Multimedia Contents

67. Humanoids

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Humanoid robots selectively immitate aspects of human form and behavior. Humanoids come in a variety of shapes and sizes, from complete human-size legged robots to isolated robotic heads with human-like sensing and expression. This chapter highlights significant humanoid platforms and achievements, and discusses some of the underlying goals behind this area of robotics. Humanoids tend to require the integration of many of the methods covered in detail within other chapters of this handbook, so this chapter focuses on distinctive aspects of humanoid robotics with liberal cross-referencing.

This chapter examines what motivates researchers to pursue humanoid robotics, and provides a taste of the evolution of this field over time. It summarizes work on legged humanoid locomotion, whole-body activities, and approaches to human–robot communication. It concludes with a brief discussion of factors that may influence the future of humanoid robots.

67.1 Why Humanoids?

Throughout history, the human body and mind have inspired artists, engineers, and scientists. The field of humanoid robotics focuses on the creation of robots that are directly inspired by human capabilities (Chap. 75). These robots usually share similar kinematics to humans, as well as similar sensing and behavior. The motivations that have driven the development of humanoid robots vary widely. For example, people have developed humanoid robots to serve as general-purpose mechanical workers, entertainers, and test-beds for theories from neuroscience and experimental psychology [67.1–3].

Notably, while this chapter focuses on robots that have been explicitly designated as humanoid robots by their creators, the lines between these robots and others can be blurry. Many robots share characteristics with humans, or have been inspired by humans.

67.1.1 The Human Example

On a daily basis, humans perform important tasks that are well beyond the capabilities of current robots. Moreover, humans are generalists with the ability to perform a wide variety of distinct tasks. Roboticists would like to create robots with comparable versatility and skill. Considering the physical and computational mechanisms that enable a person to perform a task is a common approach to automating it. Exactly what to borrow from the human example is controversial. The literal-minded approach of creating humanoid robots may not be the best way to achieve some human-like capabilities (Chap. 65). For example, dishwashing machines bear little similarity to the manual dishwashing they replace.

67.1.2 The Pleasing Mirror

Humans are humanity's favorite subject. A quick look at popular magazines, videos, and books should be enough to convince any alien observer that humanity is obsessed with itself. The nature of this obsession is not fully understood, but aspects of it have influenced the field of humanoid robotics.

Humans are social animals that generally like to observe and interact with one another [67.4]. Moreover, people are highly attuned to human characteristics, such as the sound of human voices and the appearance of human faces and body motion [67.5–7]. Infants show preferences for these types of stimuli at a young age, and adults appear to use specialized mental resources when interpreting these stimuli. By mimicking human characteristics, humanoid robots can engage these same preferences and mental resources.

Humanity's interest in itself has been reflected in media as diverse as cave paintings, sculpture, mechanical toys, photographs, and computer animation. Artists have consistently attempted to portray people with the latest tools at their disposal. Robotics serves as a powerful new medium that enables the creation of artifacts that operate within the real world and exhibit both human form and behavior [67.8].

Popular works of fiction have frequently included influential portrayals of humanoid robots and human-made humanoid creatures. For example, *Karel Čapek*'s science fiction play Rossum's Universal Robots (R.U.R.) from 1920 centers around the story of artificial people created in a factory [67.9]. Many other works have included explicit representations of humanoid robots, such as the robot Maria in *Fritz Lang*'s 1927 film *Metropolis* [67.10], and the thoughtful portrayal of humanoid robotics by *Isaac Asimov* in works such as *The Caves of Steel* from 1954 [67.11]. The long history of humanoid robots in science fiction has influenced generations of researchers, as well as the general public, and serves as further evidence that people are drawn to the idea of humanoid robots.

67.1.3 Understanding Intelligence

Many researchers in the humanoid robotics community see humanoid robots as a tool with which to better understand humans [67.3, 12]. Humanoid robots offer an avenue to test understanding through construction (*synthesis*), and thereby complement the *analysis* provided by researchers in disciplines such as cognitive science.

Researchers have sought to better immitate human intelligence using humanoid robotics [67.13]. Developmental psychologists, linguists, and others have found strong links between the human body and human cognition [67.14]. By being embodied in a manner similar to humans, and situated within human environments, humanoid robots may be able to exploit similar mechanisms for artificial intelligence (AI). Researchers are also attempting to find methods that will enable robots to develop autonomously in a manner akin to human infants [67.15]. Some of these researchers use humanoid robots that can physically explore the world in a manner similar to humans [67.16].

67.1.4 Human Environments

People inhabit environments that accommodate human form and human behavior [67.17, 18]. Many important everyday objects fit in a person's hand and are light enough to be transported conveniently by a person. Human tools match human dexterity. Doors tend to be a convenient size for people to walk through. Tables and desks are at a height that is well matched to the human body and senses. Humanoid robots can potentially take advantage of these same accommodations, thereby simplifying tasks and avoiding the need to alter the environment for the robot [67.19]. For example, humanoid robots and people could potentially collaborate with one another in the same space using the same tools [67.20]. Humanoid robots can also interface with machinery that does not include drive-by-wire controls, as shown by the teleoperated robot in the cockpit of a backhoe in Fig. 67.1 [67.21].

Robots with legs and human-like behavior could potentially traverse the same environments that humans traverse, such as rugged outdoor environments and the industrial plant shown in Fig. 67.2, which has stairs and handrails designed for human use [67.22]. In addition to mobility advantages, legs have the potential to help in other ways. For example, legs could enable a humanoid robot to change its posture in order to lean into something, pull with the weight of its body, or crawl under an obstacle [67.23, 24].

The Fukushima Daiichi nuclear disaster, which occurred in March 2011 in Japan, is a compelling example scenario for robots. The disaster resulted in human environments that were unsafe for humans. Robots capable of performing diverse tasks in these environments via remote control would have been valuable. Future humanoid robots may be able to access similar environments using narrow passageways, ladders, and other environmental features designed for people (Fig. 67.3). Likewise, they may be able to remotely perform tasks involving control panels, valves, and tools designed for people. This type of scenario

Fig. 67.1 The humanoid robot HRP-1S (HRP: humanoid robot project) driving a backhoe (courtesy Kawasaki Heavy Industries, Tokyu Construction and National Institute of Advanced Industrial Science and Technology (Japan) (AIST)). The robot can be teleoperated by a human operator to control the backhoe remotely. The same robot could potentially interface with many different unmodified machines

Fig. 67.2 HRP-1 operating in a mockup of an industrial plant (courtesy Mitsubishi Heavy Industries)

Fig. 67.3 An image of supposed disaster-response scenario DARPA Robotics Challenge

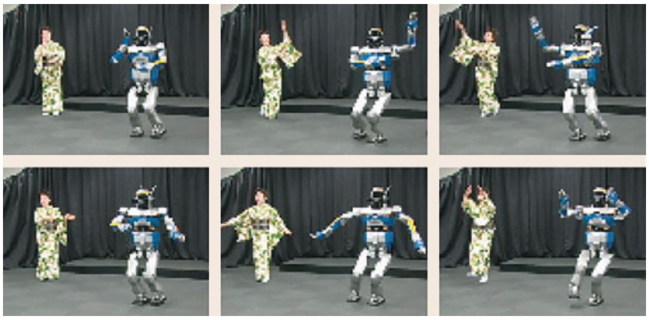


Fig. 67.4 The humanoid robot HRP-2 dancing with a human (after [67.25]). The human is a master of a traditional Japanese dance whose dancing was recorded by a motion-capture system, and transformed for use by the robot

Fig. 67.5 Actroid (courtesy Kokoro), an android designed for entertainment, telepresence, and media roles

Fig. 67.6 Atlas robot provided as a platform for the DARPA Robotics Challenge (courtesy Boston Dynamics)

has inspired the DARPA (Defense Advanced Research Projects Agency) Robotics Challenge in which robots will compete by performing related tasks. Notably, DARPA plans for some teams to compete using Atlas humanoid robots from Boston Dynamics Fig. 67.6.

