

CHAPTER 4

HUMANOIDS

Robert Ambrose, Yuan Zheng, Brian Wilcox

BACKGROUND

Science fiction has led the field of robotics, like so many other disciplines, with visions of technology far beyond the contemporary state-of-the-art. The term “robot” was coined by Czech author Capek in his 1924 production of “Rossum’s Universal Robots.” The robots were played by human actors, and dealt with the issues of slavery and subjugation that were metaphors for concerns held by human workers of the day. These first robots were also the first humanoids, at least in theater.



Figure 4.1. Capek Paris Production, 1924; Asimov, Will Smith, *I Robot*, 2004.

Robots gained another foothold in science fiction with the works of Asimov, where the term “robotics” was first defined in 1941 as a discipline of study. And once again, the form and functions of the robots being studied and built (in fiction) were humanoid. The above figures show the evolution of science fiction from the earliest works to modern media. In both cases, the robots did tasks designed for people, and they performed these tasks in environments with people present. Their functional skills were depicted as so expert that they could be safely interspersed with people, doing the tasks with no accommodation in tools, terrain, or even technique.

This chapter describes the research activities that are currently being conducted in humanoid labs in Japan, Korea, the U.S. and Europe. Humanoid robotics, beyond science fiction, began thirty years ago, with increased momentum in the last ten years. In this chapter, we first discuss definitions for what makes a system humanoid, then document the state-of-the-art in these defined characteristics. We end with a brief discussion of application domains, and the relative momentum found in the United States, Japan, Korea, and Europe.

DEFINITIONS OF THE HUMANOID SYSTEM

Form and Function

Humanoids have been played by human actors in the movies, but are quickly being replaced by computer graphics. What remains a constant is that they work around humans safely (or intentionally not), doing tasks originally done by humans, in an urban environment and with tools designed for humans.



Figure 4.2. Star Wars Episode II WA-7 Waitress robot, Star Wars Episode III General Grievous.

As computer technologies free the media from the use of human actors, the forms of their fictional robots open up to include multiple limbs and the introduction of wheels. This trend may be instructive to the engineers designing real robots, and is being exploited, as will be shown later in this chapter. So the definition of the humanoid, while superficially in form, should be anchored by function. The human jobs of waitresses and generals are distinguished by their functions. Abilities to roll, or fight with multiple limbs, are enhancements that make these fictional robots perform with superhuman skill, but the jobs are nonetheless human. And yet a machine that does high-speed, repetitive tasks in a completely non-anthropomorphic manner, such as a printing press, is not considered humanoid.

So there is a tension in the definition of the humanoid robot, as we try to balance form and function. The following definition is proposed as a harmony of both:

Humanoids are machines that have the form or function of humans.

The easy cases of machines that have both human form and function are rare today. The speculation of science fiction indicates this will change.

How Are Humanoids Built?

Modern humanoids have major subsystems that can best be defined as their lower and upper bodies. The lower bodies are legs, wheels, or tracks that provide locomotion for propelling the upper body through a workspace. The upper bodies are arms, hands and heads, able to interact with the environment and perform work. The junction of these segments is a torso, which typically carries energy storage and computers for control.

