

## FROM SCIENCE FICTION TO REALITY - HUMANOID ROBOTS

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### Abstract

*Creating the artificial human has always been the desire of mankind and the dream for many scientists and engineers. Nevertheless, it proved to be more difficult than one would imagine. We are now at a time where the technology permits us to draw closer to our quest. To conquer the quest, building humanoid robots would be a good start. We have seen various humanoid robots unveiled over the past few years. Though they are at the cutting-edge of current technology, they are a far cry from the artificial human. Nevertheless, these humanoids represent our first step towards the creation of the artificial human. This article looks at the current state, the benefits and the future research directions of humanoid robots research.*

*Key Words - Humanoids, Bipedal Robots, Locomotion, Artificial Intelligence*

### 1 Introduction

Humanoid robots research is one of the hottest topics in engineering research today, driven by the desire to create fully autonomous humanoid robots that can think and move around like human beings. From a humble beginning in the late 1970's Japan, it has grown tremendously over the past two decades - partly due to mankind's interest to create 'models' of themselves and partly due to the wide publicity surrounding the humanoid creations so far. It is a small, albeit crucial, step towards the grand aim of creating the artificial human.

The word *robot* was first coined in Karel Capek's 1921 play - "*Rossum's Universal Robots*" (*R.U.R.*) where the *Robots* were human-like machines made to replace human workers. Over the Email: [mpeccm@nus.edu.sg](mailto:mpeccm@nus.edu.sg) decades, the term robots have been used to refer to machines that perform tasks repeatedly and efficiently. Robots are now very widely used in manufacturing sector. Robotic technology have been developed and refined so successfully that an entire manufacturing process can be handled by robots alone. On the other hand, robot designs have evolved such that the main consideration is the

tasks to be achieved, not the appearance. Thus, most robots that we see today do not resemble humans in the slightest way. They are working machines meant to maximize efficiency.

Though robots have drastically changed in appearance from what it was first imagined, the desire to build human-like robots still remain. The concept of *artificial intelligence* and *artificial human* never failed to excite scientists, engineers and writers (not to mention movie producers!). It is the dream of many scientists and engineers to build artificial humans that would one day be part of our society. The creation of an artificial being is also thought to be the pinnacle of mankind's scientific and engineering achievement. This, at present, has only appeared in the realms of fantasy and science fiction. We have only progressed a small step with regards to the ultimate goal in the past few decades.

This paper surveys the historical and current research areas related to humanoid robots. Brief descriptions of these areas will be included. Due to the varsity of this research, this survey should not be taken to be exhaustive.

This paper also highlights the benefits and impacts of the research, in particular, the potential applications of Humanoid robots. The future directions of the research will be discussed at the end.

### 2 State-of-the-Art

One of the pioneering research in humanoid robot is at Waseda University where humanoid research started in 1970 [1]. A Humanoid Robotics Institute was established in Year 2000 to further advance the humanoid robotics research. Following the footsteps of Waseda University, many other educational and research institutions have started humanoid or bipedal walking research. To date, there are many stories of successful bipedal and humanoid walking robots.

Besides the Waseda bipedal robots, which is the results of more than two decades of research in bipedal walking robots [1], the best known humanoid robot today is the Honda humanoid robots [2]. The latest Honda's robot is a childlike humanoid robot called 'ASIMO'. Sony has also developed a much smaller biped walking robot called 'SDR-4X' humanoid robot which is meant for the entertainment market [3].

Of course, there are many other humanoid robots created in universities around the world, and many more bipedal walking robots. Despite the grandeur and publicity surrounding the humanoid robots today, they are still a very primitive form of the envisioned artificial humans.

### 3 Why Humanoid Research?

Now, let's look at some of the motivations behind humanoid research. Since the humanoid research spans across many disciplines, many valuable results could arise out of it. There are many benefits of humanoid research, of which, some are direct and others are indirect outcomes. Some of which could be realized in the short-term (less than 10 years) whereas others may take a much longer time. In the following subsections, the benefits of the research are categorized into three areas: scientific, technological and economic.