67.1.5 Human Interaction

People are accustomed to working with other people. Many types of communication rely on human form and behavior. Some types of natural gestures and expression involve subtle movements in the hands and face (Chap. 72). People can interpret eye gaze and facial expressions without training. Humanoid robots can potentially simplify and enhance human–robot interaction by taking advantage of the communication channels that already exist between people.

Similarly, people already have the ability to perform many desirable tasks. This task knowledge may be more readily transferred to humanoid robots than to a robot

Fig. 67.7 Petman is a humanoid robot that Boston Dynamics developed to test chemical protection clothing for the US military (after [67.26])

with a drastically different body. This is especially true of cultural actions centered around the human form (Fig. 67.4).

67.1.6 Entertainment, Culture, and Surrogates

Humanoid robots are inherently appropriate for some applications. For example, robots that resemble humans could play roles in entertainment, such as theater, theme parks, and companionship for adults (Fig. 67.5). Realism in form and function could make humanoid robots preferable to wax figures and animatronics.

A humanoid robot could serve as an avatar for telepresence, model clothing, test ergonomics, or serve other surrogate roles that fundamentally depend on the robot's similarity to a human. For example, Boston Dynamics developed the humanoid robot Petman to test clothing that is intended to protect military personnel from chemical agents (Fig. 67.7). Robotic prostheses and cosmeses also have a close relationship to humanoid robotics, since they seek to directly replace parts of the human body in function and form (Chap. 64).

67.2 History

There is a long history of mechanical systems with human form that perform human-like movements. For example, Al-Jazari designed a humanoid automaton in the 13th century [67.27], Leonardo da Vinci designed a humanoid automaton in the late 15th century [67.28], and in Japan there is a tradition of creating mechanical dolls called Karakuri ningyo that dates back to at least the 18th century [67.29]. In the 20th century, animatronics became an attraction at theme parks. For example, in 1967 Disneyland opened its Pirate's of the Caribbean ride [67.30], which featured animatronic pirates that play back human-like movements synchronized with audio. Although programmable, these humanoid animatronic systems moved in a fixed open-loop fashion without sensing their environments.

In the second half of the 20th century, advances in digital computing enabled researchers to incorporate

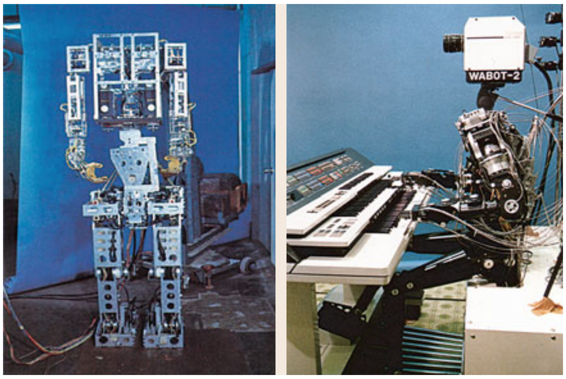


Fig. 67.8 **(a)** WABOT-1 (1973) and **(b)** WABOT-2 (1984; courtesy Humanoid Robotics Institute, Waseda University)

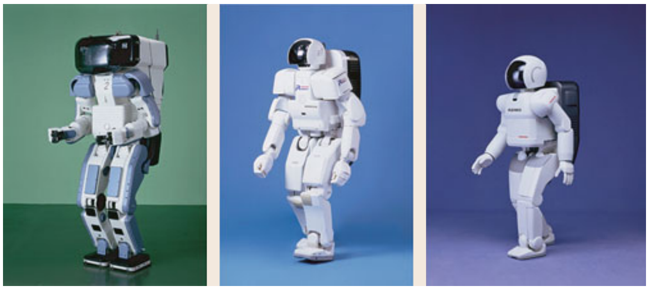


Fig. 67.9 **(a)** Honda P2 (180 cm tall, 210 kg), **(b)** P3 (160 cm, 130 kg), and **(c)** advanced step in innovative mobility (glossnoidx-ASIMOadvanced step in innovative mobility) (120 cm, 43 kg) (after [67.31]; courtesy Honda)

Fig. 67.10 The humanoid robot Cog used neural oscillators in conjunction with compliant torque-controlled arms to perform a variety of everyday tasks with human tools, such as crank turning, hammering, sawing, and playing a snare drum (after [67.32]; courtesy Sam Ogden)

significant computation into their robots for sensing, intelligence, control, and actuation. Many roboticists developed isolated systems for sensing, locomotion, and manipulation that were inspired by human capabilities. However, the first humanoid robot to integrate all of these functions and capture widespread attention was Waseda robot (WABOT-1), developed by Ichiro Kato et al. at Waseda University in Japan in 1973 (Fig. 67.8).

The WABOT robots integrated functions that have been under constant elaboration since: visual object recognition, speech generation, speech recognition, bimanual object manipulation, and bipedal walking. For instance, WABOT-2's ability to play a piano, publicized at the Tsukuba Science Expo in 1985, stimulated significant public interest.

In 1986, Honda began a confidential project to create a humanoid biped. Honda grew interested in humanoids, perhaps seeing in them devices of complexity comparable to cars with the potential to become high-volume consumer products one day. In 1996, Honda unveiled the Honda Humanoid P2, the result of this confidential project. P2 was the first full-scale humanoid capable of stable bipedal walking with onboard power and processing. Successive designs reduced its weight and improved its performance (Fig. 67.9). Compared to humanoids built by academic laboratories and small manufacturers, the Honda humanoids were a leap forward in sturdiness, using specially cast lightweight high-rigidity mechanical links, and harmonic drives with high torque capacity.

In parallel with these developments, the decade-long *Cog project* began in 1993 at the MIT Artificial Intelligence laboratory in the USA with the intention of creating a humanoid robot that would, *learn to think by building on its bodily experiences to accomplish progressively more abstract tasks* [67.13]. This project gave rise to an upper-body humanoid robot whose design was heavily inspired by the biological and cognitive sciences (Fig. 67.10). Since the inception of the Cog project, researchers across the world have initiated many humanoid robotics projects and formed communities devoted to developmental robotics, autonomous mental development (AMD [67.33]), and epigenetic robotics [67.34].

As of the early 21st century, a large number of companies and academic researchers have become involved with humanoid robots and created new humanoid robots with distinctive characteristics.

67.3 What to Immitate?

Humanoid robots come in a variety of shapes and sizes that immitate different aspects of human form and behavior (Fig. 67.11). As discussed, the motivations that have driven the development of humanoid robots vary widely. These diverse motivations have led to a variety of humanoid robots that selectively emphasize some human characteristics, while deviating from others.

67.3.1 Body Parts

One of the most noticeable axes of variation in humanoid robots is the presence or absence of body parts. Some humanoid robots have focused solely on the head and face, others have a head with two arms mounted to a stationary torso, or a torso with wheels (for example, Fig. 67.12). Some humanoid robots even combine a highly-articulate face with arms, legs, and a torso.

67.3.2 Mechanics

Humanoid robots immitate various mechanical aspects of the human body, such as its kinematics, dynamics, geometry, material properties, and actuation. As such, humanoid robotics is closely related to the field of human biomechanics.