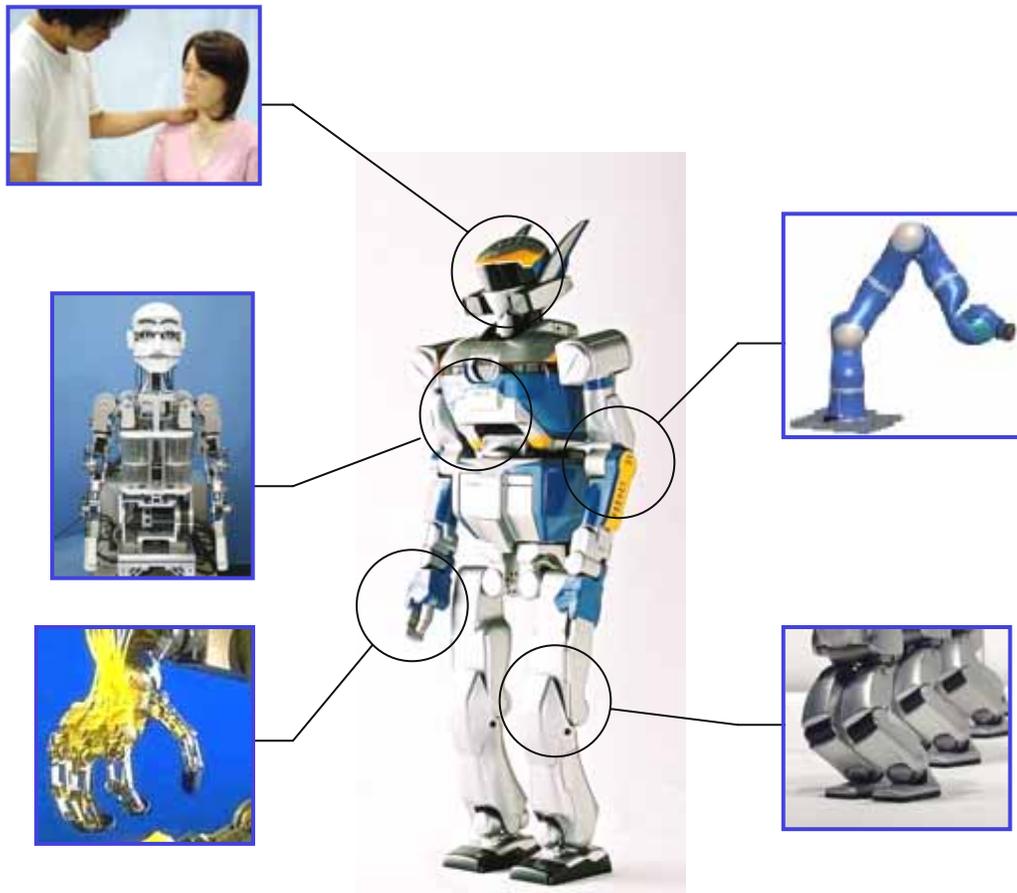


Figure 4.3. Gross anatomy of the humanoid—heads, torsos, arms, hands, legs.

During the study team’s review of labs active in humanoid research, many examples of each subsystem were found. Many humanoids had one of the above elements missing. Most labs were focused on a single subsystem, where their work was quite excellent. Eye-hand coordination and bipedal locomotion were the most common combinations of subsystems, where non-critical subsystems were omitted to allow the researchers to focus. There were few prototypes built with a full complement of upper and lower body subsystems, but these were excellent, expensive, and best known.

CURRENT CHALLENGES IN HUMANOIDS

Design, Packaging and Power

There is a high cost of entry into the humanoid research domain. With few or no commercial products, the vast majority of research platforms were built in-house. The immature nature of these systems makes copying them for use by other researchers risky, as these secondary adoption groups will not have the knowledge needed to maintain or evolve them. This will change as packaging and power challenges are overcome by design and the maturation of component technologies. This integrated design work is led by corporate teams, such as Honda, Toyota and Sony, government/corporate teams such as National Institute of Advanced Industrial Science and Technology (AIST), Korea Advanced Institute of Science and Technology (KAIST), National Aeronautics and Space Administration (NASA), and the German space agency Deutschen Zentrum für Luft- und Raumfahrt (DLR), and university-led teams with long traditions in mechatronics such as Waseda, Massachusetts Institute of Technology (MIT), and Technical University Munich (TUM).

Component technology advances have come from beyond the robotics discipline, but these have had a dramatic impact on humanoid design. The development of small, power-efficient computers have made much of the modern robot possible. Humanoids have needed more than computation. Arm and leg embodiment have required torque and power densities that were enabled by lightweight direct current (DC) motors and geared speed reducers. In particular, DC brushless motors and harmonic drives have provided the highest torque densities in electromechanical systems. These high-power limbs have been further made possible by the evolution of modern batteries, able to make these systems self-contained for brief periods of duty. In particular, lithium batteries have enabled robots to carry their own power supplies for locomotion and upper body work. New research continues in hydraulic systems (Sarcos) and low-pressure fluid power (Karlsruhe).

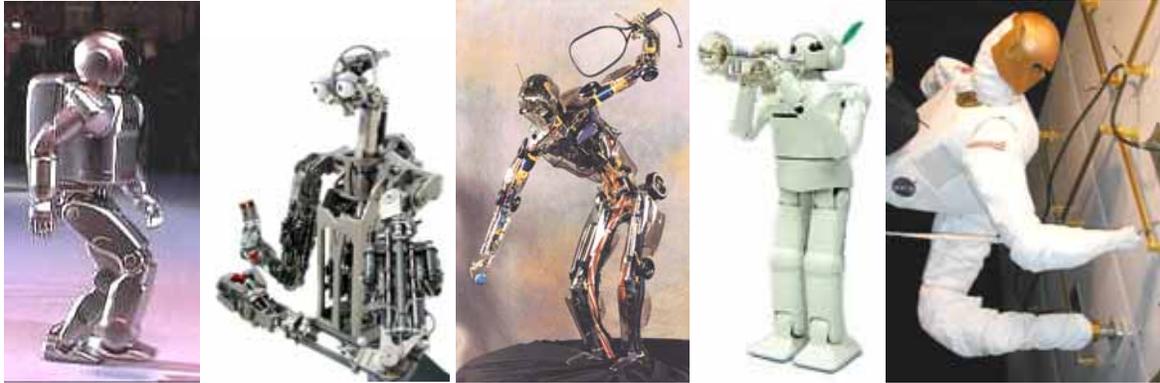


Figure 4.4. Honda, MIT, Sarcos, Toyota, NASA.