#### 3.1 Scientific

Here, we refer to those scientific discoveries which may not have direct applications or high commercial value, but are of interest to scientists performing basic research. Monetary return is not the focus for such research, though the discoveries may have commercial value.

There are numerous such benefits resulting from the humanoid robots research. For instance, the humanoid robot research can be used to study the walking gait of human beings. The robot can be an excellent test-bed for various hypotheses or models. The knowledge gained can be applied to improve rehabilitation procedure for patients who have lost their walking abilities. The outcomes could also be used to further improve the humanoid system. It is hopeful that the humanoid may one day be almost as agile and robust as the human counterpart when it comes to locomotion.

Many artificial intelligence researchers have spent most of their times developing algorithms to solve certain 'toy' problems. The algorithms usually consist of a set of computational tools to solve nothing more than a specific optimization problem. The humanoid robot research could provide a better test-bed in the study of artificial intelligence. For instance, we can study how the current state-of-the-art AI paradigms should be integrated to achieve simple tasks. We can also try to develop novel approach or framework of artificial intelligence to overcome the challenge posed by the humanoid robots research.

#### 3.2 Technological

This subsection is concerned with how the humanoid research can contribute to the growth of technologies and result in a useful system that is able to perform certain tasks.

The knowledge gained can be used to build a better prosthesis for human beings. Although the transfer of knowledge from humanoid research to prosthesis development is not very direct, there is a rapidly growing trend towards such a cooperation. Closer collaboration between humanoid researchers and prosthesis developers will be required to make a major step forward in this area.

The robot can be a test-bed for many state-of-the-art technologies, e.g. vision, tactile sensors, actuators, materials, machine learning algorithms, etc.. New technologies can always evolve, in particular, new actuator systems, AI paradigms, and so on.

Humanoid robots can also serve as a platform for technological education. Due to its multidisciplinary nature, there are many possibilities for using humanoids in education. For example, they can be used to educate students on control algorithms, mechanical design, motion control, machine vision, system integration and lots more. The technological education can also be organized in the form of games and competitions. For example, RobotCup [4] and FIRA Robot Soccer competitions [5] are two international robotics game organizations which hold annual humanoid-robots soccer-playing competitions. Their quest:

*Develop a team of humanoids to play against*

*human World Champions by the year 2050.*

As the technology advances, the humanoid robots will be able to perform more useful tasks and be more autonomous. We can envisage that the humanoid robots will be used in the military, e.g., as scouts or as decoys. They can also be adopted for search and rescue operations, and for exploration in hazardous areas.

### 3.3 Economic

This subsection discusses the economic or commercial value of the humanoid robots research. Needless to say, there are various commercial opportunities arising from humanoid robots. An immediate one is in the entertainment/toys sector. Judging from the success of Sony's *AIBO* robot dog, there is good potential for a humanoid toy robot. It is hence not surprising to see Sony developing the small humanoid toy robot (SDR-4X) that can walk, dance and even sing [6]!

In the long term, humanoids can be sold as domestic helpers. It would be able to do normal household chores, act as a security guard, look after the elderly and prepare meals. This is a potential multi-billion business that can easily overtake the automotive and aerospace industries.

## 4 Current Humanoid Research

Humanoid research encompasses a very wide range of research areas, across many disciplines and fields of study. Each of these disciplines contributes towards the development of the artificial human in their own way.

As we know, it is not easy (not to mention cheap) to build even a humanoid that could only walk. It took Honda 10 years of research to unveil P2 and a couple more to produce ASIMO [7]. It has also probably costed them billions of yen of investment. Still, the journey is not complete. We have only at best travelled a small leg of the road to a complete artificial human.

Due to the complexity of the humanoid system, the research till now is still rather fragmented. There are several distinct research areas in the development of the humanoid robot. The major research areas undertaken today are as follows:

- locomotion
- artificial intelligence

### 4.1 Locomotion

At the core of the humanoid research today is bipedal walking control. A stable bipedal walking is difficult to achieve. Human beings are blessed with a very intelligent brain, but we still need to learn to walk for several months before we can achieve stable walking behaviors.

