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Anthropomorphic action in robotics

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The word “robot” was first coined in the early 20th century and the seminal ideas of cybernetics first appeared during World War II. The birth of robotics is generally pinpointed to 1961, with the introduction of the first industrial robot on the General Motors assembly line. This “Unimate” robot was patented by George Devol and industrialized by Joseph Engelberger, who is recognized as the founding father of robotics. From its beginning in the 1960s, to its broad application in the automotive industry by the end of the 1970s, the field of robotics has been viewed as a way to improve production in manufacturing by providing a manipulator integrated into a well-structured environment. Stimulated by programs such as space exploration, the 1980s saw the creation of field robotics, where a robot’s environment was no longer closed. However, even then the robot remained in isolation, only interacting with a static world.

At the end of the 1990s, robotics began to be promoted within the service industry, which led to the development of simple wheeled mobile platforms capable of performing tasks such as cleaning or automated transportation. In the next stage of development, arms were added to the platforms, which allowed more expressive communication. This generation of robots, most recently “Pepper the Robot,” is able to enter into dialogue with humans—to welcome and guide them into public areas such as supermarkets, train stations, or airports. Incorporating arms into this type of robotic design also allowed for object manipulation and physical interaction. However the limitations of these wheeled mobile robots soon became evident, sparking a quest for more anthropomorphic robots that would be able to move within a human environment, including using stairs and moving over small obstacles. These features would allow for their mobility on any terrain; moreover, they would incorporate the capacity to perform dexterous manipulation. Achieving such “humanoid” robots has become a major challenge in the field of robotics and, if fully achieved, these devices will become the paragons of robotics science. Here I review the current status of anthropomorphic robots and how the fields of robotics, neuroscience, and biomechanics are coalescing to drive robotic innovation forward.

Anthropomorphic action

Human beings and humanoid robots share a common anthropomorphic shape. Whereas the ultimate goal of roboticists is to provide humanoid robots with autonomy, life scientists are striving to gain an understanding of the foundations of human action, in domains ranging from medicine and rehabilitation to ergonomics. Neuroscience and its quest to understand the computational foundation of the brain provides a further entry point to robotics. Despite their different scientific cultures and backgrounds, the communities of life scientists and roboticists are pursuing converging objectives.

A key to understanding anthropomorphic action that can bridge robotics and life sciences is gaining insight into the fundamental mechanisms of the human body. As an example, consider the actions in Fig. 1, performed by the humanoid robot HRP2 at Laboratory for Analysis of Architecture and Systems at the French National Center for Scientific Research (LAAS-CNRS). In the first scenario, the robot answers a single order: Give me the purple ball (1). To accomplish the assigned objective, HRP2 decomposes its task into elementary sub-tasks (Scenario (a) in Fig. 1). A dedicated software module addresses each sub-task. For instance, to reach the ball, the robot has to walk to the ball. “Walking” appears as an elementary action that is a resource to

solve the problem, and is processed by a dedicated locomotion module. In the second scenario (Scenario (b) in Fig. 1), HRP2 has to grasp a ball that is located between its feet (2). To accomplish this objective, the robot has to first step away from the ball and then grasp it. In this scenario, the significance of “stepping away” becomes a vital issue. In this experiment, there is no dedicated module in charge of “stepping,” which is a direct consequence of “grasping.” Thus, no stepping “symbol” appears as a resource for problem solving in Scenario (b). The grasping action is embedded in the robot’s body, allowing its legs to naturally contribute to the action. No deliberative reasoning is required for the robot to face complicated situations such as picking up a ball between the feet.

To design a robot capable of the embedded actions required to execute Scenario (b), we must first imagine replacing the humanoid robot HRP2 with a human being. Among all the possible motions required for grasping of an object, we must consider the underlying principle for selection of a particular motion in humans. How does the human organize his or her behaviors to reach a given objective? Where within the brain does this reasoning take place? What are the relative contributions of voluntary actions computed in frontal cortex, to reflexive actions computed by spinal reflexes, in Scenario (a) and (b)? How and why are different actions computed by different mechanisms? What musculoskeletal synergies are required to simplify control of complex motions? Such questions lie at the core of current research in computational neuroscience and biomechanics. In the remainder of this review, I will briefly discuss three viewpoints on anthropomorphic action from a robotics, neuroscience, and biomechanics perspective. I will also make mention of mathematical methods for anthropomorphic action modeling.

