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THE IMPORTANCE OF BEING HUMANOID

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A humanoid robot is a particular form of embodied agent. The form that an agent takes has a major impact on how that agent interacts with its environment and how it develops an understanding of that environment through its interactions. In this article, we explore the importance of humanoid embodiment and we argue that humanoids occupy a special niche in the spectrum of robot forms. In doing so, we highlight the implications for the way a humanoid robot can interact with its environment, including humans, for the manner in which humans interact with humanoid robots, and for a humanoid robot's capacity to develop cognitive abilities. We also consider the degree to which humanoid robots should approximate humans, addressing robot morphology, appearance, and movement. We emphasize the dual role of humanoid robots as engineering artefacts that can provide services for humans, and as platforms for scientific enquiry into the nature of human cognition. We conclude by highlighting some key research challenges for the discipline of humanoid robotics.

Keywords: Humanoid robots; human-robot interaction; embodied cognition; cognitive development; cognitive robotics; cognitive science.

1. Introduction

Humanoid robots are an important class of robot, of which there are many instantiations. For example, the IEEE Guide to the World of Robotics classifies over 30% of its featured 250 robots as humanoid.[1] Since the pioneering work of Prof. Ichiro Kato at Waseda University in the 1970's with the realization of WABOT-1,[2], humanoid robots have been recognized as a new kind of tool, one that allows interaction with humans in humanlike ways and that provides a way to learn more about human intelligence and cognition,[3] giving rise to research programs that use humanoid robots to explore human and robot cognition.[4,5] This article poses two questions about humanoid robots: what is particularly special about humanoids, and what human features should be used when designing a humanoid approximation of a human? The following two sections provide answers to these questions. The closing section highlights research challenges that need to be overcome if humanoid robotics is to realize its immense potential.

Before we continue, it is important to bear in mind that humans and humanoid robots differ profoundly in their construction, their constituent materials, and the manner in which they achieve autonomous, goal-achieving intelligence. Humanoids, are, to a greater or lesser extent, an approximation of humans. As we will see, some types of humanoid robot attempt to be as faithful as possible to the human form, such as anthropomimetic humanoids and android humanoids, while others are less concerned with seeking this degree of fidelity. However, humanoid robots differ from humans in one critical aspect: human bodies physically grow while humanoid robots are assembled machines that have a fixed physical structure. The consequence of this is that humanoid robots cannot exploit the synergy of growth and development, physical and mental. We return to these issues in Section 3. For now, let us address our first question.

2. What is Special about Humanoids?

A humanoid robot is special in a number of ways: in its ability to work seamlessly in human environments with the same objects and implements that humans use, in its physical interaction with humans, in the manner in which it can communicate non-verbally with humans, in its acceptance and trust by humans, in the way that its physical form fosters anthropmorphization, and in the manner in which it can develop its cognitive abilities by learning the same affordances that humans learn. Taken together, these six special attributes give rise to a seventh. They allow humanoid robots to play a dual role: a role in engineering as embodied agents that have the potential to assist humans in a natural manner, and a role in science by providing a platform on which to implement models of cognition and to be used as controllable interactive agents to study social aspects of cognition. Let us now look at each of these special attributes in turn.

2.1. *Operation in human environments with tools and implements that are used by humans*

Perhaps one of the most important attributes of a humanoid robot is that, by virtue of its similar morphology to humans, it is uniquely equipped to use the tools and implements that humans use, and to co-exist with humans in human habitats, be that at home, in the office, in hospitals, shops, or public spaces. While this is certainly true in principle, in practice it depends on the sophistication of the robot's sensor and actuation systems, its perceptual capabilities, its cognitive capabilities, and its motor coordination capabilities. For example, humans are very adept at dexterous manipulation, but most humanoids are not yet equipped with dexterous hands, such as the Shadow hand,[6] and those that are, such as iCub[5] and ARMAR,[7] do not yet have particularly versatile dexterity. This is partly due to the fact that many multi-fingered robot hands are under-actuated, i.e., there are fewer actuators than joints, with one actuator being responsible for the movement of more than one joint, such as those in the ring finger and the little finger. However, it is also partly due to quite primitive tactile sensing, both in terms of sensor resolution and dynamic range compared to human tactile sensing, and poor sensorimotor coordination. The handicap that this presents for dexterous manipulation is vividly demonstrated by an experiment conducted by Roland Johansson that shows how humans become incapacitated when their fingertips are anaesthetized, going from being able to adeptly strike a match to fumbling with and repeatedly dropping matches.[8]

Dexterous manipulation also requires adaptive mechanical compliance so that soft, flexible, or live objects,[9] can be handled delicately, and so that slight misalignment of fingers, tools, and objects can be adaptively accommodated. Equally, high dynamic range torque sensing is needed when manipulating delicate objects that resist movement, either because of gravity, friction, or adhesion.