This underlines the difficulty in achieving bipedal walking behaviors. Much research has been done in the area of bipedal locomotion in recent years. The approaches could be grouped into five categories: 1) model-based; 2) ZMP-based; 3) biologically inspired; 4) learning; and 5) divide-and-conquer. Various approaches for each of the categories will be presented. These categories are by no means mutually exclusive or complete. Some research may combine several of these approaches when designing a control algorithm for the bipedal walking.

**Model-based.** In this approach, a mathematical model of the biped derived from physics is used for the control algorithm synthesis. There is a spectrum of complexity for a biped model, ranging from a simple massless leg model to a full model which includes all the inertial terms, friction, link flexibility, actuator dynamics, etc. Except for certain massless leg models, most biped models are nonlinear and do not have analytical solutions. In addition, there is under actuation between the stance foot and the ground; and unknown discrete changes in the system state due to foot impact.

The massless leg model is the simplest model for characterizing the behaviors of the biped. The body of the biped is usually assumed to be a point mass and can be viewed to be an inverted pendulum with discrete changes in the support point. The massless leg model is applicable mainly to a biped that has small leg inertia with respect to the body. In this case, the swing leg dynamics can be ignored under low walking speed.

Kajita et al. [8, 9] have derived a massless leg model for a planar biped that follows a linear motion. During single support phase, the resulting

motion of the model is like a point mass inverted pendulum with variable length. The dynamic equations of the resulting linear motion can be solved analytically. From the model, the touchdown condition of the swing foot is determined based on an energy parameter. Inverse kinematics is used to specify the desired joint trajectories and simple control law is used at each joint for tracking.

When the leg inertia is not ignorable, it needs to be included in the biped model. One basic model that includes the leg inertia is the Acrobot model [10, 11]. It is a double pendulum model with no actuation between the ground and the base link (corresponding to the stance leg). This is commonly used to characterize the single support motion of the biped.

When the leg inertia and other dynamics like that of the actuator, joint friction, etc are included, the overall dynamic equations can be very nonlinear and complex. A linearization approach is usually adopted to simplify these dynamic equations. The linearization can be done with respect to selected equilibrium points to yield sets of linearized equations.

Miura and Shimoyama [12] built a 3D walking biped that had three links and three actuated degrees of freedom: one at each of the hip roll joints and one for fore and aft motion of the legs. The ankle joints were limp. The biped was controlled using a linearized dynamic model. After selecting a set of feasible trajectories for the joints, state feedback control laws were then formulated for the joints to generate compensating inputs for the nominal control inputs. The control laws ensured the convergence of the actual trajectories to the desired trajectories. Since they adopted a linearized model for the biped, the motion space had to be constrained to a smaller one so that the model was not violated. Mita et al. [13] proposed a control method for a planar seven-link biped (CW-1) using a linear optimal state feedback regulator. The model of the biped was linearized about a commanded attitude. Linear state feedback control was used to stabilize the system based on a performance function so that the biped did not deviate from the commanded attitude. For the gait control, three commanded attitudes were given within a gait interval and the biped could walk arbitrary steps with one second period. They assumed that the biped had no torque limitation at the stance ankle. The biped had large feet so that

this assumption was valid.

**ZMP-based.** A number of the researchers use the zero-moment-point (ZMP) concept, first introduced by Vukobratovic [14, 15], in the bipedal walking control algorithms. ZMP is the point on the ground which the resultant of the reaction forces from the ground acts on the biped.

The ZMP approach is popular with researchers from Waseda University, Honda, INRIA, etc. [16, 2, 17]. It is actually identical to the center of pressure (CoP) encountered in biomechanics literature [18]. A ZMP stability criterion, which states that ZMP of the biped must be within the convex hull of the feet contact area to ensure the walking stability of a biped, was introduced by Li, et al. [19]. Despite the popularity of this approach among various major research groups, it is still unclear how the criterion could result in stable walking. In fact, based on the definition by Vukobratovic and Juricic [15], ZMP must always be within the convex hull of the feet contact area [18].