Humanoid robots often consist of rigid links with kinematics that approximate the kinematics of the human musculoskeletal system. Even a rigid-link model of human kinematics can have a very high number of degrees of freedom (DOF). A humanoid robot typically imitates degrees of freedom that are pertinent to its intended use. For example, humanoid robots rarely attempt to immitate the human shoulder's ability to translate or the flexibility of the human spine [67.35, 36]

The human hand serves to further illustrate these issues. Modern humanoid robots frequently have two arms, each with seven degrees of freedom, but their hands vary considerably (Chap. 19). The human hand is highly complex with over 20 DOFs (i. e., approximately four DOFs per finger and a five-DOF thumb) in a very compact space with a compliant exterior, dense tactile sensing, and low distal mass. Researchers have approximated the human hand with varying levels of accuracy, including the anatomically correct testbed (ACT) hand, the 20-DOF Shadow Hand, the 12-DOF DLR-Hand-II (DLR: Deutsches Zentrum für Luft- und Raumfahrt), the 11-DOF Robonaut hand, and the 2-DOF Cog hand [67.37–41]. The ACT hand represents the high-fidelity end of the spectrum, since it approximates the bone structure, inertial properties, kinematics, and actuation of the human hand.

Actuation is another property of humanoid robots that varies considerably. Human actuation consists of a complex, highly-redundant system of variable-stiffness muscles. In contrast, many humanoid robots use a stiff, position-controlled actuator at each joint. There are early exceptions, such as the use of series elastic actuators in Cog's arms [67.32, 42], and various forms of compliant actuation have now become common in the arms of humanoid robots.

67.3.3 Sensors

Humanoid robots have made use of a variety of sensors including cameras, three-dimensional (3-D) cameras, laser rangefinders, microphone arrays, lavalier microphones, and pressure sensors. Some researchers choose to immitate human sensing by selecting sensors with

Fig. 67.11 Kismet is an example of a humanoid head for social interaction

Fig. 67.12 The NASA (National Aeronautics and Space Administration) Robonaut consists of an upper body placed on a wheeled mobile base

clear human analogs and mounting these sensors on the humanoid robot in a manner that mimics the placement of human sensory organs. As discussed in Sect. 67.6, this is perhaps most evident in the use of cameras. Two to four cameras have often been mounted within the heads of humanoid robots with configurations similar to human eyes.

The justifications for this bias towards human-like sensing include the impact of sensing on natural human–robot interaction, the proven ability of the human senses to support human behavior, and aesthetics. For example, with respect to human–robot interaction, nonexperts can sometimes interpret the functioning and implications of a human-like sensor, such as a camera, more easily. Similarly, if a robot senses infrared or ultraviolet radiation, the robot can see a different world than the human. With respect to behavior, placement of sensors on the head of the robot allows the robot to sense the world from a vantage point that is similar to that of a human, which can be valuable for finding objects that are sitting on a desk or table.

Prominent humanoid robots have added additional sensors without human analogs. For example, Kismet used a camera mounted in its forehead to augment the two cameras in its servoed eyes, which simplified common tasks such as tracking faces. Similarly, versions of ASIMO have used a camera mounted on its lower torso that looks down at the floor in order to simplify obstacle detection and navigation during locomotion.

67.3.4 Other Characteristics

Other common forms of variation include the size of the robot, the extent to which the robot attempts to appear like a human, and the activities the robot performs. The remainder of this chapter provides examples from three active areas of humanoid robotics research: locomotion, whole-body activities, and morphological communication.

67.4 Locomotion

Bipedal walking is a key research topic in humanoid robotics (see also Chap. 48, *Legged Robots*, for a review of this topic in the context of locomotion in general). Legged locomotion is a challenging area of robotics research, and bipedal humanoid locomotion is especially challenging. Some small humanoid robots are able to achieve statically stable gaits by having large feet and a low center of mass, but large humanoids with a human-like weight distribution and body dimensions typically need to balance dynamically when walking bipedally.

67.4.1 Bipedal Locomotion

Currently the dominant methods for bipedal legged locomotion with humanoids make use of the zero-moment point (ZMP) criterion to ensure that the robot does not fall over [67.43]. As discussed in detail in Chap. 48, control of the robot's body such that the ZMP sits within the support polygon of the robot's foot ensures that the foot remains planted on the ground, assuming that friction is high enough to avoid slipping. The ZMP can be used to plan walking patterns that make the robot dynamically stable while walking. Conventionally, biped locomotion had been offline generated by solving an ordinally differential equation with respect to the motion of the COG (center of gravity) given a desired trajectory of the ZMP. Recently, several extensions have been done for the ZMP based biped gait generation as shown in the following:

Realtime Walking Pattern Generation

By solving the ordinally differential equation in realtime, biped gait is generated in realtim [67.44, 45]. Since the realtime walking pattern generator enables us to change the landing positions of foot in realtime, it is used in various situations; in [67.46], the landing position of the foot changes in accordance with the hand reaction force as will be described more concretely in the subsection of *manipulation*. As shown in Fig. 67.13 [67.47], the walking pattern is generated in realtime in accordance with the amount of external disturbance applied to the robot. In this case, after the torso of a robot is pushed by a human, biped gait for a few steps is generated in realtime to recover the balance. In [67.48], the humanoid robot ASIMO walks in the environment with moving obstacles. By using the estimation of the object motion, the walking pattern of the robot is generated in realtime. Fig. 67.14 [67.49] shows the biped locomotion on uneven terrain. In this experiment, the shape of the environment is measured by a laser range sensor. According to the shape information of the environment, the landing position on uneven terrain is calculated in realtime.

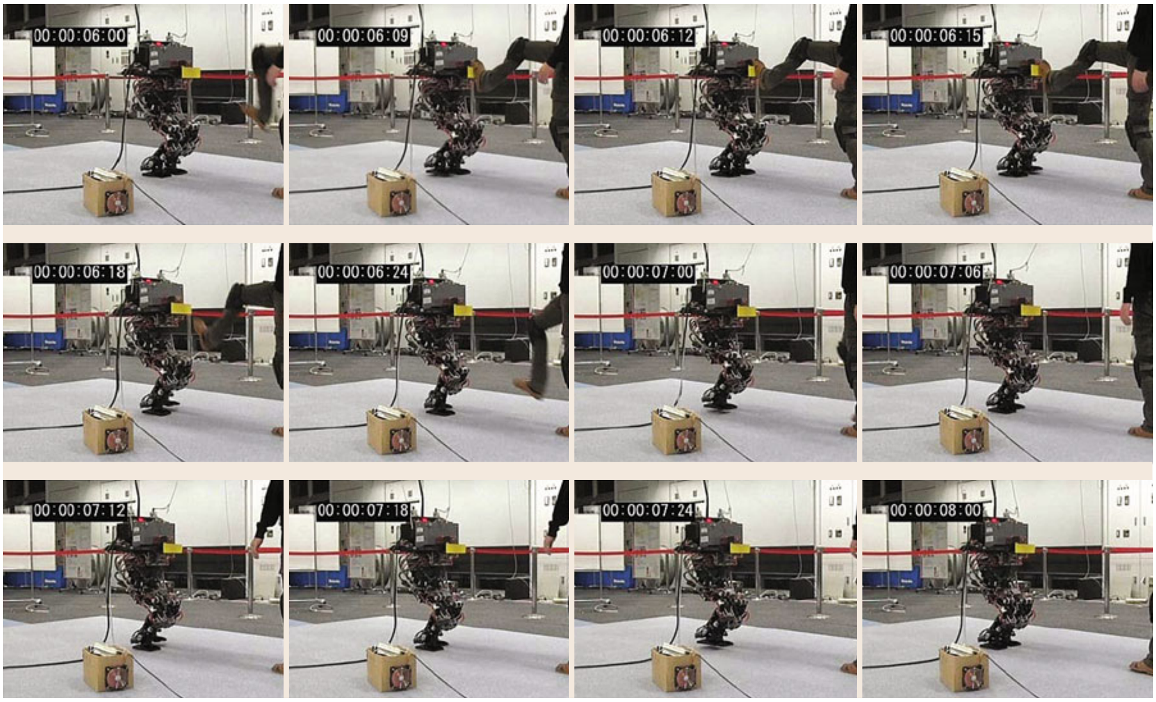


Fig. 67.13 Experiment of push recovery

Running

By additionally considering the flight phase to the ZMP based walking pattern generator, running motion of biped robot is generate [67.50–52]. Fig. 67.15 [67.52] shows an example of running motion by a biped humanoid robot. Running motion of a human-sized humanoid robot with 7 km/h is realized.

