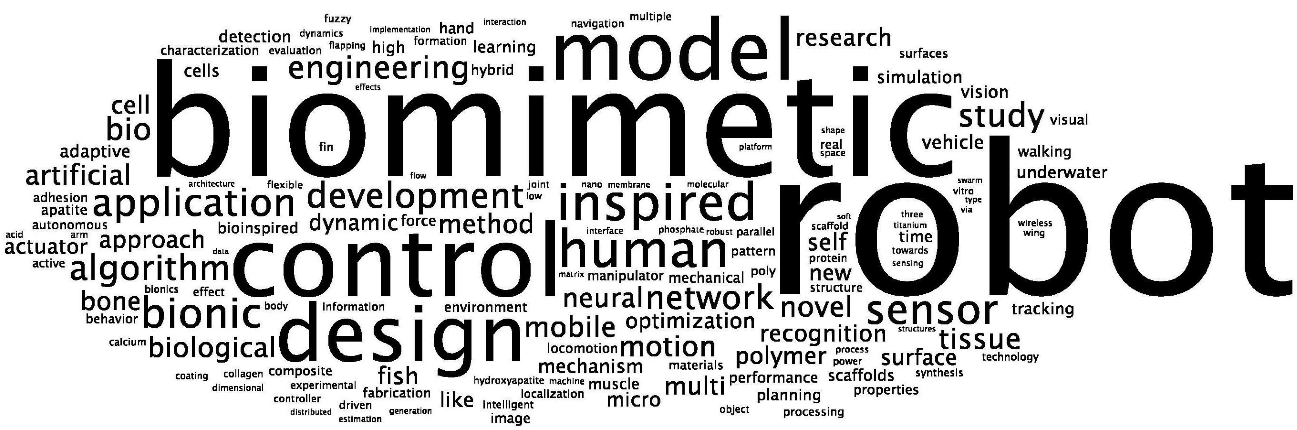

Figure 2. Popular topics in biomimetics. A word cloud showing the frequency of terms occurring in the titles of papers on biomimetic research (word size is proportional to the frequency of occurrence). Reproduced from [1] with permission.

The notion of Living Machines places a strong focus on the possibility of building integrated biomimetic or biohybrid systems as typified by biomimetic robotics. A further key domain of interest is neuromimetics—biomimetics applied to understand the neuronal basis for perception, emotion, cognition and action—and involving computational modeling of neural systems. Emerging topics within this field include the embodiment of neuromimetic controllers in hardware (termed neuromorphics), the development of brain-like control architectures of complex artifacts such as robots (sometimes termed neurorobotics [6]) and the development of novel neuroprosthetic systems (see below). It is anticipated that this research will lead to significant advances in the brain and cognitive sciences, that, in addition to promoting the design of more effective and advanced machines, will help aid in the treatment of cognitive deficits and neurological diseases.

In the remainder of this paper we focus further on how biomimetics is creating life-like robots, drawing on our own recent research in biomimetic mammalian robots including humanoids, and identifying some key unresolved challenges that constitute bottlenecks for the field. We also briefly consider neuroprosthetics as an example of a biohybrid technology that can be expected to substantive societal benefits, but brings closer the possibility of ourselves as biohybrid entities.

2. BIOMIMETIC ROBOTICS

Research on biomimetic robotics has covered a wide range of complete behaving systems that could potentially operate in, or on, different substrates—including land, sea, and air—and inspired by the different design plans found in the animal kingdom including plants, invertebrates (e.g. worms, walking and flying insects and their larvae, jellyfish, subsea crustaceans and cephalopods), and vertebrates—fish, amphibians, reptiles, mammals and birds. Recent example systems are described in [7, 8]. In [9] we describe the state-of-the-art in a number of these domains. Examination of recent and ongoing work shows that locomotion is seen as a key challenge with substantial research activity around flying in insect-like micro-air vehicles, legged walking in hexapod (insect-like) robots, quadruped (mammal-like) or bipedal (humanoid) robots, fish-like swimming, and snake or worm-like crawling. Biomimetic sensing technologies are being developed both for their potential in robot control and to operate as sensory prostheses. For instance, artificial cochlea are now well-developed with work on an implantable artificial retina underway. Research on chemosensation is advancing based on a number of model systems (but particular insects), and with potential application in quality control for food processing, medical diagnosis, drug or explosive detection, and environmental monitoring. Tactile sensing encompasses antennal, vibrissal, and fingertip-like sensors and is being developed with an emphasis on active sensing—the purposive control of sensor movement to maximize the acquisition of useful information (see below). Ultrasound systems have been developed inspired by both bats and dolphins; work emulating the fish lateral line is also underway, as are efforts to understand and copy the electroreceptive sense of electric fish.