These advanced computers, drive trains, and batteries were not developed by roboticists, but were eagerly adopted. Modern laptops, cell phones, and automobiles have driven these component markets with their large consumer bases. The fact that corporations now producing humanoids include Honda, Toyota and Sony is not a coincidence.

Bipedal Walking

The majority of the biped walking systems are humanoid in form, and use the Zero Moment Point (ZMP) algorithm (Vukobratovic and Frank, 1969, Vukobratovic et al., 1970). In this algorithm, the tipping point of the system is managed forward or backwards to walk.

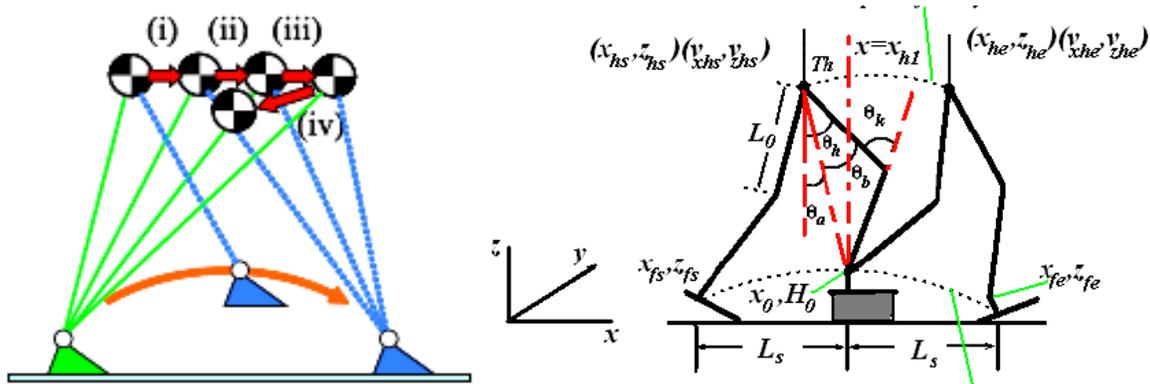


Figure 4.5. ZMP Mechanics.

Many of the most famous humanoids have pioneered the implementation of the ZMP algorithm. The robots at AIST Tsukuba and AIST Waterfront have used wheeled gantries as a safe testbed for developing and refining the ZMP walking systems. The Honda systems have many generations of success.

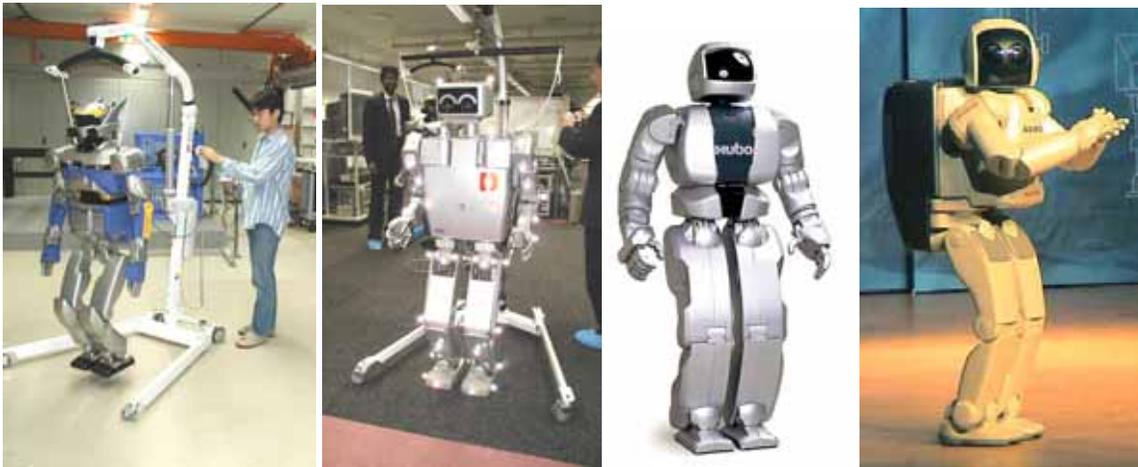


Figure 4.6. ZMP Walkers at AIST Tsukuba, AIST Waterfront, KAIST, Honda.

A more dynamic form of walking has been postulated (Zheng and Hemami, 1984, Pratt et al., 1997), and is now being attempted in highly integrated humanoid systems at Waseda and TUM. These systems use the upper body, or additional degrees of freedom, to manage the vertical component of their center of gravity. This form of walking is observable from a distance, as the robot does not need to walk with a “crouched gait.” As a result, the walking is becoming known as “straight leg walking.” The Waseda design uses a lateral hip joint to “rock” the hips, keeping the torso center of gravity moving in a smooth and horizontal line. The TUM design uses substantial mass on the upper limbs to counter balance the lower body motion, as well as additional leg joints.