A robotics perspective

In the quest for robot autonomy, research and development in robotics has been stimulated by competition between computer science and control theory, and between abstract symbol manipulation and physical signal processing, with the goal of embedding discrete data structures and continuous variables into a single architecture. This architecture is a way of decomposing complicated intelligent behavior into elementary modules, or “symbols,” capable of executing a well-defined function. Designing robot architecture requires the well-designed “placing” of these symbols.

In robotics, centralized architectures were first designed in manufacturing. In this hierarchical paradigm, the robot operates in a top-down fashion, combining pre-defined specialized functions for perception, decision, and control. Such architectures perform well in structured environments where a finite state machine can describe the world of possible actions, as is the case in production engineering (3). Other architectures promote a bottom-up view, a seminal approach introduced by Rodney A. Brooks (4). Using the concept of subsumption, he proposed a reactive robot architecture organized by integrating low level sensory-motor loops into a hierarchical structure. A behavior is decomposed into sub-behaviors organized in a hierarchy of layers. Higher levels subsume lower levels according to the context. This research gave rise to the school of so-called “bio-inspired” robotics, which emphasized mechanism design and control (5), and related schools in artificial intelligence, including multi-agent systems (6), swarm robotics (7), or developmental robotics (XX). Other types of architectures have tended to combine top-down and bottom-up views in a hybrid manner, integrating deliberative reasoning and reactive behaviors (8, 9).

The aim of all these approaches is to provide a generic solution for mobile robots as well as articulated mechanical systems, and for the robotic design to be independent of the mechanical dimensions of the system. Further developments in imposing anthropomorphic body

considerations on humanoid robot architectures will involve the promotion of “morphological computation,” with its emphasis on the role of the body in cognition (10).

A computational neuroscience perspective

How to represent action is a key issue today in human science research, a field that encompasses endeavors ranging from neuroscience to the philosophy of mind (11). The subject itself, which ponders such questions as whether there can in fact be “representation” of action, has long been controversial. However, the discovery of mirror neurons by Rizzolatti (12) provided physiological evidence to support the concept of action representation, which was promoted by philosopher Edmund Husserl at the end of the 19th century (13).

In terms of motor control, the pioneering work of Nikolai Bernstein in the 1960s revealed the existence of motor synergies (14). The work of Bizzi and colleagues then provided biological evidence of this concept (15). Since then, numerous researchers have pushed the borders of their disciplines to discover laws and principles underlying human motion, which has in turn established the fundamental building blocks of complex movements (16–18). More recently, Alain Berthoz introduced the word “simplicity” to synthesize all these works into a single concept: that is, to face the complexity of having such high dimensions in motor control space, living beings have created laws that link motor control variables and hence reduce computations (19).

A biomechanics perspective

In the 19th century, Étienne-Jules Marey introduced chronophotography to scientifically investigate locomotion, and was the first scientist to correlate ground reaction forces with kinetics. The value of jointly considering biomechanics, modern mathematics, and robotics is illustrated by the famous “falling cat” case study: Why is it that a falling cat always lands on its feet? The answer comes from the law of conservation of angular momentum: The cat can be modeled as a nonholonomic system whereby geometric control techniques perfectly explain the phenomenon (20). Thus, biomechanics provides models of motion generation (21), which have subsequently been applied in ergonomics (22) and studies of athletic performance (23).