A key challenge for robotics is to understand and emulate the capacity of natural systems to grasp and manipulate complex objects, particularly deformable ones. Here the human/primate hand is an important model, as is the octopus arm, with applications in industrial and service robotics but also in prosthetics. Current robots also fall far short of biological organisms in terms of their perceptual and cognitive capabilities. This is driving substantial efforts in cognitive science and in computational neuroscience, biomimetic in its approach, although rarely described explicitly as biomimesis. Some of this effort is transferring to artificial intelligence and robotics technologies. Learning is a key challenge with biological inspiration considered to be an important factor in recent progress to develop deep learning systems [10]. Memory is also a target with research on the substrates of spatial, semantic and episodic memory in the mammalian temporal cortex and hippocampus seen as critical for developing future technologies that retrieve information more effectively and achieve semantic understanding of its content. The hippocampal system and the cerebellum (an important structure for learning) have also been targets for research in neuroprosthetics (see below).

2.1. Tactile sensing in mammal-like robots

Based on our goal of understanding the human as a living machine we have focused our biomimetics research on the challenge of building mammal-like robots including humans. Internationally, there is a broad effort in this direction with considerable research on analogues of mammalian sensing systems (particularly human/primate vision), legged locomotion (quadruped and biped), and mammal-like cognition. Some examples of recent mammal-like robots are shown in Figure 3, and include one of the first therapeutic robots, the seal-like *Paro* [11], which is undergoing evaluation in several countries for its potential in dementia care. Amongst mammals the creatures best understood at the current time, are without doubt, the laboratory animals—*Rattus norwegicus* and *Mus musculus*—the common rat and mouse. The availability of a rich understanding of rodent biology makes these species attractive targets for biomimetics, especially as many of the biomimetic design principles we can discover in rodent biology should transfer to our own species (evolutionary biology suggests we share a common ancestor within the last 100 million years). Rodents, such as mice and rats, are notable for their reliance on tactile sensing through facial whiskers or vibrissae. Although humans do not have vibrissae, evidence suggests that the brain substrates for vibrissal processing are a good model system for understanding mammalian sensorimotor processing in general. Further, in losing our whiskers during evolution, our primate ancestors gained a new way to sense the world through touch by elaboration of the tactile sensing systems in the hands and fingertips. Our research on tactile sensing has looked across both vibrissal sensing in rodents and fingertip (haptic) sensing in humans and we see many commonalities across both.