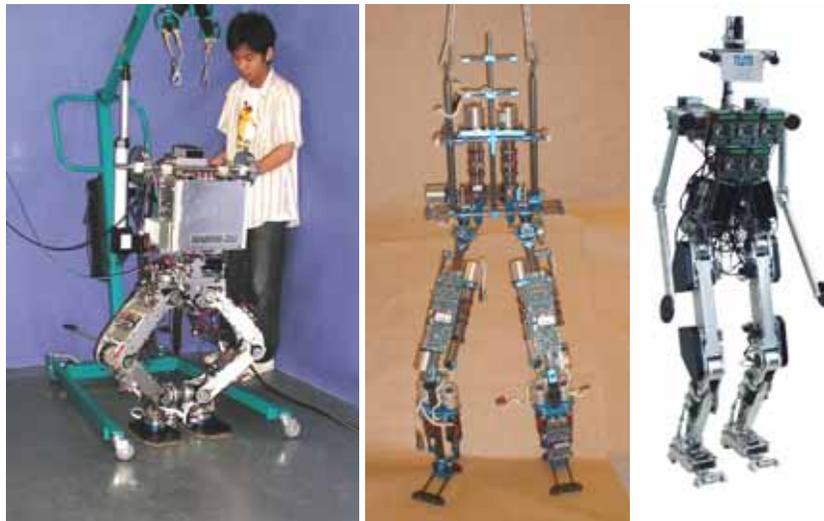


Figure 4.7. Dynamic Walkers at Waseda, MIT, TUM.

Wheeled Lower Bodies

Several labs are building new forms of lower bodies that use wheels for locomotion. These systems typically have small footprints, to allow their upper bodies to “overhang” the lower body and allow for interaction with the environment. Examples include statically stable wheeled bases, and dynamic balancing systems like a Segway. Three examples are shown in the figure below.



Figure 4.8. Dynamic balancing wheeled humanoids at NASA, Toyota and MIT.

Dexterous Limbs

The research in locomotion and navigation of mobile robots has outrun the research in dexterous manipulation. Twenty years ago, the intelligent robotics community was just forming, and there was little consensus on approaches or architectures for what we now call navigation of mobile robots. Today, this domain has greatly matured, with numerous architectures commercially available to upgrade a wheeled vehicle to a sophisticated thinking machine. But the class of interaction that such a machine can have with its environment is limited to perception, where physical contact is intentionally avoided. This technology is now being applied to the legged and wheeled systems previously described.

As complex as these locomotion functions are, the sophistication of their interaction with the environment pales in comparison to using a tool to modify the world. Understanding the world well enough to know that a change is needed and/or possible, and then forming a plan to use a known tool to implement that change is an infinitely open challenge. Emerging theories on the role of tool use and weapon-making in the evolution of human cognition bode poorly for any robotics team that intends to quickly automate a humanoid as a competent tool user.

The existing simultaneous localization and mapping (SLAM) techniques will be essential for this effort, but must be combined with symbolic, relational, associative, and generally qualitative representations of knowledge to complete the picture. A robot sees a box with rough texture on its top surface. A human looks at the same scene, and sees a workbench strewn with hand tools that bring back a lifetime of memories. Bringing the robot to the same perception level as the human tool user is the second most likely achievable step, making a humanoid equivalent to a human's apprentice. The first step is to have dexterous hands that have even crude manipulation abilities.



Figure 4.9. Dexterous hands at DLR, Shadow, NASA and Tsukuba.

Having hands will be essential in the early advancement of this research, since the learning and association of knowledge with objects will be done in the robot's own terms, with the way a tool feels when grasped stored in sensori-motor space. Key advances in dexterous hands include tactile skins, finger tip load sensing, tendon drive trains, miniature gearing, embedded avionics, and very recent work in low-pressure fluid power systems. The fundamental research in biologically inspired actuators will likely transform the nature of this domain in the next ten to fifteen years.



Figure 4.10. Dexterous arms at DLR, NASA and UMASS.

Hands must be well-sized and integrated with their arms for best effect. One of the challenges that has made entry into this research domain difficult is the small number of arm options available to the researcher, and the corresponding high cost of such systems. There are few small, human-scale arms able to be integrated for mobile applications, and most of these have low strength. Most humanoid arms are low quality, have <6 degree-of-freedom (DOF)-positioning systems with backlash and little power that appear almost as cosmetic appendages. The AIST HRP2 system is one of the few bipedal humanoids that has strong arms, and the limbs can be used to help the robot get up from a prone position.