2.2. *Physical interaction with humans*

One of the most difficult research challenges in robotics is to develop robots that can collaborate with humans. Such a robot would be quite different from what are today called collaborative robots, or cobots, such as Sawyer[10] or YuMi.[11] These are collaborative only in the sense that it is safe for people to work in close proximity to them because their torque sensing capability allows them to stop a movement if they encounter unexpected resistance, e.g., if a human gets in the way.

In contrast, a truly collaborative robot would be able to anticipate the needs of the human with whom it is collaborating and provide whatever assistance is needed. This requires advanced cognitive abilities: being able to share intentions and goals, and engage in joint attention and joint action.[12] It takes a human infant up to three years to develop the ability to collaborate with its peers, progressing through prior developmental stages, e.g., developing the ability to engage in instrumental helping.[13] Apart from the required cognitive abilities, true collaboration, especially where it involves joint manipulation of objects that both the human and the robot are working on, is also facilitated by the ability to handle objects that the human is handling and pass over the tools that the human might need. As we saw in the previous section, this is one of the key strengths of the humanoid form.

Collaborative robots need not necessarily have a humanoid form. For example, Robust.AI,[14] co-founded by Rodney Brooks, is building what it refers to as collaborative mobile robots in the form of a wheeled platform with a handlebar for transporting goods in warehouses. They "will pay attention to what you're doing, understand what you want, and collaborate with you rather than just exist safely in your space".[15] These robots, just like autonomous cars, will face the same cognitive challenges as humanoid robots in terms of the need for the robot to form a theory of mind of the human user. Nevertheless, humanoids, such as ARMAR,[7] will probably have the edge when it comes to versatile collaboration with humans, and versatility is perhaps the attribute we seek most in robots, especially humanoid ones, mirroring the versatility that is one of the chief characteristic hallmarks of human behavior.

2.3. *Non-verbal communication with humans*

In the long-term, it is foreseen that humanoid social robots will serve people in a variety of ways and operate in everyday environments, often in open spaces such as hospitals, exhibition centers, and airports, providing assistance to people, typically in the form of advice, guidance, or information. The people interacting with these robots will have no special training and they will expect the robot to be able to interact with them on *their* terms, not the robot's, preferring robots that exhibit legible and predictable behavior.[16] In addition to verbal communication, humans use spatial and non-verbal cues to communicate. Spatial interaction includes proxemics, involving conventions about use of the space surrounding an agent, localization and navigation, socially appropriate positioning, initiation of interaction, and communication of intent. Non-verbal interaction involves gaze and eye movement, deictic, iconic, symbolic, and beat gestures, mimicry and imitation, touch, posture and movement, and interaction rhythm and timing.[17] To be effective and human-friendly communicators, robots should use the same cues. This speaks strongly in favour of using the humanoid form, since this is the only form that can mimic these human non-verbal gestures in a legible manner. In other words, the robot should be able to speak the gestural language of humans.

It is important to bear in mind that some of the messages conveyed in non-verbal communication are often subtle and implicit in the way that humans move, originating in the control of the flexible human musculoskeletal system by the nervous system, giving rise to characteristic forms of motion. We pick up on this theme in Section 3.3 on human-like biological motion. In addition, some of the social messaging by humans are exapted functions,[18,19] i.e., functions that evolved for one purpose being co-opted to serve another function. Hand gestures, for example, are arguably exapted from manual manipulation with precision and power grasps. This may have implications for the shaping and dynamics of gestural communication, and their emulation by humanoid dexterous hands. The hand-state hypothesis suggests that the social role of the mirror neuron system in understanding the actions of others is an exaptation of its original role in providing feedback on one's own manual grasping actions.[20]

To be truly effective, non-verbal communication should be intentional, in the sense that it reflects a cognitive goal to engage purposefully with the human. For example, see the scenario described in the article on cognitive robotics in the Encyclopedia of Robotics,[21] which depicts an iCub humanoid robot using joint attention and deictic gesture to signal the location of something a human is looking for.

