KI-Zeitschrift, 4/08, pp. 5-9, December 2008

Humanoid Robots – From Fiction to Reality?

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Humanoid robots have been fascinating people ever since the invention of robots. They are the embodiment of artificial intelligence. While in science fiction, human-like robots act autonomously in complex human-populated environments, in reality, the capabilities of humanoid robots are quite limited. This article reviews the history of humanoid robots, discusses the state-of-the-art and speculates about future developments in the field.

1 Introduction

Humanoid robots, robots with an anthropomorphic body plan and human-like senses, are enjoying increasing popularity as research tool. More and more groups worldwide work on issues like bipedal locomotion, dexterous manipulation, audio-visual perception, human-robot interaction, adaptive control, and learning, targeted for the application in humanoid robots.

These efforts are motivated by the vision to create a new kind of tool: robots that work in close cooperation with humans in the same environment that we designed to suit our needs. While highly specialized industrial robots are successfully employed in industrial mass production, these new applications require a different approach: general purpose humanoid robots. The human body is well suited for acting in our everyday environments. Stairs, door handles, tools, and so on are designed to be used by humans. A robot with a human-like body can take advantage of these human-centered designs. The new applications will require social interaction between humans and robots. If a robot is able to analyze and synthesize speech, eye movements, mimics, gestures, and body language, it will be capable of intuitive communication with humans. Most of these modalities require a human-like body plan. A human-like action repertoire also facilitates the programming of the robots by demonstration and the learning of new skills by imitation of humans, because there is a one-to-one mapping of human actions to robot actions.

Last, but not least, humanoid robots are used as a tool to understand human intelligence. In the same way biomimetic robots have been built to understand certain aspects of animal intelligence, humanoid robots can be used to test models of aspects of human intelligence.

Addressing all of the above areas simultaneously exceeds the current state of the art. Today's humanoid robots display their capabilities in tasks requiring a limited subset of skills. After some brief historical notes, this article will review the state-of-the-art in humanoid robotics and discuss possible future developments.

2 History

The concept of human-like automatons is nothing new. Already in the second century B.C., Hero of Alexander constructed statues that could be animated by water, air and steam pressure. In 1495 Leonardo da Vinci designed and possibly built a mechanical device that looked like an armored knight. It was designed to sit up, wave its arms, and move its head via a flexible neck while opening and closing its jaw. By the eighteenth century, elaborate mechanical dolls were able to write short phrases, play musical instruments, and perform other simple, life-like acts.

In 1921 the word robot was coined by Karel Capek in its theatre play: R.U.R. (Rossum's Universal Robots). The mechanical servant in the play had a humanoid appearance. The first humanoid robot to appear in the movies was Maria in the film Metropolis (Fritz Lang, 1926). Westinghouse Electric Corporation exhibited at the 1939 and 1940 World's Fairs the tall motor man Elektro. Humanoid in appearance, it could drive on wheels in the feet, play recorded speech, smoke cigarettes, blow up balloons, and move its head and arms. Elektro was controlled by 48 electrical relays and could respond to voice commands.

Humanoid robots were not only part of the western culture. In 1952, Ozamu Tezuka created Astroboy, the first and one of the world's most popular Japanese sci-fi robots. In 1973 the construction of a human-like robot was started at the Waseda University in Tokyo. Wabot-1 was the first full-scale anthropomorphic robot able to walk on two legs. It could also communicate with a person in Japanese and was able to grip and transport objects with touch-sensitive hands. The group of Ichiro Kato also developed Wabot-2, which could read music and play an electronic organ. It was demonstrated at the Expo 1985 in Tsukuba, Japan. Wabot-2 was equipped with a hierarchical system of 80 microprocessors. Its wire-driven arms and legs had 50 degrees of freedom.

Many researchers have also been inspired by the movie Star Wars (George Lucas, 1977) which featured the humanoid robot C3-PO and by the TV series Star Trek - The Next Generation (Gene Roddenberry, 1987) which featured the humanoid Data.