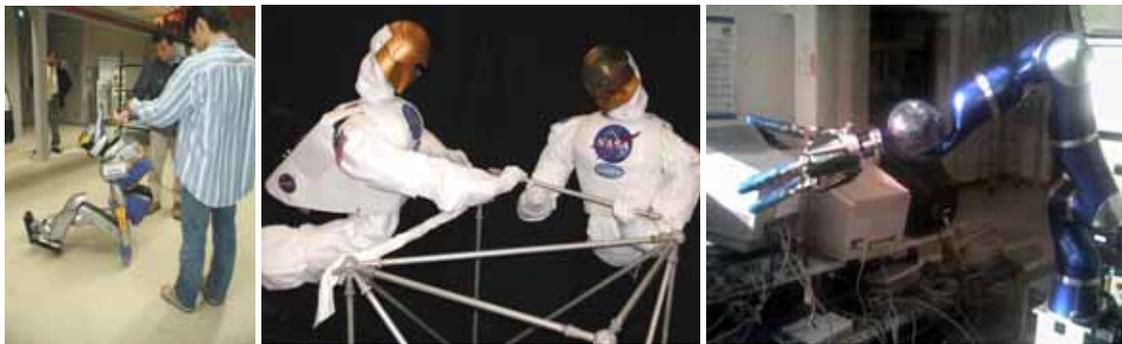


Figure 4.11. Strong dexterous arms at AIST Tsukuba, NASA and DLR.

The best arms in the field have integrated torque sensing, and terminal force-torque sensors that allow for smooth and fine force control. The arms have 7+ DOF, and are able to handle payloads on the order of 5 kg or higher. They have embedded avionics allowing for dense packaging and modular application.

Mobile Manipulation

Mobile manipulation is achieved when combining a lower body able to position itself with ease, and a dexterous upper body able to perform value-added work. While this combination is not necessarily humanoid, people are ideal examples of mobile manipulators. Active balancing bases or legs have small footprints, allowing their upper limbs to get close to the environment, while maneuvering in tight urban environments. Dual and dexterous upper limbs offer primate-like workspace and grasping abilities that can work with the interfaces and objects in those same urban environments. This class of machine can redistribute force and position control duties from lower bodies to upper bodies, where differences in drive trains and sensors offer complimentary capabilities. Pioneering work in this discipline was done at Stanford,

and the work continues at the University of Massachusetts (UMASS), Carnegie-Mellon University (CMU), and the DLR.



Figure 4.12. Mobile Manipulation at CMU, Stanford, RWTH Aachen and DLR.

Human-Robot Interaction

Where humanoids are a subset of mobile manipulation, they are also an important part of the ongoing research in Human-Robot Interaction (HRI). There are many aspects of HRI that have little to do with human function or form on the robot side of the interaction. But there are strong advantages to humanoid systems in human interaction. The large public response to humanoids has included a strong educational outreach program on the part of Honda, Sony and national labs. The connection to science fiction may have a role in this phenomenon.



Figure 4.13. Human-Robot Interaction at Honda, Osaka Univ., MIT and KAIST.

But there is also a thrust in the science of interaction, where social and psychological factors are at play. Research at Osaka University and other sites is exploring the “Uncanny Valley” first postulated by Mori in 1970, where the degree of human-like form and motion in human faces (Minato et al., 2004) is found to have a local minima in reaction. There is a growing but still young body of research in this arena, with many active workshops in HRI, android science, and views on the Uncanny Valley in the last several years.



Figure 4.14. The Uncanny Valley, and robots at Osaka University.

Key Technologies

Key technologies for humanoid robotics include the following:

- a) Improved design and packaging of systems with new component technologies that are smaller, stronger, faster, and offer better resolution and accuracy
- b) Dense and powerful energy storage for longer endurance, heavy lifting, and speed
- c) Improved actuators that have higher power densities, including auxiliary subsystems such as power supplies, signal conditioning, drive trains, and cabling
- d) Improved speed reduction and mechanisms for transferring power to the humanoid's extremities
- e) Improved force control for whole body dynamics
- f) Better tactile skins for sensing contact, touch and proximity to objects in the environment
- g) Advanced navigation that perceives and selects footfalls with 1 cm scale accuracy at high body speed
- h) Vestibular systems for coordinating upper limbs and head-mounted sensors on dynamic bodies
- i) Dexterous feet for dynamic running and jumping
- j) Dexterous hands for tool use and handling of general objects

This list shows that humanoid robotics has matured to an engineering discipline, where design issues of packaging, actuator technology and power/energy considerations are paramount. Conversely, the fact that so few prototypes exist makes access to them problematic, leaving researchers without design and engineering skills disengaged. A maturing field with few commercial options is unusual.