Social robots also need to be able to interpret the intentions of the people with whom they are interacting. This is difficult to achieve because humans do not necessarily articulate their specific needs explicitly when they interact with social robots (or, indeed, with other humans). As Sciutti et al. note, "the ability of the robot to anticipate human behavior requires a very deep knowledge of the motor and cognitive bases of human-human interaction".[16] Conversely, humans also need to be able to infer the unspoken intentions of the robot. In essence, humans need to be able to form a theory of mind of the robot. Arguably, this is easier if the morphology is humanoid, exactly because such a theory of mind would be based on the non-verbal gestural and spatial communication that human's use. Gestural behaviors provide essential cues for a theory of mind, at least as far as the goals of an intended action are concerned. Also, the vitality with which actions are performed by an agent — softly, gently, neutrally, vigorously, or rudely — expresses positive or negative attitudes towards others and provides important information about the affective state of the agent.[22] In this context, strong human facial likeness is not necessarily the primary channel of non-verbal communication: indeed, it has been shown that facial cues can be very misleading when forming a theory of mind, especially where emotions are involved.[23]

Furthermore, since people make predictions based on what they are used to, as they do when forming a theory of mind, robot behaviors need to be tuned to the socio-cultural context in which they are operating, and their spatial, non-verbal, and verbal communications should reflect the social and cultural norms of their interaction partners.[16,24] This leads us to the next issue: acceptance, trust, and adoption.

2.4. *Acceptance by humans*

Acceptance of technological advances by humans determines whether or not an invention becomes an innovation, i.e., whether or not it produces social and economic benefits through widespread adoption and a consequent change in the people's practices.[25] Adoption depends on social infrastructure: the conventions that govern people's behaviour, the practices they find acceptable and unacceptable, and their sense of what is trustworthy. Cultural competence, i.e., an awareness of social norms and cultural expectations, is a key element in fostering this acceptance.[26,24] Humanoid robots, especially humanoid social robots, need to be able to leverage this acceptance through inclusive, culturally sensitive spatial, non-verbal, and verbal behavior.

The ability to evoke a positive emotional or affective response in a human also contributes to acceptance, as does the complementary ability of a robot to convey the impression of emotion or affect to reinforce what it is saying and the manner in which it is saying it. This is clearly evident in a video of the Kismet robot head asking the same question ("Do you really think so?') in different tones of voice, with matching facial expressions.[27] Similarly, it is easier to emulate recognizably respectful behavior and cultural sensitivity, e.g., bowing to elders and periodically lowering eye gaze,[24] if the robot can mimic the gestures that humans would use in similar circumstances. It is easier and more convincing to accomplish this if the robot has a humanoid form. However, the form, i.e., the morphology, is not the only consideration. The appearance and the way the robot moves must also be considered. We address these three issues in Sections 3.1 – 3.3.

2.5. *Fostering anthropomorphization*

Humans have a natural propensity for anthropomorphization, i.e., the tendency to attribute human characteristics and project human agency onto inanimate objects or animals.[28] Heider and Simmel demonstrated that humans interpret certain types of stereotypically human movement combinations (e.g., successive movement with momentary contact, simultaneous movement with prolonged contact, simultaneous movements without contact, successive movements without contact) as acts of animated beings, mainly people, even when these movements are exhibited by simple two dimensional shapes such as circles and triangles.[29] Humans also attribute motives to these acts. An artefact with a humanoid form leverages this propensity, thereby facilitating natural interaction of the type that humans engage in among themselves.[30,31]

2.6. *Development of cognitive abilities*

There are many stances on what exactly cognition is,[32] on what are the desirable characteristics of cognitive models,[33,34] and how the components of cognition are orchestrated in a cognitive architecture.[35] However, one thing is clear: cognition does not come fully formed in humans. The human capacity for cognition requires development before cognitive capability is realized. This takes several years.[12] Indeed, higher order cognitive functions, expecially those for which the pre-frontal cortex is responsible, continue to develop into adulthood.[36]

Does this matter for humanoid robotics? After all, humanoids are machines, not humans, even if they have a human form. The answer depends on the paradigm of cognition that one adopts when modelling and implementing cognitive systems. There are three principal paradigms:[12] the cognitivist (sometimes referred to as the symbolic[35]), the emergent, and the hybrid (which endeavours to combine the cognitivist and the emergent). Each takes a completely different stance on the role played by the body of an agent in cognitive activity.

In the cognitivist paradigm, it plays no direct role, a position referred to as computational functionalism.[37] Cognition comprises computational operations defined over symbolic representations and these computational operations are not dependent on the instantiation. The form of the body is arbitrary, provided it is capable of supporting the required computations.