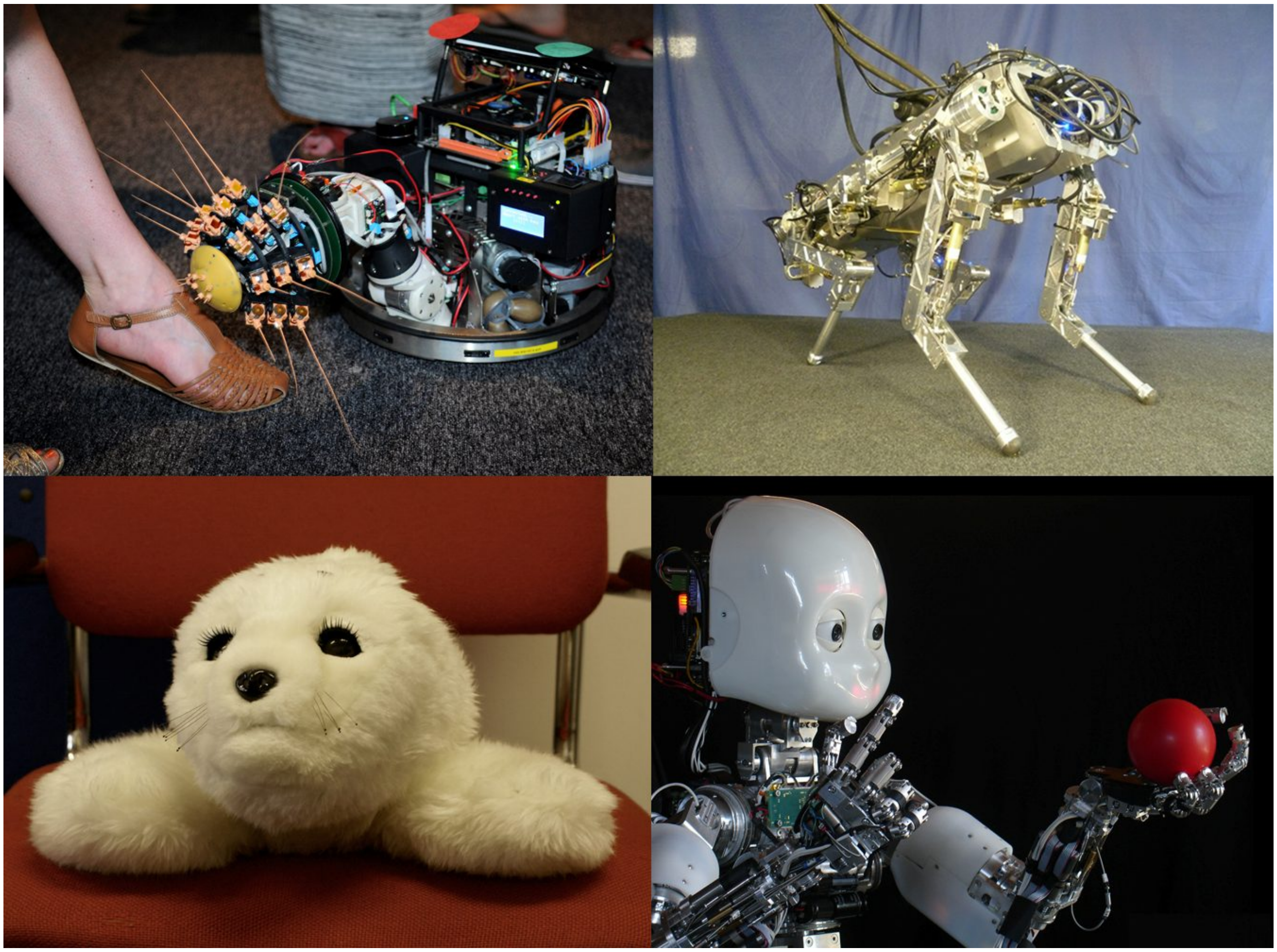

Figure 3. Mammal-like robots. TopLeft: Shrewbot, a robot that emulates the mammalian whisker system, developed by Bristol Robotics Laboratory and the Active Touch Laboratory Sheffield [12]. TopRight: The quadruped robot HyQ, under development by the Italian Institute of Technology [13]. BottomLeft: Paro, a seal-like robot developed for use as a therapeutic robot [11]. BottomRight: The iCub humanoid, developed by the Italian Institute of Technology and partners in the RoboCub project [14], and now used as a research platform by many groups internationally.

In order to better understand mammalian tactile sensing, we conducted a range of biological studies of rodent vibrissal sensing alongside the development of three different whiskered robot platforms—Whiskerbot [15], Scratchbot [16, 17], Shrewbot ([12], and figure 3), and the BIOTACT G2 Sensor [18]. Each robot was designed to explore specific questions about vibrissal tactile sensing. For instance, in Whiskerbot we looked at early sensory processing in an embodied spiking neuron model of the primary afferent nerve fibers coupled to fiber-glass whiskers instrumented with strain gauges and controlled by shape-memory-alloy artificial muscles. Our research with this model demonstrated to us the importance of fine control of the movement and positioning of the whisker for effective sensing [19] and led us to build additional degrees of freedom for whisker and head positioning into our later robots. As this work has progressed with have also added more elements to the brain-based control architecture. The basic design principle is to follow the layered nature of mammalian brains, in which spinal cord, hindbrain, midbrain and forebrain systems can be understood as adding successive layers of control, and with key structures, such as the basal ganglia, providing integration and action selection across layers [20]. For instance, Figure 4 illustrates the layered architecture of the mammalian brain and its translation, at an abstract level, into a series of control loops for the Scratchbot robot which successfully emulates rodent exploratory whisking behavior.