In 1986 Honda began a robot research program with the goal that a robot "should coexist and cooperate with human beings, by doing what a person cannot do and by cultivating a new dimension in mobility to ultimately benefit society." After ten years of research, Honda introduced in 1996 P2 to the public, the first self-contained full-body humanoid. It was able to walk not only on flat floors, but could also climb stairs. It was followed in 1997 by P3 and in 2002 by Asimo.

In the U.S. Manny, a full-scale android body, was completed by the Pacific Northwest National Laboratory in 1989. Manny had 42 degrees of freedom, but no intelligence or autonomous mobility. Rodney Brooks and his team at MIT started in 1993 to construct the humanoid upper-body Cog. It was designed and built to emulate human thought processes and experience the world as a human.

Another milestone was the Sony Dream Robot, unveiled by Sony in the year 2000. The small humanoid robot, which was later called Qrio, was able to recognize faces, could express emotion through speech and body language, and could walk on flat as well as on irregular surfaces.

More recent examples of humanoid robot appearances in the movies include David from A.I. (Steven Spielberg, 2001), and NS-5 from I, robot (Alex Proyas, 2004).

3 State-of-the-Art

Although, from the above, it may seem that the most important issues for construction and control of humanoid robots have been solved; this is not at all the case. The capabilities of current humanoid robots are rather limited, when compared to humans.

3.1 Bipedal Locomotion

The distinctive feature of full-body humanoids is bipedal locomotion. Walking and running on two legs may seem simple, but humanoid robots still have serious difficulties with it. I see two opposing approaches to bipedal walking. The first-one is based on the zero-moment-point theory (ZMP), introduced by Vukobratovic [1]. The ZMP is defined as the point on the ground about which the sum of the moments of all the active forces equals zero. If the ZMP is within the convex hull (support polygon) of all contact points between the feet and the ground, a bipedal robot is dynamically stable. The use of the ZMP to judge stability was a major advance over the center-of-mass projection criterion, which describes static stability. Prominent robots, which rely on ZMP-based control, include Honda Asimo and Sony Qrio. Asimo was shown in 2006 to be capable of 6km/h running. However, its gait with bent knees does not look human-like. It does not recycle energy stored in elastic elements, the way humans do it and, hence, it is not energy-efficient. Furthermore, Asimo requires flat, stable ground for walking and running and can only climb certain stairs.

A completely different approach to walking is to utilize the robot dynamics. In 1990 McGeer showed that planar walking down a slope is possible without actuators and control [2]. Based on his ideas of passive dynamic walking, actuated machines have been built recently [3]. These machines are able to walk on level ground. Because their actuators only support the inherent machine dynamics, they are very energy-efficient. They are easy to control, e.g. by relying on foot-contact sensors. However, because they use round feet, these machines cannot stand still. So far, these machines can also not start or stop walking and are not able to change speed or direction.

What is missing in current humanoid robots is the ability to walk on difficult terrain and the rejection of major disturbances, like pushes. Such capabilities were demonstrated by the quadruped BigDog [4]. This robot, however, is not suited for indoor use due to its combustion engine and hydraulic actuators. First steps towards bipedal push recovery have been done in simulation using Pratt's concept of capture point [5]. It is difficult to transfer these simulation results to physical robots, partly due to the lack of suitable actuators. Although hydraulic actuators (e.g. Sarkos biped used at ATR and CMU) and pneumatic actuators (e.g. Lucy designed at Brussels [6]) have been used for bipeds to implement compliant joints, their walking performance is still not convincing.

3.2 Perception

Humanoid robots must perceive their own state and the state of their environment in order to act successfully. For proprioception, the robots measure the state of their joints using encoders, force sensors, or potentiometers. Important for balance is the estimation of the robot attitude. This is done using accelerometers and gyroscopes. Many humanoid robots also measure ground reaction forces or forces at the hands and fingers. Some humanoid robots are covered with force-sensitive skin. One example for such a robot is CB^2 [7], developed at Osaka University.