In the emergent paradigm, however, the body plays a central, causal role: a position referred to as *embodied cognition*.[38,39] Emergent agents are embodied and embedded in the world around them, developing through real-time interaction with their environment, a process referred to as ontogenesis. In embodied cognition, the way the cognitive agent perceives the world derives not from a purely objective world independent of the agent, but from actions that the agent can engage in whilst still maintaining its autonomy. The space of possible actions facilitated by, and conditioned by, the particular embodiment of the cognitive agent determines how that cognitive agent perceives the world. Thus, through this ontogenetic development, the cognitive system constructs and develops its own understanding of the world in which it is embedded, i.e., its own agent-specific and body-specific knowledge of its world.

Wilson and Foglio sum this up neatly as follows: "Many features of cognition are embodied in that they are deeply dependent upon characteristics of the physical body of an agent, such that the agent's beyond-the-brain body plays a significant causal role, or physically constitutive role, in that agent's cognitive processing."[40] In other words, embodied cognition asserts that thought is tightly constrained by the body but also enabled by it, a stance developed in the book *How the Body Shapes the Way We Think* by Rolf Pfeifer and Josh Bongard.[41] Consequently, in the emergent paradigm, the humanoid form is crucially important for robot cognitive development: for there to be compatible cognitive abilities and mutually consistent understanding of the world, with similar affordances, the robot's embodiment must be compatible with the human's embodiment.

2.7. *A platform for empirical research in human cognition*

We noted in the introduction to Section 2 that the six special attributes give rise to a seventh special feature of humanoid robots: they can play an important role in the empirical study of cognition in humans by providing a platform on which to implement and test models of cognition. This is a natural consequence of their humanoid morphology, giving them the capacity to engage in an ontogenetic process that mirrors that of human infants. For example, the iCub cognitive humanoid robot,[5] developed in the RobotCub project,[4] was conceived with the twin goals of creating an open humanoid platform for research in embodied cognition, and advancing our understanding of cognitive systems by exploiting this platform in the study of cognitive development.[42,34] With the same height as a two or three-year old child, the iCub was designed so that it could develop its perceptual, motor, and cognitive capabilities for the purpose of performing goal-directed manipulation and communication tasks. Humanoids, such as the iCub, can be used in two distinct ways: as models of cognitive development and as repeatable stimulus agents to study perception, cognition, and interaction in humans.[43]

3. What Human Features Should Be Used When Designing a Humanoid Approximation of a Human?

Having established the importance of the humanoid form, we turn our attention now to the degree to which a humanoid should resemble a human. There are three aspects to this: (i) robot morphology, i.e., the number and arrangement of the effectors and sensors; (ii) robot appearance, i.e., the degree to which the physical appearance approximates that of a human; and (iii) and the manner in which the robot moves. We consider these in the following three sections.

3.1. *Human-like morphology*

Robots have sensors, actuators, effectors, and controllers. The sophistication of these components varies, but most robots, including humanoid robots, use high-quality electric motors for actuators and light-weight stiff materials for effectors. Such components provide, to a greater or lesser extent, accuracy and repeatability, features that are not necessarily characteristic of humans, who tend to have softer, more compliant, and more elastic components. Some researchers,[44,45] on the basis that conventional components restrict the types of interaction such robots can engage in, limiting the knowledge they can acquire from their environment through experience, with a consequent impact on the development of their cognitive skills, take a different approach that is more anthropomimetic than anthropomorphic. ECCE1,[44] for example, has simulated bones, muscles, and tendons, as do the Kenshiro and Kengoro anthropomimetic humanoid robots.[45]

This approach allows one to experiment with a more explicit implementation of biological motion where each joint is actuated by two muscles in an agonist-antagonist configuration. The downside of this approach is that by at least doubling the number of motors needed, the mechanical complexity of the system increases, making a multiple joint humanoid very difficult to implement and use. These approaches also make evident the poor quality of currently available "artificial muscles" based on pneumatic solutions with respect to the lightweight and high-power elastic muscles that actuate biological systems, including humans. Such a technology still very much needed in robotics.

An alternative solution with respect to electrical or pneumatic actuation is based on oleo-dynamic actuators. These are used in several humanoid robots, from the pioneering work of Stephen Jacobsen — who, besides building the first dexterous hand known as the Utah Artificial Arm and many robots for films and amusement parks, founded SARCOS, the company that implemented CB-i,[46] the 50 degrees of freedom humanoid used by Mitsuo Kawato as a test-bed for computational neuroscience,[47,48] — to the latest realization of Atlas[49] by Marc Raibert, founder of Boston Dynamics.

With that said, we focus here on the morphology of humanoid robots, i.e., the number and arrangement of their actuators, effectors, and sensors, rather than on their material properties.