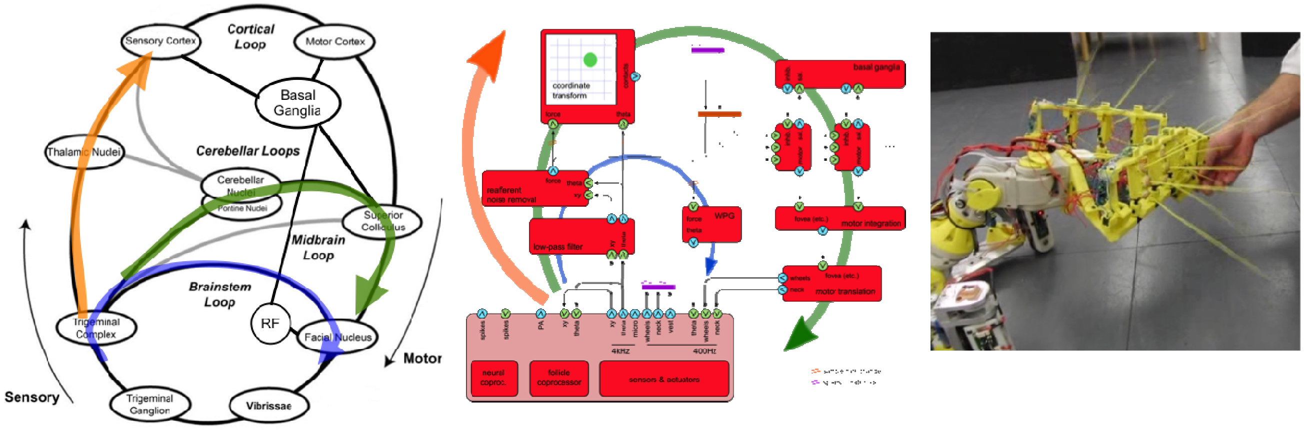

Figure 4. Brain-like control architecture implemented in the biomimetic robot Scratchbot. The control architecture for vibrissal sensorimotor control can be envisaged as series of nested loops (or a layered architecture) with circuits linking perception and action at the brainstem, midbrain and cortical levels (bold arrows, left figure). These loops together with models of integrative structures such as the basal ganglia and cerebellum were implemented in the control architecture (centre figure) of the *Scratchbot* robot (right). Later models have also investigated the role of cortical and hippocampal loops [17, 19]. Figures adapted from [16, 17].

Focusing on the active sensing strategies of rodents we have developed a model of attention and modulation of vibrissal movements that accurately captures the sensing behavior of awake exploring animals, and also provides a unifying account of the substrates for attentional decision-making across both primate vision and rodent vibrissal touch [21, 22]. Combining research on biomimetic tactile perception for both rodent-like vibrissal sensing and haptic (fingertip) sensing in the iCub humanoid robot [23, 24], we have also developed a general cross-modal theory for active perception for robust 'where' and 'what' perception in unstructured environments. Called *Simultaneous Object Localization and IDentification* (SOLID) [25]. This method combines decision-making by threshold crossing of the posterior belief with a sensorimotor control loop that actively controls sensor location based on those beliefs (Figure 5) and is parsimonious with leading computation accounts of decision making in animals, which involve the sequential accumulation of evidence to threshold, consistent with numerous psychological and electrophysiological experiments [26]. Work in computational neuroscience also indicates these principals may relate to the macro-architecture of the brain, in particular the basal ganglia and cortex [27]. This close connection with neuroscience is a strength of the computational formalism, in that it allows insights from animal perception to be transferred to robot perception.