**Biologically Inspired.** Since none of the bipedal robots matches the biological bipeds in terms of mobility, adaptability, and stability, many researchers try to examine biological bipeds so as to extract certain algorithms (reverse engineering) that are applicable to the robots.

Grillner [20] found from experiments on cats that the spinal cord generated the required signal for the muscles to perform coordinated walking motion. The existence of a central pattern generator (CPG) that is a network of neurons in the spinal cord was hypothesized.

The idea of CPG was adopted by several researchers for bipedal walking [21, 22, 23]. In particular, Taga [21, 22] applied a neural rhythm generator to a model of human locomotion. The neural rhythm generator was composed of neural oscillators (a system of coupled nonlinear equations) which received sensory information from the system and output motor signals to the system.

Based on simulation analysis, it was found that a stable limit cycle of locomotion could emerge by the principle of *global entrainment*. Passive dynamic walking phenomenon was discovered by McGeer [24, 25]. It was partly inspired by a bipedal toy that was capable of walking down a

slope without any actuator system, and partly based on the observation that human beings do not need high muscle activities for walking. He showed that stable human-like walking motions down a slope can be achieved by two rigid links (connected by pin-joint) powered only by gravity. The passive walker provided much insight into the mechanics of human walking.

**Learning.** It is evident by observing toddlers who are just starting to walk that human walking is a learned process. Learning is also commonly applied to systems whose models are hard to derive or implement. In some cases, learning is used to modify a nominal behaviors that are generated based on a simplified model.

Wang, Lee, and Gruver [26] presented a neuromorphic architecture based on supervised learning for the control of a three-link planar biped robot. Based on the biped's dynamic model, a control law was obtained by nonlinear feedback decoupling and optimal tracking approach. Then, they used a hierarchical structure of neural networks to learn the control law when the latter was controlling the biped.

Miller [27] designed a learning system using neural networks for a biped that was capable of learning the balance for side-to-side and front-to-back motion. With the help of several control strategies, the neural networks learn to provide feedforward control to the joints. The biped had a slow walking gait after training.

Benbrahim and Franklin [28] applied reinforcement learning for a planar biped to achieve dynamic walking. They adopted a "melting pot" and modular approach in which a central controller used the experience of other peripheral controllers to learn an average control policy.

Chew and Pratt [29] adopt a general control architecture for bipedal walking in which reinforcement learning is used only to learn those subtasks that are not easily solved by analytical approach.

**Divide-and-conquer.** Due to the complexity of the bipedal walking control problem, many implementations break the problem into smaller sub-problems that can be solved more easily. Intuition of the problem is usually required for such an approach, both in deciding how to break

down the problem and how to solve the smaller sub-problems. Intuition can be obtained by observing the behaviors of bipedal animals (similar to the biologically inspired approach), by analyzing simple dynamic models, etc.

Raibert's control algorithms [30] for hopping and running machines mostly utilized the divide-and-conquer approach. For example, the control algorithm for a planar one-legged hopping machine was decomposed into: 1) the hopping motion (vertical); 2) forward motion (horizontal) and; 3) body posture. These sub-tasks were considered separately and each was implemented using simple algorithm. This resulted in a simple set of algorithms for the hopping task.

Pratt, et al. [31] presented an intuitive control algorithm based on a divide-and-conquer approach for planar bipedal walking task of a biped. The walking cycle was first partitioned into two main phases: double support and single support. In the double support phase, the task of the controller consisted of three sub-tasks: 1) body pitch control; 2) height control and; 3) forward speed control. In the single support phase, the task of the controller consisted of two subtasks: 1) body pitch control and 2) height control. The resulting algorithm was simple and low in computation since no dynamic equations were used. This approach, with force-controlled actuators [32], has successfully produced natural bipedal walking behaviours.