Humans have two legs which they use for standing still, walking, running, and lowering the upper body by bending the knees. The upper body can also be raised by flexing the ankle muscles. Not all humanoids have two legs which they can use for these purposes. Some have a form of extended torso, which in the case of the Pepper humanoid robot is still referred to as a leg[50] with a thigh, a knee joint, and a tibia,[51] and with movement being effected using wheeled locomotion. This limits the robot's ability to match the movements of a human when working collaboratively on tasks that, for example, involve the human and the robot lifting and lowering objects. Some humanoid robots, such as the ARMAR robot[7], the PR2 robot,[52] and the R1 robot[53] accommodate this by using prismatic joints in the torso that allow the height of the upper body to be adjusted. Not having legs means that wheeled-locomotion humanoid robots cannot step over obstacles or climb stairs, such as the Asimo[54] or the HRP-4[55] robots can.

Humans have an articulated torso, in the sense that it can twist and bend. Although ARMAR and PR2 have articulated torsos with prismatic joint to adjust the height of the robot's upper body, some humanoid robots, such as iCub[5] and Pepper,[50] have articulated torsos that allow them to bend. Pepper has two degrees of freedon, hip pitch and hip roll, while iCub has three (tilt, swing, pan).[56] Others, such at ARI[57] have no degrees of freedom in their torso. The lack of an ability to bend the torso can be a disadvantage when interacting in a culturally sensitive manner in social settings involving humans because the ability to bow is sometimes required to communicate respect to the interaction partner,[24] as well as, for example, when picking up objects from the floor.

Despite the significant mass (or maybe because of it), humans move their heads with very fine control. Developing the ability to control head movements is an important element of neonatal development, with newborn babies acquiring the ability to control head posture approximately three months after birth. Infants persist in tracking moving objects with head movements, despite its difficulty and even though it is easier to track the object with eye movements alone. von Hoftsten notes that "this is an expression of important developmental foresight because eventually, the ability to engage the head will result in much more flexible tracking skills".[42] The importance of being able to control the attitude of the head is reflected in almost all humanoid robots, with some having one degree of freedom, e.g., Atlas,[58] some two (pan and tilt) e.g., ARI[57] and ARMAR,[7] and others having three, e.g., iCub.[56]

The ability to direct visual gaze quickly using saccadic eye movements and stabilize gaze on objects using smooth pursuit is very important in humans and, like head movement, it is an important element of neonatal development. Smooth pursuit starts to improve around six weeks of age and attains adult levels from around fourteen weeks, while vergence develops from week four for distances greater than twenty centimetres and it can be used to guide reaching actions by week twenty.[42] Most humanoid robots do not provide this type of articulated eye movement, relying on head movment to adjust the robot's gaze. A notable exception is the iCub,[5] which has three degrees of freedom in its eyes, allowing pan, tilt, and vergence. The eye movements are coordinated with the head movement, also through an inertial system emulating the vestibular system, allowing the iCub to exhibit very natural movements when attending to objects in its environment. In turn, this natural movement is important in human-robot interaction because it allows humans to engage with the robot to establish eye contact (mutual gaze) and joint attention.

Humans blink periodically. That is, humans have eyelids that allow them to close their eyes. Furthermore, when observing someone, we expect them to blink, and it can be unnerving to interact with someone who does not blink. Indeed, blinking can be an important element in human nonverbal communication.[59] With the exception of android robots, such as Geminoid DK,[60] Erica,[61], and Sophia,[62] few humanoid robots have eyelids that allow them to emulate this natural behavior. Once more, the iCub[5,59] is a notable exception.

Humans also have eyebrows. Again, these play an important roles in non-verbal communication, both in humans and in robots, as demonstrated by the Kismet robot head.[27] Few humanoid robots, including androids, have independent control of their eyebrows. In the case of Geminoid DK,[60] the eyebrows move but it appears that the movement is linked to the eyelid movement. Sophia[62] can actuate the forehead and the eyebrows move as a consequence. The iCub[5] does not have physical eyebrows but makes extensive use of eyebrow-shaped LEDs to give the impression of raised and lowered eyebrows during interactions. This allows it to convey a sense of emotion or affective state. The omission of an ability to independently articulate eyebrows is a shortcoming of many humanoid robots because, at least in some cultures, a raised eyebrow is an important non-verbal gesture to acknowledge the presence of someone, and thereby show respect in a culturally sensitive manner.