Fig. 67.14 Experiment on biped gait on uneven terrain

Extension of ZMP Based Method

Althogh the ZMP is a two dimentional information defined for the interaction between a robot and the ground surface, a robot applies 6 dimensional force/moment onto the ground. Hence, just by regulating the position of the ZMP, it is impossible to control all dimension of the interaction force/moment. More concretely speaking, the robot may slip on the ground surface or may loose contact with the ground. Research on biped locomotion considering full 6 dimensional force/moment has been don [67.53, 54].

Human-Like Walking Motion

The biped locomotion generated just by using the ZMP may not be a human-like one. Challenge has been done to generate a human-like biped gait of a humanoid robo [67.55]. Fig. 67.16 [67.55] showws a biped locomotion where single toe support, knee stretching and human like swing leg trajectory are applied. It is compared with the human walking motion where the model belongs to *Walking Studio Rei*.

Force/Moment Controller

Bipedal walking needs to be robust to unexpected disturbances encountered during the execution of planned

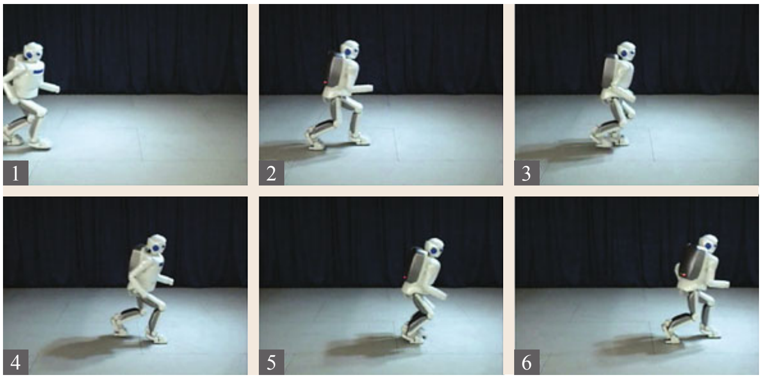


Fig. 67.15 Example of running motion

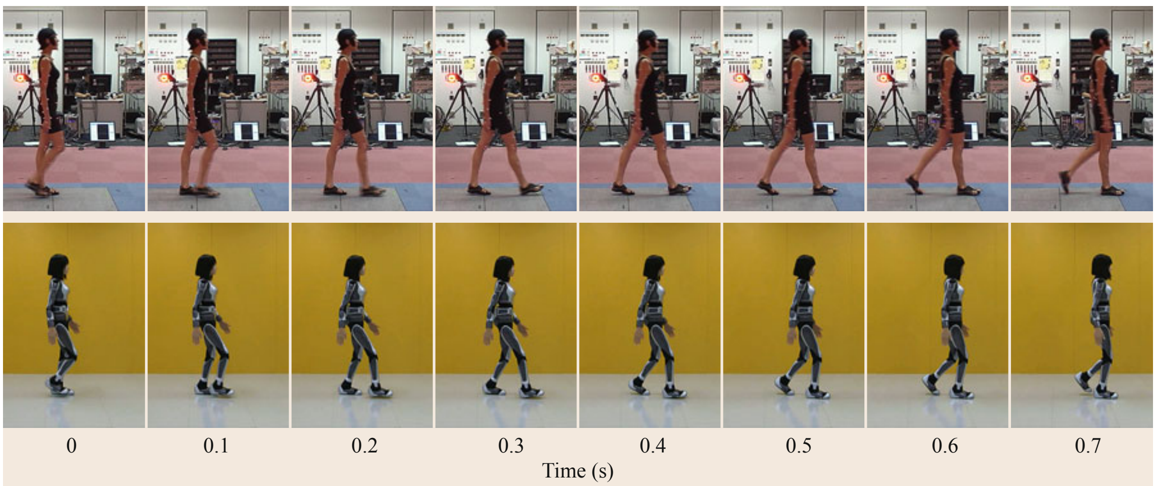


Fig. 67.16 Human like walking motion compared with human motion

walking patterns. In these situations, walking can sometimes be stabilized with feedback control and appropriate sensin [67.56]. Many humanoid robots, such as Honda's ASIMO, make use of accelerometers, gyroscopes, and six-axis force/torque sensors to provide feedback to the robot during locomotion.

Force/torque sensors have long been applied to manipulators for the implementation of force control, but force/torque sensors with sufficient robustness to handle foot impact for a full-size humanoid robot are relatively new. When the foot of the robot touches down, the foot receives an impact which can disturb its walking. This impact can be rather large, especially when the robot is walking quickly. Some feet now incorporate a spring and damper mechanism as shown in Fig. 67.17 in order to mitigate these problems.

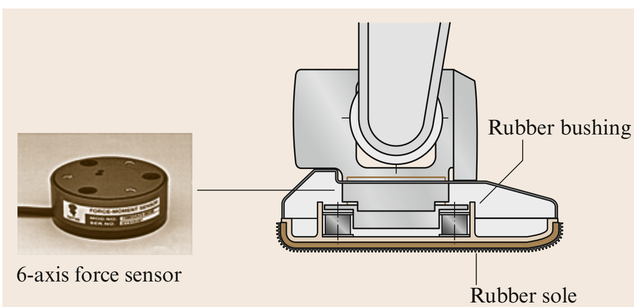


Fig. 67.17 Example of a humanoid foot structure for legged locomotion that uses compliance and force/torque sensing

Passive-Gait-Based Approach

Alternative to the ZMP-based approach, researchers have begun to use the principles of bipedal passive-dynamic walkers to develop powered bipedal walkers that walk with high efficiency in a human-like way by exploiting natural dynamics (Fig. 67.18 [67.57]).

67.4.2 Other Various Locomotion Styles

Most humanoid robots have two legs and two arms. Here, in addition to the legs, the arms can be used to

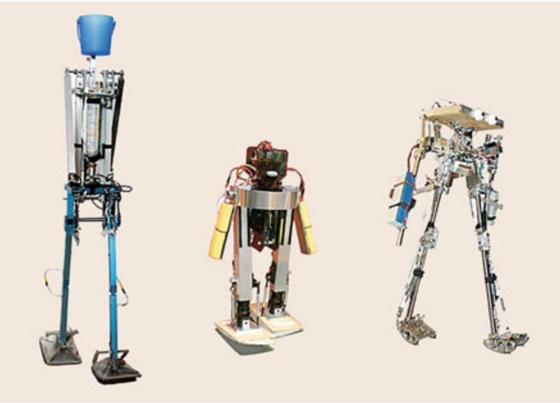


Fig. 67.18 These robots from Delft, MIT and Cornell (*left* to *right*) are designed to exploit their natural dynamics when walking (after [67.57]; courtesy Steven H. Collins)

enhance the mobility of a humanoid robot. For example, when a robot walks while grasping a handrail, the contact could potentially increase the stability of the robot. Attempt [67.58] have been done to generate the motion of a humanoid robot by using the arms in addition to the legs to enhance its mobility of it. As shown in Fig. 67.19 [67.58], a humanoid robot walking on uneven terrain sometimes uses to increase the robot's stability.