Fundamental Research Challenges

A fully capable and embodied humanoid makes a strong research testbed. Such a system can serve to answer the following questions:

- What are the best leg, spine and upper limb arrangements, in both mechanisms and sensors, to enable energy-efficient walking?
- How should robots represent knowledge about objects perceived, avoided and handled in the environment?
- What are the algorithms for using upper body momentum management in driving lower body legs and wheeled balancers?
- How can a mobile manipulation robot place its body to facilitate inspection and manipulation in a complex workspace, where a small footprint and high reach requirements collide?
- How should vision/laser based perception be combined with tactile/haptic perception to grasp objects?
- What roles do motion and appearance have in making people accept and work with robots?
- How can people interact with humanoids to form effective and safe teams?

REVIEW SITES

Regions Visited by the Assessment Team

The study team visited Japan, Korea, Spain, France, Germany, Italy, Britain, Switzerland, and Sweden, in addition to the review of labs in the United States. The following map shows the distribution of humanoid systems found in research labs during the review.

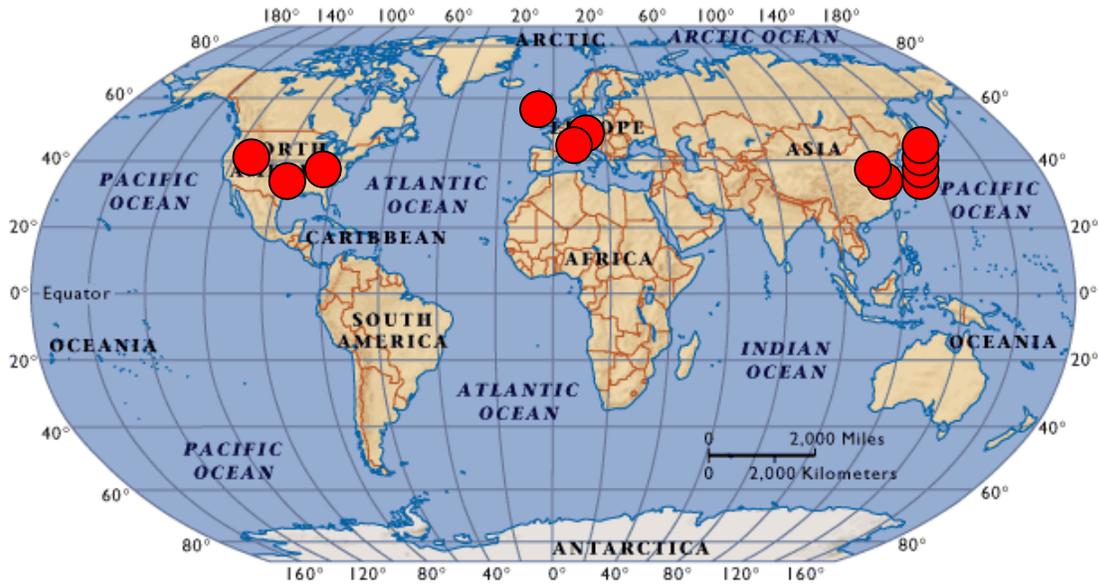


Figure 4.15. Humanoid systems reviewed.

OBSERVATIONS, APPLICATIONS, AND CONCLUSIONS

Quantitative Observations

Japan has the largest population of humanoid systems. The study team visited AIST Tsukuba, AIST Waterfront, Tsukuba University, Tokyo University, Osaka University, Fujitsu, multiple labs at Waseda, Sony, and Advanced Telecommunications Research Institute (ATR). The field of humanoid robotics was founded in Japan with the work of Ichiro Kato and the Wabot project at Waseda University in 1970, and Waseda continues this tradition today with a strong program producing more humanoid graduate degrees than any other school.

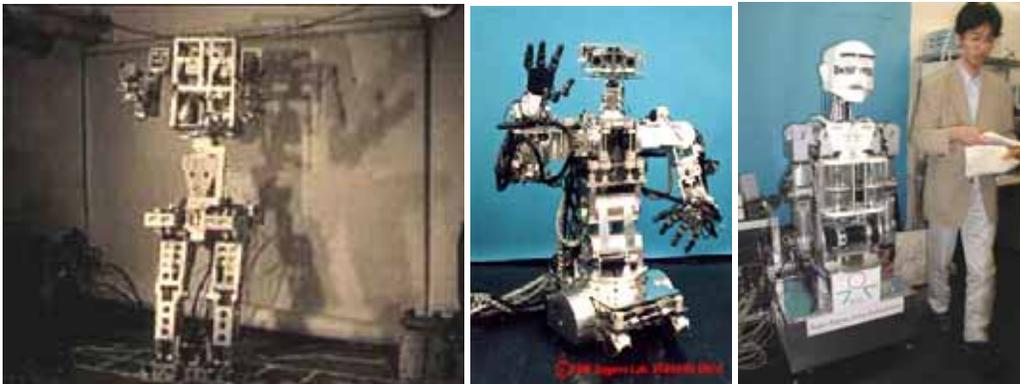


Figure 4.16. Humanoid systems Waseda, past and present.