Apart from its involvement in oral communication, the mouth is also an important channel in non-verbal communication, and it is one of the key elements of facial expression. Again, this was convincingly demonstrated by the Kismet robot head.[27] For the most part, and with the exception of android robots, humanoid robots do not feature labio-mandibular articulation, i.e., the combined control of the lips and jaw. This has significant implications for non-verbal communication in human-robot interaction.

Finally, humans have two arms, with a hand at the end of each. While the arm is essential for positioning the hand in whatever pose is required, something that humanoid robots with six (or more) degree-of-freedom arms can do, it is the hands with four fingers and a prehensile thumb that stand out as one of the chief characteristics of humans or primates. The hand enables dexterous manipulation of objects of varied shapes and sizes. This manipulation is a key element in acquiring an understanding of the capabilities of these objects, i.e., what they can be used for. This is referred to as the *affordance* of an object, a concept introduced by the ecological psychologist James J. Gibson[63] to convey the idea that the perception of the potential use to which an object can be put depends as much on the action capabilities of the observing agent as it does on the object itself. Thus, dexterous hands play a dual role: flexible grasping and manipulation of objects, and providing a haptic sensory interface for constructing representations of the objects in an agent's environment, yielding an understanding of the agent-specific use to which an object can be put. As we noted above, most humanoid robots are not equipped with dexterous hands, and those that are, such as iCub[5] and ARMAR,[7] have limited dexterity. This limits their abilities in both manipulation and learning object affordances.

There is one final, compelling reason why humanoid robots should have a morphology that is as close to humans as possible. It relates the seventh special attribute of humanoid robots: their role as a platform for research in human cognition (see Section 2.7). When we use humanoid robots, such as the iCub,[5,4] as a way to pose questions about particular aspects of the development of embodied cognitive behaviour, and answer these questions empirically, the morphology of the humanoid robot needs to be as similar as possible to that of the embodied cognitive agent being studied, i.e., the human. This use of a humanoid as platform for research in human intelligence also extends to anthropomimetic concerns, such the Kenshiro and Kengoro human mimetic humanoid robots.[45]

The questions we wish to pose will dictate the choices we need to make when designing the humanoid robot, its morphology, its appearance, and the manner in which its movements are controlled. For example, in studying the development of prospective control of gaze in babies, visual, vestibular, and proprioceptive sensing must be accommodated to achieve coordinated eye-head movement, moving the eyes to salient visual targets, stabilizing gaze on these targets, and compensating for movement of the robot. Moving the eyes to a new target is effected with high speed saccadic eye movements and stabilizing them on a moving target is effected with smooth pursuit eye movements. When the robot is moving relative to the target, the smooth eye movements need to anticipate those body movements in order to compensate for them correctly. Fixation is maintained through a coordinated action of the vestibulo-ocular reflex and smooth pursuit. Similarly, when the fixated target moves, the eyes must anticipate its forthcoming motion. Both visual and vestibular mechanisms operate to compensate for head movements. The visual mechanism stabilizes gaze on the optic array by minimizing retinal slip, while the vestibular mechanism stabilizes gaze in space. All of these considerations were factored into the design of the iCub head, for example, to facilitate its use for empirical research in human cognition.

3.2. *Human-like appearance*

How closely should humanoid robots resemble human appearance? Bartneck et al. refer to an untested prediction by Mori[64,65] that "the more humanlike robots become, the more likable they will be, until a point where they are almost indistinguishable from humans, at which point their likability decreases dramatically".[17] Mori referred to this as the *uncanny valley*, a negative emotional response towards robots that bear a close, but not sufficiently close, resemblance to humans, especially when the robot alters its facial expressions. Androids are robots that resemble humans in appearance, as well as form. Should humanoids necessarily be androids? If so, how do designers avoid building androids that lie in the uncanny valley? If not, does it matter how dissimilar they are from human appearance?

Kazuhiko Kawamura, in an article in this special issue, recounts a panel discussion on the future of humanoid robots organized by the Disney Institute in 2000. He notes that Joe Engelberger, who developed the first industrial robot in the United States, the Unimate, in the 1950s, opened the panel by saying that "Well, I'm keen on a humanoid robot, but I don't think it has to be a Stepford wife. The appearance does not mean very much to me". Marvin Minsky, a pioneer of artificial intelligence, followed up by saying that "building mechanical robots that look like people so that they evoke emotional reaction is just a waste of time."