A human-scale robot should expect to fall from time to time in realistic conditions. A humanoid robot may fall down due to a large disturbance even if the motion is planned carefully and a sophisticated feedback controller is applied to the robot. In this event, the robot could be damaged significantly during a fall, and could also damage the environment or injure people who are nearby. An important area of research is how to control the robot's fall in order to gracefully recover or minimize damage. The Sony QRIO (Quest for cuRIOsity) can control its falling motions in order to reduce the impact of touch down [67.50], although it is of a relatively small size (which simplifies the problem). *Fujiwara* et al. developed a falling motion controller for a human-size humanoid robot that is falling backwards [67.59]. Figure 67.20 shows an example of a controlled falling motion. The general problem is still very much an active area of research. Similarly, there is also the issue of getting back up again [67.60] (Fig. 67.21).

67.4.3 Localization and Navigation Among Obstacles

In order for a humanoid robot to walk in unmodeled environments, localization and obstacle detection are essential. Wheeled robots encounter similar issues while navigating, but full bipedal humanoids have more-specialized requirements. For example, bipedal humanoids have the ability to control contact with the world through their highly articulate legs.

Artificial landmarks can simplify localization. As shown in Fig. 67.22, Honda's ASIMO uses a camera mounted on its lower torso that looks down at the floor to find artificial markers for position correction [67.61]. Accurate positioning is important for long-distance navigation and stair climbing, since slippage usually occurs while walking and accumulated positional and directional errors can lead to severe failures.

Obstacle avoidance is also an important function for locomotion. Disparity images generated by stereo vi-

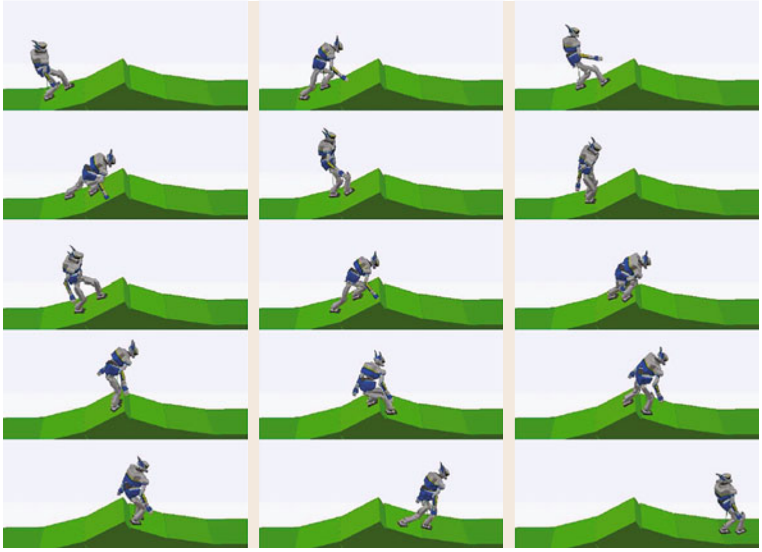
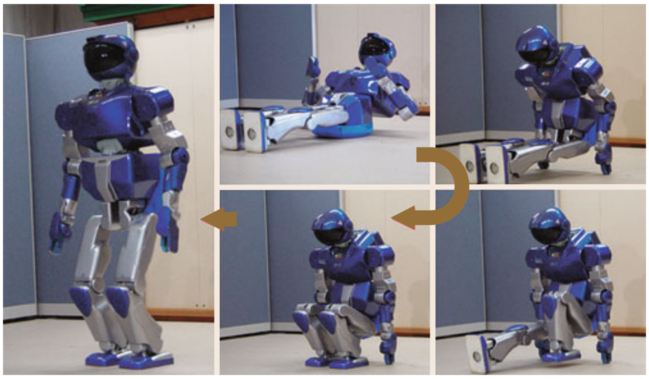


Fig. 67.19 Humanoid robot walking on uneven terrain by utilizing hand contact

Fig. 67.20 Example of controlled falling-down motion

Fig. 67.21 The humanoid robot HRP-2P getting up from a lying-down position ►



sion have been utilized for this purpose. For example, the plane segment finder [67.62] developed by *Okada* et al. helps detect traversable areas. Figure 67.23 shows the result of detecting clear areas of the floor plane appropriate for gait generation.

Humanoids require a great deal of computation due to the need for sophisticated sensing and control. Customized computational hardware may help mitigate this problem. For example, Sony's humanoid robot QRIO is equipped with a field-programmable gate array (FPGA) to generate disparity maps in real time from the stereo cameras. This real-time vision system has been used to detect floor areas, stair steps, and obstacles for navigation [67.63, 64].

67.4.4 Generating Motions when in Contact with an Object

Many approaches to whole-body motion generation assume that the robot is only in contact with the ground. When a humanoid robot's hands make contact with the environment, it can no longer maintain balance using the conventional ZMP property defined by the center of pressure of the supporting feet [67.65]. This leads to significant challenges for whole-body activities, especially since the properties of the environment with which the robot is making contact may not be known in advance.

Harada et al. have introduced generalized ZMP (GZMP) as a method of handling some of these issues, such as the hand reaction forces generated from contact with the environment [67.66]. Researchers have developed methods that directly make use of the six-dimensional force/torque acting on the robot at the hands, which can be sensed with conventional force/torque sensors placed at the wrists [67.67]. Researchers have also developed specialized methods for generating stable robot motion while an object is being manipulated [67.46, 65, 68–70].

Fig. 67.22 ASIMO and artificial landmarks on the floor

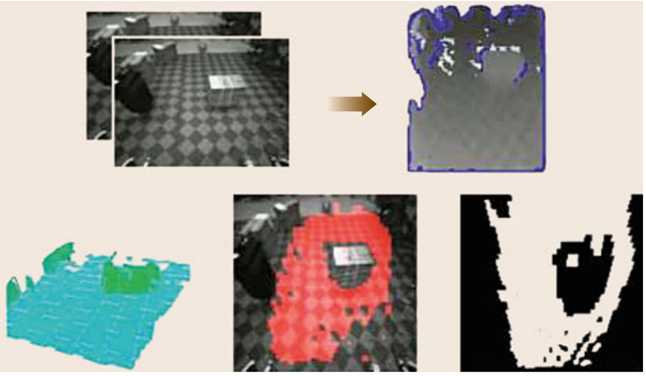


Fig. 67.23 Plane segment finder for detecting traversable floor area

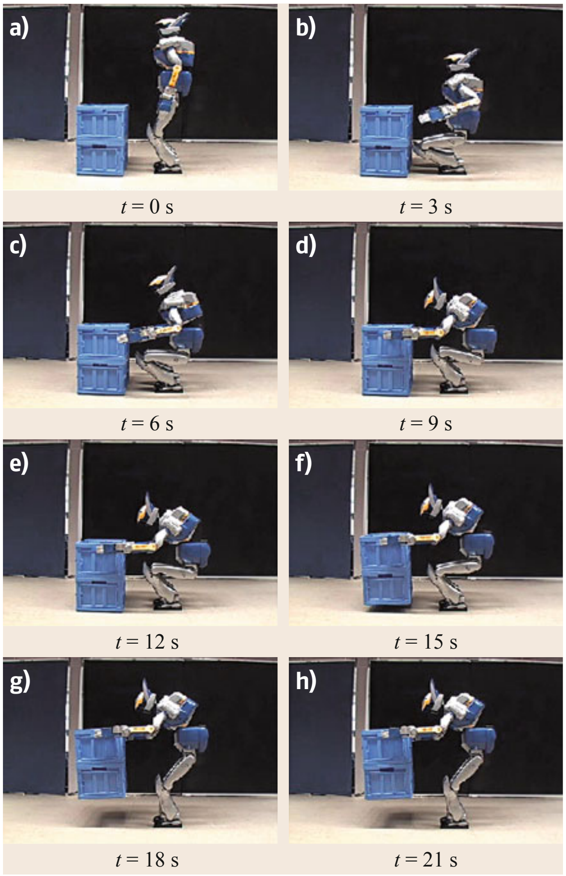


Fig. 67.24 (a–h) Lifting an object while moving the waist to compensate for the load (after [67.71])