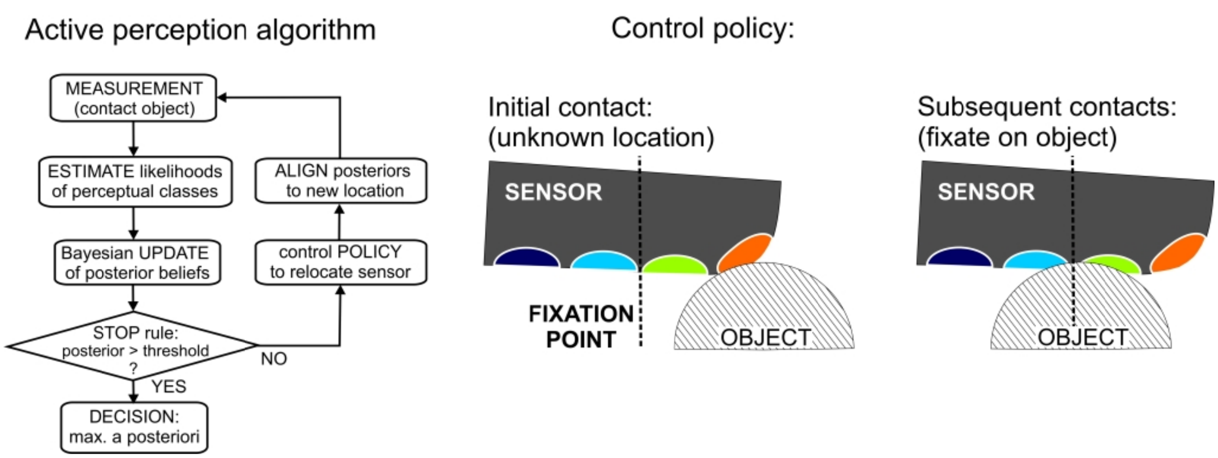

Figure 5. General cross-modal theory for active perception in artificial devices [25]. The left diagram shows the algorithm for active perception that has a recursive belief update while controlling sensor location according to a belief-based control policy. The right diagram illustrates the 'fixation point' control policy for a tactile fingertip, where a relative move is made to a preset fixation point on the object using a best estimate of current location from the current location beliefs. Provided the fixation point is a good location for perception, this control policy can progressively improve the perception during the decision making process.

2.2. Biomimetics and social robotics

We are at the start of a period of radical social change where robots will enter more and more into our daily lives [28, 29]. As robots become more omnipresent and take on more roles within our homes, offices, schools, hospitals, towns and cities, the problem of making robots more socially compatible with humans is becoming increasingly pressing [30, 31]. However, in order to safely and meaningfully interact with humans, robots, independent of their specific morphology, must develop an advanced understanding of both the physical and the social world. The lack of a social awareness is one of the main stumbling blocks for the expansion of the field of service robotics [32]. Indeed, robots that interact directly with humans form a very small proportion of robots currently sold. Thus many potential applications for robotics, including economically and socially important uses in everyday human environments, remain to be unlocked. To escape this bottleneck, progress is needed in a number of domains including: the categorization and understanding of the context and scenario at hand; the acquisition and use of episodic knowledge of events for planning; the use of non-formal modes of knowledge representation including visual, tactile, auditory and diagrammatic representational schemes; the acquisition and use of procedural skills for physical interaction; context-dependent learning and action generation; semantic perception and memory; the assessment of the intention of other agents; verbal and non-verbal communication, etc. These challenges are such that some have argued that *social robotics* must be seen as a paradigm shift for the field [30] requiring a more multi-disciplinary human-centred approach towards robot design [33]. Indeed, here we propose that it is primarily through an emphasis on psychological capacities of biological systems that human compatible robots, and their virtual counterparts 'avatars', can escape from both their social incompetence and the "uncanny valley" [34] that currently prevents robots from being effectively assimilated into human environments. Hence, the current challenge in social robotics is of great interest from a biomimetics perspective because there are no technological solutions in place today and because the construction of such human compatible machines will also exercise the sciences of mind and brain and test basic biological design principles from neurons and circuits to brain systems and social groups.

To progress towards a better model of the natural social brain, that could be effectively employed in future robots, we have developed one of the most advanced brain-based cognitive architectures available today, the, so called, *Distributed Adaptive Control* (DAC) theory of mind and brain [35-38] (Fig 6). DAC has been successfully deployed in a large number of robot tasks, has been validated against a broad set of neuroscience and psychological data and has given rise to a successful and novel approach towards neurorehabilitation that is being deployed in clinics today [see [38] for a review]. At its most abstract level, DAC proposes that brains evolved to act and that the HOW of action is realized through 5 fundamental processes that can be characterized as:

1. **Why**: the motivation for action in terms of needs, drives and goals;
2. **What**: the objects in the world that actions pertain to;
3. **Where**: the location of objects in the world and the self;
4. **When**: the timing of action relative to the dynamics of the world;
5. **Who**: the hidden states of other agents.