Mathematical methods for anthropomorphic action modeling

From a mechanistic point of view, the human (or humanoid) body is both a redundant system and an underactuated one. It is redundant because its number of degrees of freedom is usually much greater than the dimension of the tasks to be performed. It is underactuated because there is no direct actuator allowing the body to move from one place to another place: To do so, the human must use its internal degrees of freedom and actuate all his limbs following a periodic process, namely bipedal locomotion. Actions take place in the physical place, while they originate in the sensory-motor space. Thus geometry is the core abstraction linking three fundamental action spaces (24): the physical space where the action is expressed, the motor space, and the sensory space. The emergence of symbols can be understood by the geometric structure of the system configuration space. Such a structure depends on the role of the sensors in action generation and control. As an example, in a recent study, we highlighted the role of the gaze to explain the geometric shape of human locomotor trajectories (25).

Whereas an action, such as “walk to” or “grasp” is defined in the real world, it originates in the control space. The relationship between “action in the real world” and “motion generation” in the motor control space is defined in terms of differential geometry, linear algebra, and optimality principles (26, 27). Optimal control is based on well-established mathematical machinery ranging from the analytical approaches initiated by Pontryagin (28) to the recent developments in numerical analysis (29). It allows for motion segmentation as well as motion generation. On the other hand, inverse optimal control is a way to model human motion in terms

of controlled systems. Specifically, if given an underlying hypothesis of a system, as well as a set of observed natural actions recorded from an experimental protocol performed on several participants, optimization acts to determine the cost function of the system. From a mathematical point view, the inverse problem is much more challenging than the direct one. Recent studies have been published in this area that have utilized numerical analysis (30), statistical analysis (31), and machine learning (32, 33).

Movement is a distinctive attribute of living systems. Movement is the source of action. Robots are computer-controlled machines endowed with movement ability. Whereas living systems move to survive, robots move to perform actions defined by humans. Exploring the computational foundations of human action then appears as a promising route to better engineering the future humanoid robots. As movement science, geometry offers the suitable abstraction allowing for fruitful dialog and mutual understanding between roboticists and life scientists.

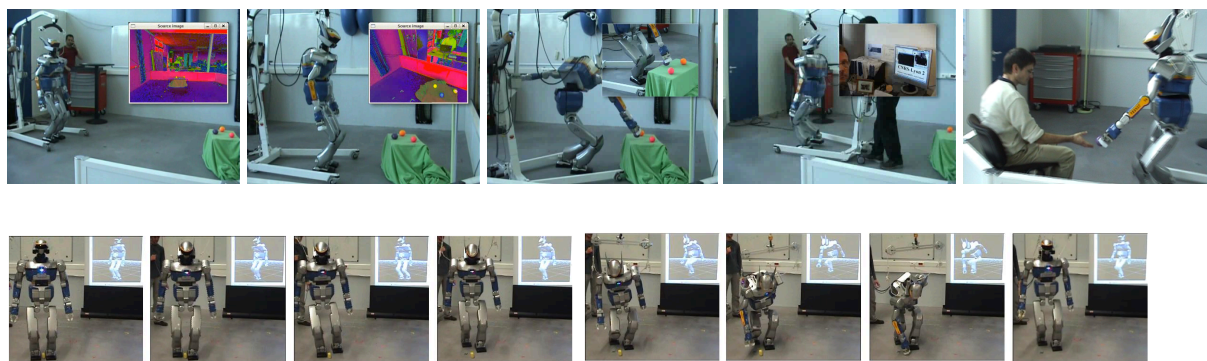


Figure 1: An introductory example of embodied intelligence.

Top panels. Scenario (a): The global task “Give me the ball” is decomposed into a sequence of sub-tasks [locate the ball], [walk to the ball], [grasp the ball], [locate the operator], [walk to the operator], and [give the ball]. The motions [walk to], [grasp], [give] appear as symbols of the decisional process that decomposes the task into sub-tasks.

Bottom panels. Scenario (b): To grasp the ball between its feet, the robot has to step away from the ball. In this experiment “stepping away” is not a software module, nor a symbol. It is an integral part of the embodied action “grasping.”

The action in Scenario (a) is well segmented. The action in Scenario (b) is not: Unlike the command “walk to,” “stepping away” does not constitute a symbol.

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