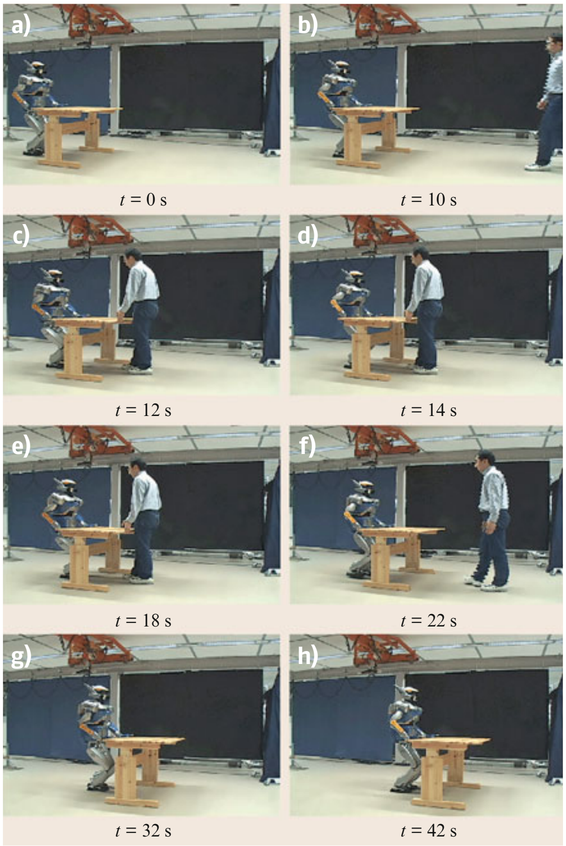


Fig. 67.25 (a–h) Example of pushing manipulation and cooperation (after [67.46])

Carrying an Object

In a manner analogous to the previously described methods, coarse motions that do not consider the hand reaction forces can be modified [67.65, 68, 71, 72]. Figure 67.24 shows an experimental result of carrying an object that weighs 8 kg [67.71]. Based on measurements of the hand reaction force, the position of the waist is modified to compensate for the load and maintain stability.

Pushing an Object

As another example of using force sensing to adapt behavior, consider the problem of pushing a large object placed on the floor. For such a task, if the gait pattern is determined before the robot actually moves, the robot may not stay balanced if the weight of the object or the friction coefficient between the object and the floor is different from the predicted values. To address this problem, the gait pattern can be adaptively changed depending on the output of a force sensor at the end of the arms in order to handle changes in the object's weight and the friction coefficient [67.46].

Figure 67.25 shows an experimental result for this approach [67.46]. In the experiment, the table weighs about 10 kg. Even though the motion of the table is disturbed externally during the experiment, the robot stays balanced by adaptively changing its gait pattern based on the measured forces.

67.5 Whole-Body Activities

The two previous sections have focused on humanoid locomotion and manipulation separately. This section outlines whole-body motions that require coordinated control of arms and legs to perform various tasks, such as carrying a bulky objects, climbing a ladder, or going through narrow spaces with contact supports on the environment. Humanoid motion is characterized by their redundancy and underactuation (Chaps. 10 and 17). Unlike fixed industrial robots, it has a floating base (usually it is set at the pelvis) that can only be controlled through the leg locomotion or multiple contact motion involving arms and legs. It is therefore essential how to define the desired task and to generate the motion that achieves it. Since humanoids have a redundant structure, a general approach is first to generate coarse motion, and then to transform it into a whole-body coordinated joint trajectory that is executed by a controller maintaining the stability through sensor feedback, as illustrated in Fig. 67.26. The first half of this section addresses the first two components of this general approach.

The latter half of this section deals with issues related to various complex whole-body motion that the basic conversion methods addressed in Sect. 67.5.2 could not always resolve. Resolution of various concurrent tasks, including those expressed as inequality and dynamic constraints is presented in Sect. 67.5.3. This framework can be applied to a reaching task while keeping the visibility of the object, as well as footstep planning. Finally, motion generation including multiple contacts is introduced as an advanced topic in Sect. 67.5.4. A wide variety of its application is expected to extend the activity fields of humanoids in cluttered environments where the humanoid should maintain its balance by supporting its body on non-coplanar contact points.

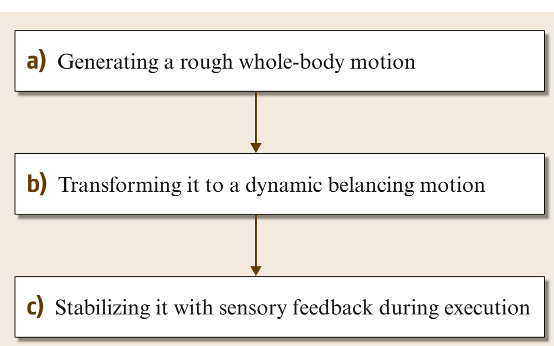


Fig. 67.26 Overview of motion-generation stages for a balancing robot

67.5.1 Coarse Whole-Body Motion

There are several ways to generate coarse humanoid motion:

1. Using motion capture system
2. Using graphical user interface (GUI)
3. Using automated motion planning
4. Using abstract task specification.

Using Motion Capture System

As humanoid robot has a human-like structure, a natural and common way of motion generation is using measured human motion. Motion retargeting from recorded human motion to digital characters is a well-studied area in computer animation. Typically a human subject performs actions while wearing easily detected markers on his or her body. The motion of these markers is recorded by cameras placed in the room, and software then infers the 3-D positions of these markers over time. A number of studies have been reported to convert the capture motions to humanoid whole-body motions through learning [67.73] and optimization [67.74, 75]. Figure 67.27 shows an example: the captured motions of a woman performing a Japanese traditional dance [67.76] that the performance in Fig. 67.4 is based on. Kinematic similarity allows using the captured motion as a reference for a humanoid's whole-body motion, by computing the corresponding joint angles from forming virtual links with several markers. However, due to dynamic differences, such as mass distributions and torque generation, captured motions are generally not stable nor feasible when applied to a humanoid. It is therefore necessary to adapt them to humanoid body as explained in Sect. 67.5.2.

Using GUI

Tools such as those used in character animation for computer graphics can also be used to design movements for humanoid robots. If the designer were forced to control each of the many degrees of freedom independently or to takes care of the balance, the process would be tedious and inefficient. One solution that enables non robotics expert to design robot motion is key-pose based approach on GUI, which allows the designer to define the *key-poses* of the desired motion with the help of inverse kinematics of the end effectors. The interface take care of the interpolation and dynamic balance compensation so that the input motion is feasible for the humanoid as explained later in Sect. 67.5.2. Figure 67.28 illustrates the overview of a GUI interface developed as *Choreonoid* for this purpose [67.77, 78].