Although some humanoid robots use super-human senses, such as laser rangefinders or ultrasonic distance sensors, the most important modalities for humanoid robots are vision and audition. Many robots are equipped with two movable cameras. These cameras are used as active vision system, allowing the robots to focus their attention towards relevant objects in their environment. Movable cameras make depth estimation from disparity more difficult, however. For this reason, fixed calibrated cameras are used for stereo. Most humanoid robots are equipped with onboard computers for image interpretation. Interpreting real-world image sequences is not a solved problem, though. Hence, many humanoid vision systems work well only in a simplified environment. Frequently, key objects are color-coded to make their perception easier.

Similar difficulties arise when interpreting the audio signals captured by onboard microphones. One major problem is the separation of the sound source of interest (e.g. a human communication partner) from other sound sources and noise. Turning the microphones towards the source of interest and beamforming in microphone arrays are means of active hearing. While they improve the signal-to-noise ratio, the interpretation of the audio signal is still difficult. Even the most advanced speech recognition systems have substantial word error rates.

Due to the described difficulties in perception, some humanoid projects resort to teleoperation, where the signals captured by the robot are interpreted by a human. Examples for teleoperated humanoids include the Geminoid [8] developed by Ishiguro, the Robonaut [9] developed by NASA, and the PR1 [10] developed at Stanford.

3.3 Human-Robot Interaction

Many humanoid research projects focus on human-robot interaction. The general idea here is that the efficient techniques which evolved in our culture for human-human communication allow also for intuitive human-machine communication. This includes multiple modalities like speech, eye gaze, facial expressions, gestures with arms and hands, body language, etc. These modalities are easy to interpret by the human sensory system. Because we practice them since early childhood, face recognition, gesture interpretation, etc. seem to be hard wired in our brains. A smile from a robot does not need much explanation.

In order to address these modalities, communication robots are equipped with expressive animated heads. Examples include Kismet and Leonardo, developed at MIT [11, 12], and WE-4RII developed at Waseda [13]. Movable eyes, head, and chests communicate where the robot focuses its attention. When the robot looks at the interaction partner, the partner feels addressed. Some robots animate their mouth while generating speech. This helps the listener to detect voice activity. Some robots have an emotional display. By moving eyebrows, eyelids, the mouth, and possibly other parts of the face, a number of basic emotions can be expressed. The expression of the emotional state can be supported by adapting pitch, loudness, and speed of the synthesized speech.

Robots with anthropomorphic arms and hands can be used to generate gestures. At least four joints per arm are needed [14]. One example for a upper-body robot used to generate a variety of gestures is Joy, developed at KAIST, Korea [15]. The generated gestures of humanoids include symbolic gestures, such as greeting and waving, batonic gestures, which emphasize accompanying speech, and pointing gestures, which indicate a direction or reference an object. The size of objects can also be indicated with arms and hands. The robot head can be used for pointing, nodding and shaking as well. Robots with articulated fingers like Hubo, also developed at KAIST [16], may even be used to generate sign language.

Full-body humanoids can use their entire body for communication using body language. Wabian-RII, for example, was programmed to generate emotional walking styles [17]. Another example is HRP-2, which reproduced a Japanese dance captured from a human dancer [18].

The most extreme form of communication robots are androids and gynoids, which aim for a photorealistic human-like appearance. Their faces are covered with silicone skin, they have human-like hair, and they are dressed as humans. Some of these robots are modeled after living persons, such as Repliee Q2, developed in Osaka [19], and the copy of Zou Ren Ti, developed at XSM, China. These robots, however, heavily suffer from the uncanny valley effect [20]. There is not a monotonous increase in attractiveness as robots become more human-like, but there is a sudden drop in attractiveness close to perfect human-likeness.

While the synthesis-part of multimodal interaction works reasonably well, the insufficient perception performance of the computer vision and audition systems and the lack of true meaning in the dialogue systems so far prevent humanoid robots from engaging in truly intuitive multimodal interactions with humans.