## 4.2 Artificial Intelligence

Another epicenter of humanoid research is the development of the robot intelligence. This area falls within the machine learning or artificial intelligence research. The goal of artificial intelligence (AI) [33] "is the development of paradigms or algorithms that require machines to perform cognitive tasks, at which humans are currently better". The main task is to make the robot able to perceive, make their own decisions, learn and interact with human beings.

The state-of-the-art research in robot intelligence can be found in places like MIT's AI Lab [34, 35]. The lab has built a humanoid robot called 'Cog' which has only the upper body. Through the construction of Cog, many basic capabilities of human beings, e.g., sound localization system, hand-eye coordinations, emotion, etc. have been demonstrated.

Brooks [34] adopted the behavior-based approach in building robots that could operate in the physical world. This approach is different from the traditional artificial intelligence in that no goal or plan is assigned to the robot. Instead, basic behaviors are programmed into the system. In each behavior, numerous actions are coupled to other actions or perceptions. By natural interaction between the robots and the environment, interesting high level tasks could be performed.

Artificial intelligence is actually a rather broad research area by itself, as there are many forms of intelligence a robot may possess. We can divide artificial intelligence research into several smaller sub-topics as in the following subsections.

**Robot Emotions.** This is the ability of the robot to express emotions similar to that of a human being. There are a number of research to create a robot that could express emotions, usually through facial expressions [36]. Cynthia Breazeal at MIT AI Lab has built a robotic head called 'Kismet' [35]. It is part of the COG humanoid project. Waseda's WE-3RV (Waseda Eye No.3 Refined V) is a human-like robot head specially designed for its humanoid robot [37]. The purpose is to enable the humanoid robot to communicate naturally with a human by means of human-like emotion. The emotions are usually in response to external stimuli like visual, auditory, olfactory and cutaneous sensations. The emotions are manifested by means of facial or/and vocal expression.

**Robot Learning.** For the robot to work in an unstructured environment, learning ability is very important. Various machine learning tools like neural networks [38], evolutionary algorithms [39, 40] and reinforcement learning [41, 42] have been applied for robots to learn a particular task or function. For example, the reinforcement learning algorithms has been applied to let bipedal robots learn how to walk [29, 28]. It can also be applied to let the robot learn other motions, for example, hand coordination to perform some useful tasks [43].

Human-Robot/Robot-Robot Communications, Interactions, Coordinations. Ability to communicate with other robots and human beings is an important aspect of humanoid robot since the robot will eventually be placed within the human environment. With this feature, humans can send information to the humanoid and the humanoid

can convey its state to humans. To achieve those tasks that require the coordination among few robots, communications among the robot become very important too [44].

## 5 What Needs to be Done?

So far, the state-of-the-art humanoid robots are the Honda humanoid robots. We could see that they are still rather primitive in comparison with the human counterparts. There are still many pieces of the puzzle to fix before we are able to achieve our ultimate goal of creating an artificial human. There are a few areas where the humanoid research will probably focus in the future.

These potential areas are discussed in the following subsections.

### 5.1 Agility/Robustness

Human beings are very agile with regards to the execution of tasks in an unstructured environment. In contrast, all current humanoid robots can only perform reasonably well only in a structured environment. Furthermore, they are not able to work in various environments seamlessly.

For example, human beings are able to walk across an unstructured terrain. We are able to constantly evaluate the situation and plan the location of the next foot step. The enabling technologies are the perception, decision making, locomotion capabilities, etc. Much research needs to be done in these few areas in order for the humanoid to be really useful. Beside agility, robustness is also very critical. For example, how much external disturbance can the humanoid take before failing? If the algorithm requires certain model for the motion control, is the algorithm robust to errors due to modelling and sensors drift? It will be impractical if a robot needs to be constantly calibrated.