This can be abbreviated to the H5W problem where each of the Ws designates a large set of sub questions of varying complexity [39]. This H5W problem is hypothesized to be an exclusive set that dominates the design of brains. Whereas artificial intelligence has pursued the elusive construct of "intelligence" (going back to early psychologists such as Galton and Binet), DAC proposes that the unifying phenomenon we should focus on both to explain mind and brain and to construct it in artificial systems is consciousness. The DAC theory proposes that consciousness is a key component of the solution to the H5W problem, especially dealing with "Who", that has emerged during biological evolution through the necessity for animals to co-exist with con-specifics and with other species. Essentially the proposal is that the interaction with the social real-world requires fast real-time action that depends on parallel control loops. The conscious scene in turn allows the serialization of this real-time processing and the optimization of these parallel control loops. For instance, the human cerebellum, a brain structure that operates fully outside of consciousness, comprises about 15,000,000 parallel loops each controlling the timing of specific event triggers [40]. Hence, such a massive level of parallelization leads to a new kind of credit assignment problem where potentially many thousands of policies have to be optimized in parallel in the face of a dynamic and ambiguous world.

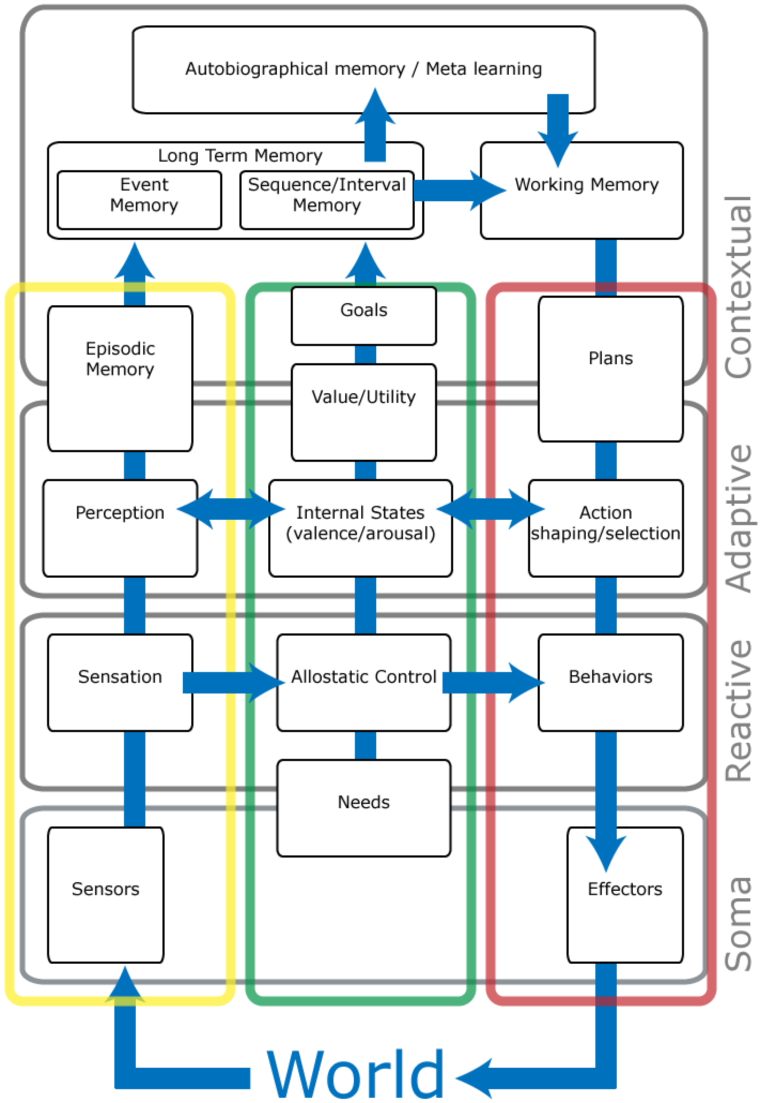

Figure 6. The Distributed Adaptive Control (DAC) architecture for perception, cognition and action, proposes that the brain is based on four tightly coupled layers of control called Soma, Reactive, Adaptive and Contextual [35-38]. Across these layers we can distinguish three functional columns of organization: exosensing: the sensation and perception of the world (yellow), endosensing: detecting and signalling states derived from the physically instantiated self (green) and the interface between self and the world through action (red). The arrows show the primary flow of information, mapping exo- and endosensing into action. At each level of organization increasingly more complex and memory dependent mappings from sensory states to actions are generated dependent on the internal state of the agent. DAC proposes that both interactions with the physical and the social environment can be explained from this comprehensive perspective.