3.4 Dexterous Manipulation

Another key human capability is dexterous manipulation. The human hand has about thirty degrees of freedom. It is not easy to reproduce its strength, flexibility, and sensitivity. Among the most advanced robotic hands are the Shadow hand, which is driven by 40 air muscles [21] and the four-finger hand developed by DLR and HIT [22].

Dexterous manipulation not only requires capable hands, but also hand-arm coordination and the coordination of two hands and the vision system. Due to the high number of joints involved, controlling grasping and manipulation is challenging. Three examples for manipulation-oriented humanoid robots are the Robonaut [9], which is using the space tools designed for humans, Justin, for which DLR developed an impedance-based control scheme [23], and Twendy-One, which is equipped with passive impedances in the actuators [24].

While the performance of these robots is impressive, they cannot grasp and manipulate unknown objects. This is mainly due to deficits in the perception of grasping affordances. Also the interpretation of the touch and force sensors integrated in the hands must be improved in order to allow for blind adjustments of the grip in the way humans do it.

3.5 Learning and Adaptive Behavior

To be useful in everyday environments, humanoid robots must be able to adapt existing capabilities and need to cope with changes. They are also required to quickly learn new skills.

Fortunately, humanoid robots have the unique possibility to learn from capable teachers, the humans in their environment. This is called imitation learning [25] or programming by demonstration [26]. Imitation learning has been applied, for example, to complex motions like swinging a tennis racket or generating gestures [27] and to manipulation tasks. One difficulty of imitation learning is the perception of the teacher. Frequently, external motion capture systems relying on special markers or attached motion sensors are used to sense the motion of the teacher. Another difficulty is the mapping between the human body and the robot's body. Some human motions may not be possible for the robot, e.g. due to lack of joints, limited joints angles or dynamic constraints. On the other hand, the robot might have degrees of freedom that are not constrained by the captured motion. These must be controlled by optimizing secondary criteria such as energy use. A frequently used possibility to simplify imitation is also to rely on kinesthetic teaching, where the teacher directly moves the limbs of the robot. While the imitation of human motion patterns greatly assists in the generation of humanoid motion, it does not suffice. Because of the differences between the teacher and the robot, for true imitation the robot must infer the intentions of the human teacher and come up with its own strategy to accomplish the same goals.

Another possibility to optimize the behavior of humanoid robots is reinforcement learning [28]. Here, the robot revives rewards or punishments while interacting with the environment. The problem now is to find the policy of actions which maximizes the discounted future reward. Many techniques for reinforcement learning exist. Among the most promising techniques are stochastic gradient techniques, which have been used to optimize bipedal walking patterns [29] and natural actor-critic learning [30], which has been shown to learn hitting a ball with a bat. One general difficulty with reinforcement learning is the generation of the rewards. It cannot be assumed that the environment generates a reward structure sufficient for the learning of complex tasks. Rather, intermediate rewards must be generated by the robot itself when successfully accomplishing subtasks or when meeting intrinsic needs. On the other hand, the robot must generate negative rewards when violating intrinsic constraints, for example when falling. Especially in such situations it is crucial to learn from few examples.

In addition to the learning of behavior, learning and adaptation are also important for perception. Computer vision and speech recognition, for example, must adapt to changing lighting conditions and varying auditory backgrounds. The robots are required to familiarize themselves with new objects in their environment and also need to learn new words and names. For navigation, some humanoid robots construct maps of their surroundings. One example for successful mapping with a humanoid has been presented by Gutmann et al. [31] using Sony Qrio.

4 Application Domains

Because the capabilities of humanoid robots are rather limited, there are few real-world applications for them so far. The most visible use of humanoid robots is technology demonstration.