The study team was not invited to Honda or Toyota facilities. This was likely due to proprietary concerns. However, the impact of Honda's history is well understood in the community. The quiet development of the E series humanoids, and the then the public release of the P series in 1997, was a major turning point in humanoid history. The evolutionary approach was remarkably organized and strategically guided. Recent work at Toyota indicates a similar interest and desire to build multiple forms of humanoids.



Figure 4.17. Honda and Toyota humanoids.

The prototypes at AIST Waterfront and AIST Tsukuba are the class of the field. These systems have taken a novel evolutionary path, developing the HRP-1 and HRP-2 systems with sub-generations that were legs only, then with arms, then re-integrated as the HRP final units. The study team saw HRP-2 unit #01 at AIST Tsukuba, and unit #12 at AIST Waterfront. Unit #12 was substantially upgraded, with new stereo vision in the head, and a new, waterproof hand on a dexterous wrist. Both systems were fully operational, and demonstrated excellent performance. The robots were built as a partnership between the Japanese government (Ministry of Economy, Trade and Industry (METI)) and industry (Kawada Industries), with university groups now using the robots as testbeds for research.



Figure 4.18. AIST humanoids.

Both Sony and Fujitsu were very gracious in hosting our study team, and presented business plans for their products. Both have smaller scale humanoid products that appear commercially viable. Their work is well known, and follows the same evolutionary path as the larger humanoids developed at Waseda, AIST and Honda. The systems have high strength to weight ratios, and are tolerant of falls. The Sony system has well developed visual perception, human interaction, and eye-hand coordination capabilities paired with a fast, power-efficient and well-packaged torso and set of limbs. The Fujitsu system has a large limb range of motion, allowing it to get up from the floor, and stand on a single leg.



Figure 4.19. Sony and Fujitsu humanoids.

The study team was impressed by the Korean population of humanoid systems, many of which were in quiet development during our visit. These have since been released for public review. The designs at KAIST and Korean Institute of Science and Technology (KIST) were particularly far along at the time of the site visits in October 2004, and were shown to the public in 2005. These robots demonstrate that Korea is a power to be reckoned with in humanoid research, and they show an acceleration of capability and skill. One important note on both systems is their attention to both legs and hands. Both robots have multi-fingered, multi-DOF end-effectors able to grasp and hold objects of modest scale. The humanoid system at the Pohang Science and Technology University (POSTECH) has not been made public, but represents a novel approach to leg mechanisms that is important, as many of these systems have made only minor changes to the Honda anatomy. This lower body was shown to the study team, and is being developed by a team with a deep understanding of dynamics and control that has informed their design work.

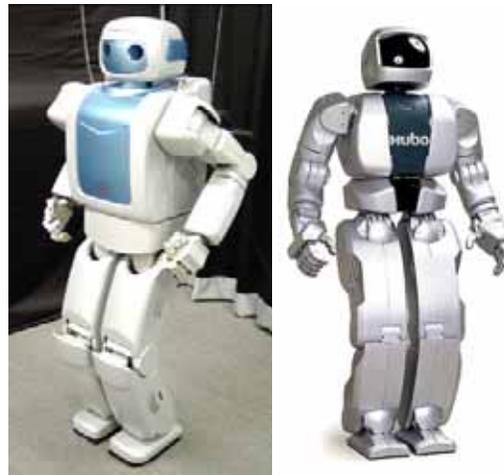


Figure 4.20. KIST (NBH-1) and KAIST (KHR-3) humanoids.

Qualitative Observations

Japan has the strongest program in the world, but Korea has the best first derivative, making major strides in the last five years. Both countries seem to have a healthy mix of government labs, corporations, and universities in teams. Asia is leading the world in biped locomotion, and business development of humanoids.

The U.S. leads in algorithm development for the control of limbs, but with few testbeds this theory is not being proven, and is being re-discovered in Asia where it is tested and refined. The use leads in upper body applications, with dexterous manipulation, grasping and eye-hand coordination skills. The U.S. has the

lowest first derivative, with few active programs, and will soon to be overtaken in these final areas of dominance.

Like the U.S., the European work has been lacking a larger scale organization, plan or strategy. Also like the U.S., the European community has pockets of excellent work, such as the novel fluid-powered hands in Karlsruhe, the smooth walking at TUM, and the beautifully engineered dexterous limbs at DLR.

Applications

In every lab visited, the discussion turned to the question, “What is the killer app?” for humanoids. This slang phrase was used in all countries. In Japan, the work was motivated by support of the “Silver Society,” a term used in several labs to describe the technology needs of an aging population. The humanoid form and function was proposed as ideal for this market, with Japan’s cultural tendency to embrace robots and technology in general producing a “pull.” Since our study tour, Waseda has demonstrated lifting a person from a bed, as would be needed in a nursing home.