When the disturbances become too great, the robot is bound to fail while trying to achieve a given task. For example, the robot may trip and fall while walking over an unstructured terrain. This event is unavoidable since human beings also experience such event once in a while. Given the current state-of-the-art technologies, it is impossible to achieve global stability for bipedal locomotion. However, this shortcoming can be

overcome by failure recovery capability. Morimoto and Doya [45] studied how a three-link, tow-joint robot could learn to stand up by trial and error. Though the results were still in their infant stage, the research is a step in the right direction. More research needs to be done in this area.

## 5.2 Artificial Intelligence

Robot emotion research may be interesting, but it is not the most important part of the robot intelligence. The robot should be able to perform day-to-day tasks without constant guidance and supervision by a human operator.

The robot should be able to perform reasoning based on the general knowledge about a problem and generate at least a solution for the problem. If the knowledge is insufficient, the robot should be able to learn new set of knowledge by exploration. This area is still rather primitive and new framework for intelligence is needed to break through the current limitations.

For a humanoid robot to be able to reason, it will need to perceive the current state of the environment. Currently, the sensors implementations are still quite limited compared with the human counterpart. More advanced sensors designs are needed for the robot to detect the current state of the surrounding. For example, instead of isolated tactile sensors (usually at the robot's hand), the robot should have artificial skin which provides a continuum tactile sensing capability so that it can know, for example, the location of the resultant external disturbing force.

For the humanoid robots to coexist with humans, we need some form of communication between humans and humanoid [46]. The communication should be *intuitive* to human and easy to implement in the robot. The communication can be separated into two parts: human-to-robot and robot-to-human. For the human-to-robot part, the main purpose is to issue commands and provide feedbacks. Two intuitive methods of human-to-robot communication are through gestures and voice commands. For the robot-to-human part, the robot should indicate its intention clearly so that human could react or cooperate in the right way. The robot could use auditory signal and facial expression for that purpose.

## 5.3 Energy Source

Often neglected is the length of operation of the robot. A humanoid robot, with its myriad of sensors, actuators and computers, do consume a significant amount of power. In order for the robot to be useful, it should be able to function in the field for several hours before requiring replenishment.

Current forms of batteries are rather heavy, and would be a burden for the humanoid to carry and a contribution to fast energy drainage. At the moment, the Honda ASIMO can operate for about 25 minutes before needing a recharge. This limits the robot to be merely an exhibit item, rather than an useful machine that could assist human beings.

Hence, much work is required to invent a new energy source for the robot. For example, it is desirable for new battery design have much higher energy-to-weight ratio, and yet be able to fit into the compact space of a humanoid robot. We can also evaluate whether the emerging energy technologies like the fuel-cell or even the micro-engine can be harnessed for the robots.

## 5.4 Safety

Before the humanoid robot can be allowed to operate in the human environment, it needs to pass the safety issue. Safety could be achieved through proper hardware and software designs. Before we could adopt any design, we have to first identify the possible safety issues concerning humanoid robots. For example, the robots will have to operate in close proximity to humans. They should therefore not have very "stiff" motion control implementations which are used in industrial manipulators.

To achieve low impedance or low stiffness motion control, one effective approach is to adopt force/torque control at the joints. This involves the use of force- or torque-control actuators [47, 48, 32]. Such actuators are not new, but have yet to find 'mainstream' applications in humanoid robotics. Currently, only few humanoid or walking robots [31, 49, 50] use force-controlled joints.

## 6 Conclusion

Judging from the increase in popularity and the amount of research on humanoid robots, this

research area is bound to grow tremendously. What has started in Japan in the late 1970s has now gained worldwide interest. From East Asia to South Asia, and from Europe to America, various institutions and universities have embarked on humanoid projects. As humanoid robot research grows in popularity, the amount of effort placed to create the artificial human grows. This increased effort will see more advances in humanoid robots technology. As we progress, the robots become more intelligent and more lifelike. It is not important to predict when we can develop a completely autonomous and intelligent humanoid robot. Most importantly, as the technologies are ever and always advancing, the line separating the realm of science fiction and reality will bound to fade in the future.

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