4.1 Technology Demonstration

Famous humanoid robots like the Honda Asimo [32] or the Toyota Partner Robots [33] do not accomplish any useful work. They are, however, presented to the media and demonstrate their capabilities like walking, running, climbing stairs, playing musical instruments or conducting orchestras on stage and during exhibitions. Such a showcase of corporate technology attracts public attention and strengthens the brand of the car manufacturers. Hence, the huge development costs of these advanced humanoids might be covered from the marketing budgets.

4.2 Space Missions

Another area where money is not much of an issue is missions to space. Since human life support in space is costly and space missions are dangerous, there is a need to complement or replace humans in space by human-like robots. The two prominent projects in this area are the NASA Robonaut [9] and DLR's Justin [23]. Both use a humanoid torso mounted on a wheeled base. The humanoid appearance of the robots is justified, because they can keep using space-certified tools which have been designed for humans and because the humanoid body makes teleoperation by humans easier.

4.3 Manufacturing

While in industrial mass production robot arms are used which are not anthropomorphic at all, the Japanese company Yaskawa sees a market for human-like dual-arm robots in manufacturing. It recently announced the Motoman-SDA10 robot [34] which consists of two 7DOF arms on a torso that has an additional rotational joint. Each arm has a payload of 10kg. Yaskawa aims to directly replace humans on production lines. The robot is able to hold a part with one arm while using a tool with the other arm. It can also pass a part from one arm to the other without setting it down. Sales target for the SDA10 is 3000 units/year.

4.4 Household

An obvious domain for the use of humanoid robots is the household. Some humanoid projects explicitly address this domain. They include the Armar [35] series of robots developed in Karlsruhe, Twendy-One developed at Waseda University, and the personal robot PR1 [10] developed in Stanford. While these robots demonstrate impressive isolated skills needed in a household environment, they are far from autonomous operation in an unmodified household.

4.5 Robot Competitions

A currently more viable application for humanoid robots is robot competitions. RoboCup and FIRA, for example, feature competitions for humanoid soccer robots. These robots are fully autonomous and play together as a team. When they fall, they get up by themselves and continue playing. The participating research groups either construct their own robots or they use commercial humanoid robot kits available, e.g., from Robotis and Kondo. RoboCup also selected the Aldebaran Nao humanoid robot as successor of the Sony Aibo in the Standard Platform League. Another popular competition for humanoid robots is Robo-One, where teleoperated robots engage in martial arts. There are also competitions for robots in human-populated environments like the AAAI mobile robot competition, where the robots are supposed to attend a conference, and RoboCup@home where the robots are supposed to do useful work in a home environment. Because they provide a standardized test bed, such robot competitions serve as benchmark for AI and robotics.

5 Prospects

After four decades of research on humanoid robots impressive results have been obtained, but the real-world capabilities of humanoids are still limited. This should not discourage further research. In fact, research on cognitive robots, including humanoids, is gaining momentum. More and more research groups worldwide are targeting this application.

A good part of the difficulties humanoid robots face comes from perception. Here, more advanced methods are developed every year to cope with the ambiguities of sensory signals. The continuous improvements of computer vision and speech recognition systems will make it easier to use humanoid robots in unmodified environments. Advances are also to be expected from the mechanical side. Multiple research groups develop muscle-like actuators with controllable stiffness. Such compliant actuation will significantly contribute to the safe operation of robots in the close vicinity of humans. Compliance also leads to control schemes that support the dynamics of the body instead of imposing inefficient trajectories on it. Insights from biophysics and neuroscience also give ideas for robust control strategies, which degrade gracefully in case of disturbances or component failure.

In general, research on humanoid robots strengthens the respect for the biological model, the human. Much remains to be learned from it in areas like perception, mechanics, and control. I am convinced that it will be possible to understand many of nature's inventions which account for its astonishing performance.

Two remaining issues could hinder the widespread application of humanoid robots: costs and system complexity. Here, the toy industry played a pioneer role with the introduction of simple, inexpensive humanoid robots. The low costs needed for the toy market are possible because of the high volumes. Children are growing up now with robotic companions. As personal robots mature, they will meet prepared users.

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