Were they right? The answer hinges on the degree to which its appearance and behavior engenders acceptance and trust. We have already noted the importance of culturally competent behavior in this context. The issue here concerns the impact of appearance. This does not seem to be as crucial as behavior, provided the appearance is not so human-like as to trigger an uncanny valley reaction, exacerbated by incongruous facial or body movements. It can be somewhat human-like in appearance. For example, the iCub face was modelled on a non-threatening caricature of a child's face. Significantly, the final selection from eight or so design options was not made by the designers, but by a group of schoolchildren, thereby ensuring no uncanny valley reaction. Alternatively, the appearance might be distinctly robotic, e.g., the ARMAR humanoid. Ideally, a formal understanding of the source of the negative emotional response, such as that proposed by Roger Moore,[66] focussing on conflicting perceptual cues, e.g., facial features and eye movements, might be used to evaluate the design parameters. This helps keep in mind that appearance is only one aspect contributing to the uncanny valley, the other being the expected, context driven behavior including implicit and explicit social messages. The way humans move is important and should also be considered, as explained in the next section.

3.3. *Human-like biological motion*

Biological motion, and specifically the movements that are planned and executed by humans, exhibits a characteristic profile. This is modelled in two complementary ways: covariation of kinematic and geometrical parameters, and minimization of some global cost.[67] The first is formalized by the so-called two-thirds power law. This empirical law describes a regular relationship between the instantaneous tangential velocity and the curvature of the trajectory of human movement. Specifically, the law is formulated as follows.[67]

$$A = KC^{2/3} \tag{1}$$

where A is the angular velocity, K is a piecewise constant velocity gain factor, and C is the path curvature ($C = 1/R$, where R is the radius of curvature of the trajectory). This it is also referred to as an equivalent one-third power law[68] that states the movement velocity V decreases as the path curvature of the movement C increases, or, equivalently, as the radius of curvature R decreases, as follows.

$$V = KC^{-1/3} \tag{2}$$

$$= KR^{1/3} \tag{3}$$

This simple formulation applies when the trajectory has no inflections points.[69] A more general model which covers a wider class of movements and accounts for inflection points is formulated as follows.[67]

$$V(s) = K(s)\left(\frac{R(s)}{1+\alpha R(s)}\right)^{1/3} \tag{4}$$

where s is the curvilinear coordinate, i.e., the distance along the trajectory, and α is a constant in the range 0 to 1. This velocity-curvature approach is relevant when planning movements using motor programs, i.e., representations of the intended trajectory that capture invariant structural aspects of the intended action. These structual aspects are then complemented by parameters such as duration and force during execution.

The second formalization of the characteristic velocity profile of biological motion — minimization of some global cost — is captured by the minimum-jerk model. This postulates that maximum smoothness is a key criterion for planning point-to-point movements and that this can be achieved by minimizing a cost function C that is proportional to the mean square of the jerk, i.e., the derivative of the acceleration, as follows.

$$C = 1/2 \int_{t_1}^{t_2} \left[\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2\right] dt \tag{5}$$

The resultant point-to-point motion has a smoothly-varying bell-shaped velocity profile, with no discontinuities in velocity.

It has been argued that, while the velocity-curvature covariations captured by the two-thirds power law are implicit in the minimum-jerk hypothesis, both have value in modelling biological motion and in movement planning.[67] It has also been suggested that the two-thirds power law, generally attributed either to smoothness of the movement or to mechanisms that damp the noise inherent in the motor system to produce smooth motion, might also result from correlated noise inherent in the motor system.[70]

Young infants exhibit a preference for the motions produced by a moving person over other motions, i.e., biological motion, and there is evidence to support the hypothesis that the detection of biological motion is an intrinsic capacity of the human visual system.[71] Furthermore, it has been argued that the ability to process biological motion is the hallmark of social cognition.[72]

The ability to perceive biological motion provides humans and robots with several benefits.[16] These include the ability to detect the presence of humans, even when the human is not visible, but the tool being used by the human is visible, the ability to anticipate movements when combined with a knowledge of the tool being used, and the ability to infer the affective state of the interacting partner.

While this provides a strong case for ensuring that all human-robot interaction systems can perceive biological motion,[73,74,75] there is also an equally compelling case for ensuring that humanoid robots produce movements with a biological motion profile.[30,31] For example, it allows them to embed in their movements the implicit messages that humans use in non-verbal communication,[16] thereby enabling a humanoid robot to communicate non-verbally in a manner that humans find natural. In physical human-robot collaboration, with a robot guiding the human, Maurice et al.[69] showed that humans are better at moving along with the guiding robot when the robot follows a biological two-thirds power law velocity pattern, compared to a non-biological one. Huber et al.[76] showed that the reaction time of humans in tasks where the robot hands over an object to the human is significantly shorter when a biological, minimum-jerk velocity profile is used, and humans also feel confident when physically interacting with the robot. Finally, Karlinsky et al.[68] use the one-third power law velocity profile to effect biological walking motion in a HRP-2 humanoid robot, demonstrating improved performance in terms of energy expenditure and faster movement.