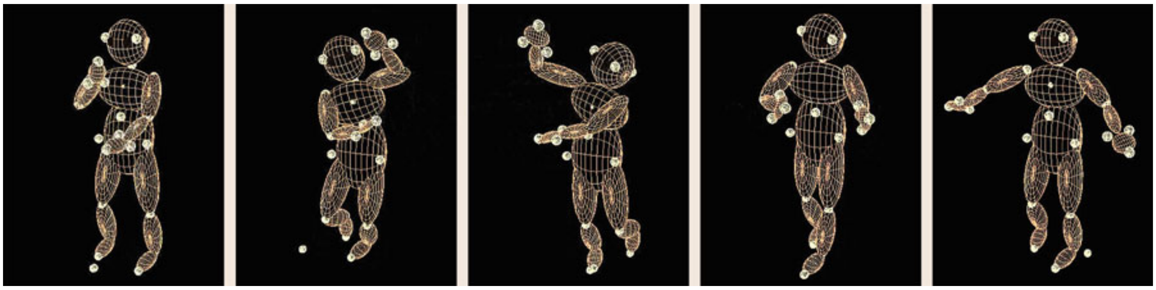


Fig. 67.27 A sequence of captured motion of dancing (after [67.76])

Using Automated Motion Planning

The previous two methods are based on mainly joint angles from a motion capture system or a GUI. If the purpose of the robot motion is going from one configuration to another without collisions and how the humanoid moves does not really matter, automated motion planning can provide efficient solutions (Chaps. 36 and 47).

Fast path-planning techniques such as rapidly-exploring random trees (RRT) can compute basic collision-free postures with static balance [67.79, 80] or walking paths [67.81] automatically with a simplified model. Figure 67.29 illustrates a humanoid carrying an object whose lower body is modeled by a bounding box. Given geometric models of the humanoid and the environment, initial and goal configurations, the planning system automatically searches for a path free of collisions at both upper and lower bodies. This coarse path can be converted into dynamically stable whole-body motion a walking pattern generator including upper-body motion compensation as described in Sect. 67.5.2. For further reading on humanoid motion planning, the readers are referred to a book dedicated to this subject [67.82].

Using Abstract Task Specifications

Tasks for a humanoid to execute are not always specified in the joint space, but often in the workspace. For instance, if the humanoid wants to grasp an object on the table or floor, this task is expressed as the hand position and orientation in Cartesian space [67.83–87]. Another example is teleoperation: it is easier for the operator to guide an operational point, such as the end-effector or the head of the humanoid, rather than to give a whole-body joint configuration [67.88]. These tasks are represented in an abstract way by a smaller number of DOF than the redundant structure of humanoid. Figure 67.30 shows a motion of bimanual manipulation based on abstract representation of motion as a sequence of attractor points acting in the task space [67.89].

On the other hand, other constraints such as balancing or joint limits should also be taken into account to generate a whole-body motion to achieve the task.

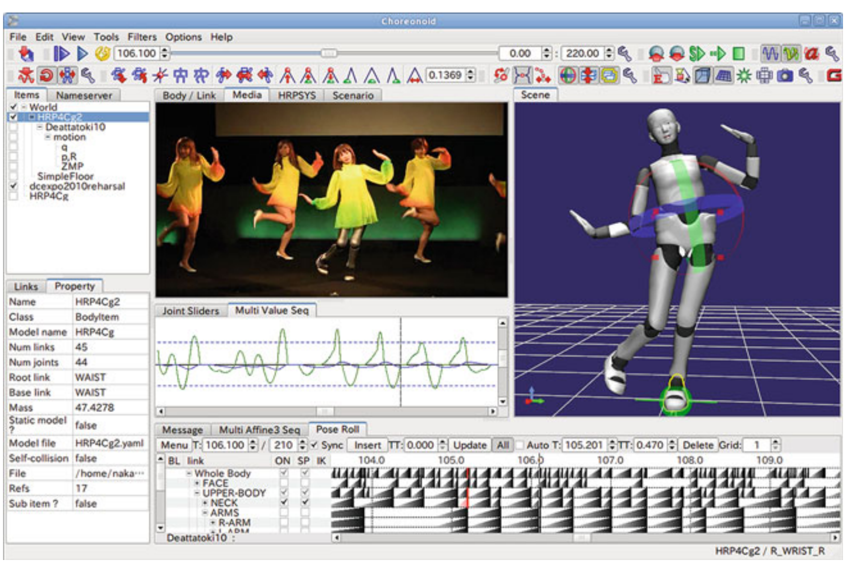


Fig. 67.28 A motion choreography tool working within the Choreonoid framework. In this tool, whole body motions of biped humanoid robots can be created with key-frame editing similar to computer graphics (CG) character animations (after [67.78])

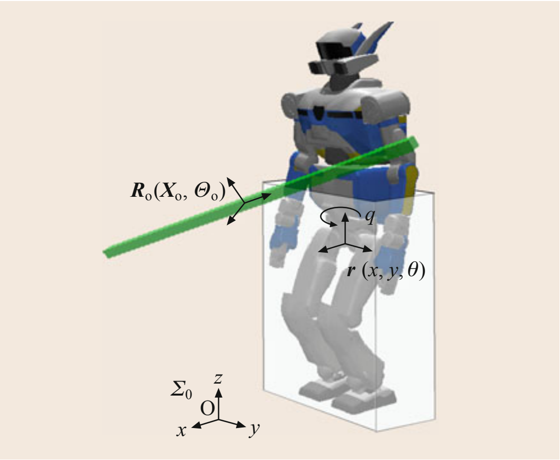


Fig. 67.29 Humanoid modeled by rectangle box with a bar. In the first stage the geometric and kinematic path planner generates collision-free path for the 9-DOF system including robot waist on the plane (3-DOF) and object (6-DOF)

A mechanism is therefore necessary that derives a humanoid positioning as well as a whole-body target posture from the abstract goal specification. Whereas the previously introduced GUI including automatic balancing is useful for cases with large free space, cluttered environments require integration of search techniques to compute a valid whole-body posture from the task [67.90, 91]. Motion generation for multiple tasks and constraints is later discussed in Sect. 67.5.3.

67.5.2 Generating Dynamically Stable Motions

The methods presented in Sect. 67.5.1 can be useful when generating coarse motions for a humanoid robot, such as dance performance, manipulating or walking. However, for some of these methods the motions generated will not take into account the dynamic stability of the robot, and may result in the robot falling over. This subsection presents some approaches for converting coarse motions to dynamically-stable motions, dynamic balancing algorithms and task-balance functional decomposition. In the former approach, all the joints including upper body are involved for whole-body balancing based on the reference motion, like kicking motion that needs upper body motion compensation. The latter uses mainly lower body for balancing or walking while upper body takes care of the desired tasks such as manipulation.

Dynamic Balancing

A framework called autobalancer is one of the pioneering studies for the dynamic whole-body balancing for humanoids. It all joint angles at every sample in time by solving a quadratic programming (QP) optimization problem in order to convert a given motion to a balanced one [67.92]. This method can be effective for a motion in which static balancing is dominant, such as when the humanoid is standing. The autobalancer calculates a whole-body motion first by fixing the center of gravity (COG) on the vertical axis which passes through a point in the support polygon of the humanoid. Then it keeps inertia moments around the COG at acceptable values in order to satisfy the balancing conditions. This technique was combined with a fast sampling-based motion planner to derive a dynamically motion by exploring configurations with balance constraints [67.79].