The first steps of translating this theory to concrete real-world interaction between humans and machines have been realized for interactive spaces such as Ada [41] and humanoid robots such as the iCub (Figure 7). In the latter case we have developed an experimental functional android assistant (EFAA) which is able to engage in self-regulated dyadic interactions including the construction of both a task and user model combined with informational transparency through the use of natural language. This research demonstrates that biomimetic theories on mind and brain such as DAC can be effective drivers of technological innovation whilst in parallel finding validation through robot-based experimentation.

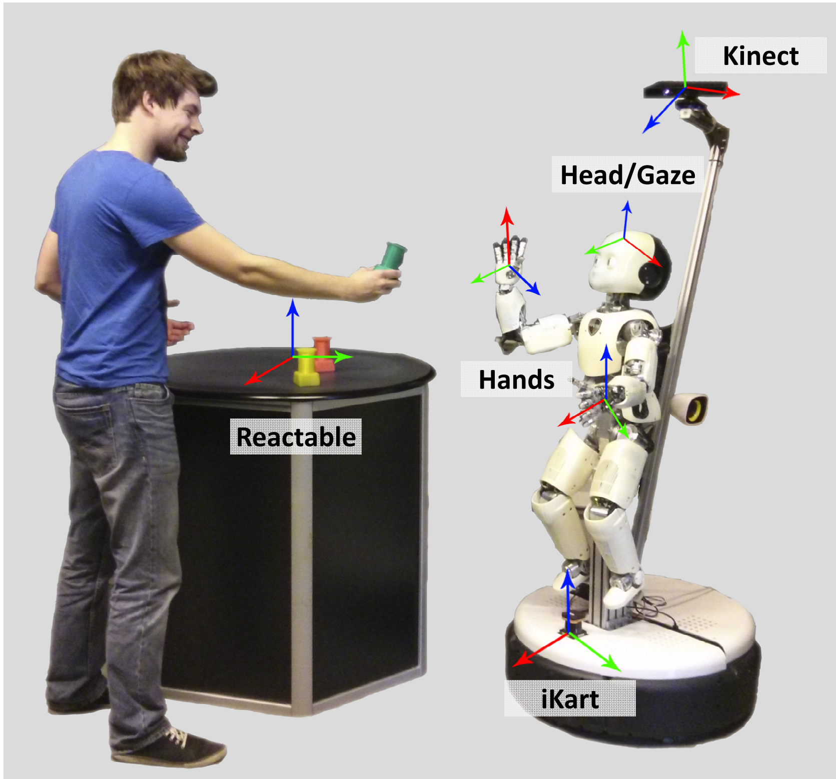

Figure 7. The EFAA human-robot interaction platform showing the multiple different reference frames that are integrated in the biomimetic control architecture (Reactable, iKart, Kinect, the two robot hands and its head).

3. BIOHYBRID THROUGH NEUROPROSTHETICS

Moving towards biohybrid systems, an area of great interest is the domain of neuroprosthetics. Interfaces between the central nervous system and peripheral systems have existed for some time and now include retinal and cochlear implants, and brain-computer interface systems that can control artificial limbs (see [42] for a review). Indeed, recently it has been shown that human patients can control anthropomorphic robot arms using brain activity alone [43]. However, the big challenge of bi-directional coupling of a prosthetic system with the Central Nervous System is only just beginning to be addressed [44. 45]. In order to realize such a bi-directional system three fundamental problems must be overcome [46]. First, the function of the circuit to be replaced must be understood and captured in a real-time form. Second, the inputs and outputs to and from the circuit that is to be replaced must be identified and their signals correctly analyzed and synthesized. Third, steps 1 and 2 must be physically realized in a small, efficient and low-power form that can support implantation.

Some of the most advanced neuroprosthetic systems for bi-directional replacement, realized so far, have targeted the cerebellum (Fig 8). Here two approaches can be distinguished. On the one hand, Berger et al [44] have emphasized a model fitting approach in which a transfer function between inputs and outputs is inferred and subsequently used to replace a neuronal circuit. An alternative approach [45] emphasizes the emulation of the fundamental physiological and anatomical properties of the underlying circuit in order to get higher precision in the reconstruction of its functional properties. This is of great importance since the exact conditions under which neuroprosthetic system are to be interfaced to the brain are not fully specified. In addition, in the latter case, not only is an engineering problem solved, but basic principles underlying mind, brain and behavior are identified and validated. In other words, the domain of neuroprosthetics can provide a very valuable test-bed for the advancement of a biologically grounded biomimetics.