4. Research Challenges

Having argued that humanoid robots occupy a special niche in robotics, and having considered the degree to which they should approximate humans, we suggest here four key challenges that remain for humanoid robotics, elements of which were stated as requirements by Adams et al.[3] almost a quarter of a century ago. These concern (i) cognitive versatility and flexibility, (ii) cognitive architectures, (iii) culturally and emotionally appropriate behavior, and (iv) the ability to collaborate. While progress has been made on these issues, much remains to be done.

We made the case that humanoid robots are ideally placed to work seamlessly in human environments by virtue of their physical morphology. Achieving this ability to perform everyday activities autonomously is, however, not a trivial goal.[77] Many skills are required: from dexterous grasping and manipulation, to timely action planning and action execution in the absence of explicit instructions. This points to the need for robots to have the cognitive ability to anticipate the need to act and to anticipate the motor and perceptual outcomes of those actions,[42] to exploit knowledge through reasoning,[78] to learn and develop,[34] and to adapt to new circumstances, both environmental and social.[79] While there have been many advances in cognitive systems over the past 40 years,[a] more research is required to achieve the versatility and flexibility of human cognition,[80] as opposed to (or, to some extent, in addition to) the virtuosity of modern deep learning in artificial intelligence.

Achieving this versatility will require significant effort, not just in mechatronics, sensors, actuators, effectors, and controllers, but equally in the cognitive architectures[81] that orchestrate the many processes that are involved in achieving the core cognitive abilities of perception, attention, action selection, memory, learn-

[a]For an overview of the advances in cognitive systems, see this collection of short videos by fifteen leading researchers delivered during the 2021 TransAIR Workshop on Cognitive Architectures for Robot Agents — Current Capabilities, Future Enhancements, and Prospects for Collaborative Development: `https://transair-bridge.org/workshop-2021/`.

ing, reasoning, meta-reasoning,[35] as well as prospection,[82] and their development[34] as the humanoid robot interacts with its environment. The iCog[83] initiative is one example of the type of research that is needed in this area.

When the need to interact naturally with humans while carrying out everyday activities is factored in, the challenge becomes even greater. Perhaps the key element in effective human-robot interaction, from the perspective of the robot, is the need to be able to form a theory of mind[84,85,86] of a human interaction partner, inferring their intentions and goals, and anticipating their actions and the action outcomes. The robot then has to follow up in an appropriate manner, i.e., acting in a helpful way, and in a manner than engenders trust in the robot. Factoring in culturally sensitive spatial, non-verbal, and verbal behaviors is crucial to establish the long-term mutual relationship needed for the successful adoption of humanoid robots. As pointed out over twenty years ago,[3] the resultant social dynamics need to be modulated by an emotional model that accounts for the affective state of the human interaction partner. This model can then be used to communicate by modulating biological motion in non-verbal interaction and the vocal timbre in spoken interaction. This in turn helps foster acceptance, trust, and confidence on the part of the human interaction partner.

If one wishes humanoid robots to be able to collaborate with humans, the bar is lifted even higher because it requires the robot to develop the ability to form shared goals and shared intentions, and the ability to engage in joint action and joint attention, with saliency being co-determined by the robot and the human, detecting eye contact and following each other's gaze (e.g., see again the scenario described in the article on cognitive robotics in the Encyclopedia of Robotics[21]). While this is a significant challenge, collaboration also affords opportunities. Just as humans learn by imitation, so can humanoid robots, and the ability to work alongside a human affords a robot the opportunity to learn from demonstration,[87,88,89] one of the top industrial priorities for cognitive robotics.[9]

5. Conclusion

Although we have made much progress, there is still a long road ahead before we arrive at our goal: humanoid robots that can work autonomously, prospectively, and flexibly with humans, learning, developing, and adapting as they do so. That road will no doubt have many twists and turns as our discipline of humanoid robotics advances, but it will certainly be a rewarding journey. The likelihood of these rewards materializing will be much increased if we travel the road together in a multidisciplinary group of roboticists, engineers, psychologists, neuroscientists, cognitive scientists, social scientists, ethnographers, artists, and philosophers. Together, by being scientifically empathetic of each other's complementary perspectives, humanoid robotics will surely realize its immense potential, and we may be able to strengthen the virtuous cycle between the use of robots to study humans and the study of humans to built better robots (or more "humane" robots).

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