In Korea, we were regularly welcomed with a description of the national programs for technology, where robotics was selected as one of the key technologies for advancing their national gross national product (GNP). This top-down strategy, and national goal, was unique in the world. Korean researchers were deeply interested in ubiquitous systems, and were looking at humanoids as a component of urban technology designed for service tasks.

A brief listing of applications being pursued by humanoid researchers includes:

- *Military & Security* Search and rescue, mine/improvised explosive device (IED) handling, logistics, and direct weapons use
- *Medical* Search and rescue, patient transfer, nursing, elder care, friendship
- *Home Service* Cleaning, food preparation, shopping, inventory, home security
- *Space* Working safely with space-walking astronauts, caretakers between crews
- *Dangerous Jobs* Operating construction equipment, handling cargo, firefighting, security
- *Manufacturing* Small parts assembly, inventory control, delivery, customer support

Conclusions

Humanoids are now being developed in Asia, the U.S., and Europe, though a clear business plan has yet to emerge. The early systems are expensive and brittle, being used as testbeds to develop walking, manipulation and human-interaction capabilities. As these skills mature, and are coupled with better engineered machines, the potential is unlimited. The only questions are: when will these future humanoids become viable, and who will make the first “Model T”-equivalent system.

The lack of a clear business plan will not limit interest and investment in humanoids for two reasons. First, there is an emotional and cultural drive towards building machines that look and work like humans. The Japanese eager embrace of robot technology is equaled only by the U.S. interest in the dangers of humanoids depicted in our science fiction. The Korean focus on humanoids as a part of a highly wired and ubiquitous urban landscape is a third view, with building-integrated systems gradually yielding to mobile, human-like robots that can be upgraded more quickly than a home. Many of the current prototypes are viewed as “mascots,” as symbols of the future and their developer’s quest to lead. Wherever humanoids go, they will evoke strong emotions and opinions, from love to hate. But the drive to build them is strong, and not motivated by economics in the near term.

There is a second reason for the inevitability of humanoids. They encompass a large set of robotics domains. The archetypical humanoid, though not yet realized, will be able to locomote through most terrain, as humans do. They will be able to perform value added work, building with hands that take inspiration from human limbs, handling objects and using tools with dexterity. They will slip into our society seamlessly, but over time as the technology matures, filling roles not well suited to humans. They will fit into our buildings, they

will walk through our society, and they will manipulate the objects of modern life. Humanoids represent a massively complete system design, combining the research of cognition with navigation, perception, and manipulation. The completeness of this form yields a spectrum of functions that can not be ignored. Most researchers would be able to use a humanoid platform today for their research, if one existed that they could afford.

The humanoid is where the robot began, in the imagination of the science fiction writers of the 20th century. Now it seems to be the engineers turn. The 21st century will see humanoids leave the pages of fiction and step, roll or run into our world.

REFERENCES

- Hirukawa, H., F. Kanehiro, K. Kaneko, S. Kajita, K. Fujiwara, Y. Kawai, F. Tomita, S. Hirai, K. Tanie, T. Isozumi, K. Akachi, T. Kawasaki, S. Ota, K. Yokoyama, H. Handa, Y. Fukase, J. Maeda, Y. Nakamura, S. Tachi and H. Inoue. 2004. Humanoid robotics platforms developed in HRP. *Robotics and Autonomous Systems* 48:4, 165–175
- Minato, T., K. F. MacDorman, M. Shimada, S. Itakura, K. Lee, and H. Ishiguro. 2004. Evaluating humanlikeness by comparing responses elicited by an android and a person, Proceedings of the Second International Workshop on Man-Machine Symbiotic Systems (pp. 373–383). November 23–24. Kyoto, Japan.
- Nakamura, Y., H. Hirukawa, K. Yamane, S. Kajita, K. Yokoi, M. Fujie, A. Takanishi, K. Fujiwara, S. Nagashima, Y. Murase, M. Inaba, and H. Inoue. 2001. The Virtual Robot Platform. *Journal of Robotics Society of Japan* 19:1, 28–36.
- Pratt, J., Dilworth, P., Pratt, G. 1997. Virtual Model Control of a Bipedal Walking Robot. Proceedings of the IEEE International Conference on Robotics and Automations (ICRA), Albuquerque, U.S..
- Vukobratovic, M. and A. A. Frank. 1969. Legged Locomotion Studies: On the Stability of Biped Locomotion. Proceeding 3rd International Symposium on External Control of Human Extremities, Belgrade.
- Vukobratovic, M., A. A. Frank, and D. Juricic. 1970. On the Stability of Biped locomotion. *IEEE Trans. Biomed Engineering*, BME-17:1, 25–36.
- Zheng, Y.F. and H. Hemami. 1984. Impact Effect of Biped Contact with the Environment, *IEEE Trans. of Systems, Man and Cybernetics*, SMC 14:3, 437–443.