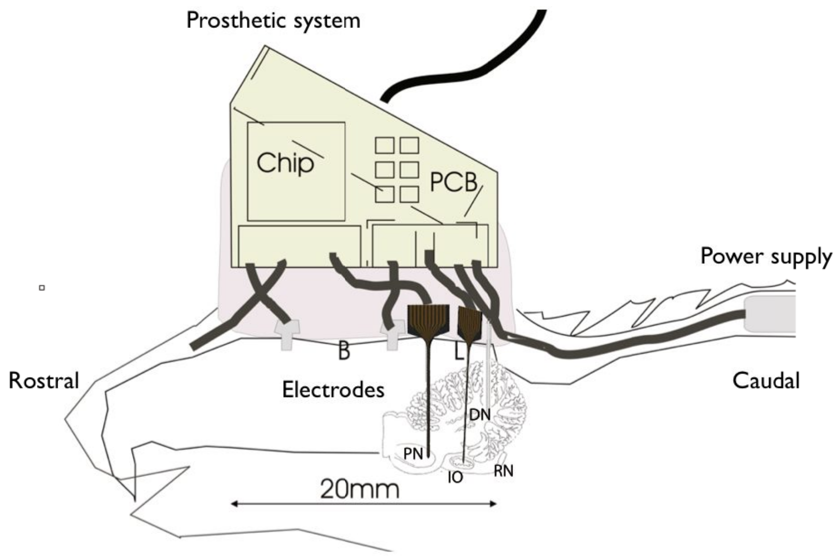

Figure 8. Design for a cerebellar neuroprosthetic prototype. An integrated computational system emulates the circuit properties of the cerebellum based on a theoretical model. This emulated cerebellar micro-circuit is interfaced to the input and output structures, the Pons (PN) and Inferior Olive (IO) and Deep Nucleus (DN) respectively. This paradigm has been successfully applied in in vivo replacement experiments [47]. Adapted from [45].

5. SOCIETAL IMPACTS

Expectations about the positive societal benefits of advanced biomimetic and biohybrid brain-based technologies vary from the unconditionally positive [48] to the more guarded and cautious [49, 50]. The latter worry about the risk that benefits will be for the few not the many—contributing to a more unequal society—or that we risk dehumanizing ourselves by advancing too far down a path of self-modification and enhancement. This broad debate is set to continue and become even more pressing as these technologies move from science fiction towards technological fact. Given the changing nature of our planet with a growing population, shifting demographics in the developed world, and increasing risk through climate change, it can be argued that the status quo is not an option and that further advances in technology, with advanced biomimetics a key part of this, are needed to meet the needs and the aspirations of future generations [29].

One emerging concern [51, 52] is that increasingly intelligent and autonomous technologies are being developed to the point where a "singularity" is reached beyond which these systems could continue to improve themselves in a runaway fashion without human help. Worst-case scenarios suppose that, in the future, *homo sapiens* might even be replaced by machines as the dominant "species" on our planet. In our view, the standard argument for this technological singularity ignores a basic truth about human nature—that we have always appropriated external systems to help ourselves think, and that we have, since the beginnings of human culture, used artifacts to improve ourselves and the collective capabilities of our societies [53, 54]. With technologies such as microscale mobile computing, prosthetics and implants, humankind is moving towards a future in which biomimetics helps us to engineer many more biocompatible technologies. Thus rather than technology and humanity becoming more distinct, we might expect an ever-closer relationship with technology—that is, for people to become more biohybrid themselves, through the development of personalized systems that are directly interfaced to the body. In order that advances in these technologies are seen as a benefit rather than a threat we should ensure that progress in biomimetics and biohybrid systems is made with broad societal consent. This will require engagement with the general public, and with a wide range of stakeholder groups, about our research aims and the technological advances we wish to pursue, and a willingness to adapt those aims to address concerns that are well-founded. By taking this approach we can hope that "Living Machine" technologies will be developed for the future benefit of all humankind.

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