Resolved momentum control (RMC) [67.93] is a framework for whole-body control based on the linear and angular momentum of the entire robot. The robot is regarded as a single rigid body whose linear and angular momentum is to be controlled. At each point in time, this framework uses least squares to find joint velocities that will achieve the desired linear and angular momentum of the robot. Elements of the momentum can also be left unspecified as free variables, which is often done in practice with elements of the angular momentum. In addition to elements of the momentum, resolved momentum control requires that desired velocities for the feet be specified. This method has been applied to teleoperation [67.88] or stable reaching or kicking motions [67.93]. Other methods like dynamics

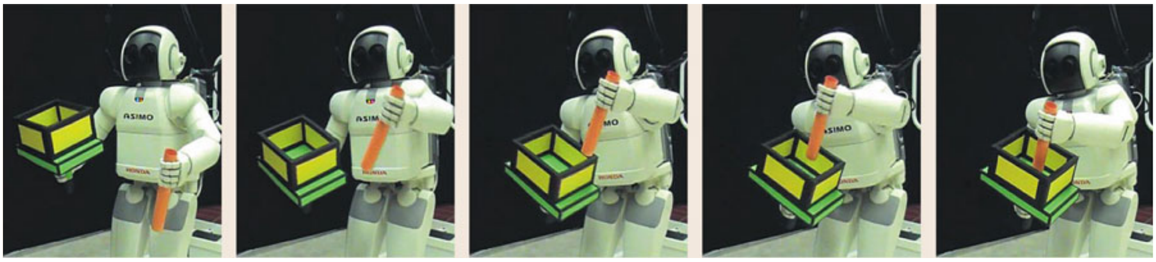


Fig. 67.30 Bimanual manipulation by humanoid robot ASIMO based on a motion representation using attractor dynamics in task space (after [67.89])

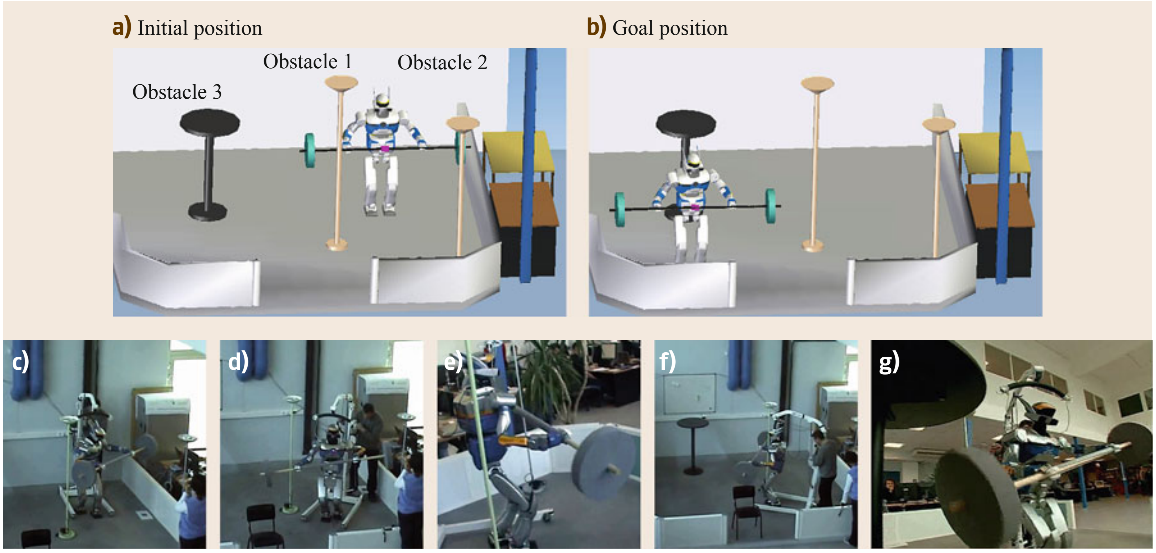


Fig. 67.31a–g A 3-D collision-free motion for bar-carrying task by humanoid robot HRP-2 from starting **(a)** an intial position to final configuration (goal position) **(b)** using whole-body motion (after [67.81]). The robot rotates the bar horizontally to make the bar go through a gap between poles whose distance is shorter than the of the bar **(c–e)**. By making use of the concave part of the carried object **(f)** for 3-D collision avoidance, it arrives at the goal configuration with another avoidance motion **(g)** (VIDEO 594, VIDEO 598)

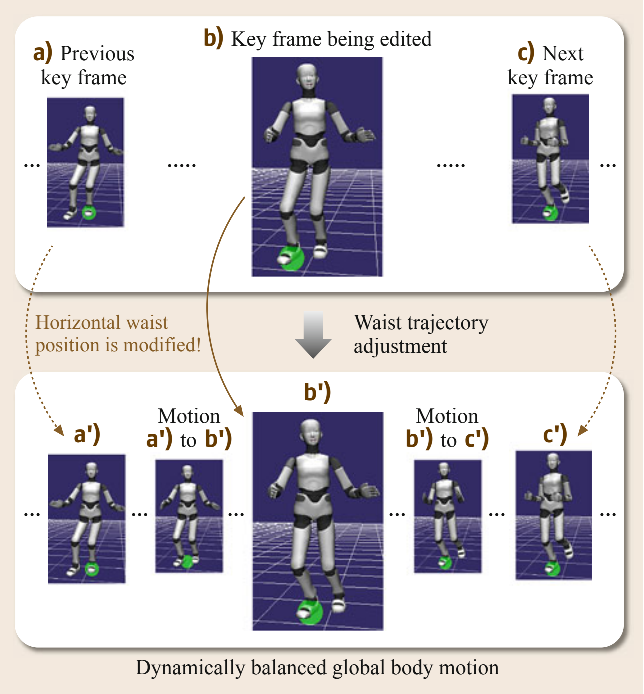


Fig. 67.32 Waist trajectory adjustment, which is automatically processed immediately after every time key poses are modified. As a result, horizontal waist positions of key poses are slightly modified and a dynamically balanced motion is obtained (after [67.77])

filter that makes reference motions dynamically feasible by a humanoid [67.94], upper-body motion compensation for Waseda bipedal humanoid (WABIAN) [67.95] have also been proposed as this type of approach.

Task-Balance Functional Decomposition

In this approach, dynamic stability is maintained during whole-body motion based on pattern generation or a balance compensation by the legs to maintain the ZMP inside the foot support area, while upper body is in charge of specified tasks such motions as manipulation or designed movement.

An iterative two-stage motion planning method has been proposed for a humanoid to perform manipulation and locomotion at the same time [67.81]. At the first stage, the motion planner generates the upper-body motion with a walking path of the bounding box of the lower body as in Fig. 67.29. The second stage overlays the desired upper-body motion on the dynamically stable walking motions generated by a dynamic walking pattern generator based on preview control of ZMP for a linear inverted pendulum model [67.96] (Chap. 48 and Sect. 67.4). This upper-body motion during walking induces errors in resulting ZMP from the reference, which may make the humanoid instable. By applying the preview control again to this ZMP error the necessary compensation motion can be computed as a horizontal offset on the waist position. If the resulting whole-body motion is not collision-free, the planning process goes back to the first stage to reshape and this procedure is repeated until a valid motion is obtained. Figure 67.31, VIDEO 594 and VIDEO 598 show the resulting collision-free manipulation motion of a bar-shaped object in an environment populated with obstacles.

Lower-body motion compensation for dynamic balance is also used for GUI-based motion designing [67.77]. The GUI accepts a sequence of key-poses for the desired motion as the input and interpolates between them to compute the whole-body motion of the humanoid. Since the generated motion is not dynamically stable in general, both the key poses and the interpolated motion are adjusted to be dynamically balanced by applying the waist trajectory adjustment in such a way that the trajectory of the ZMP from body motion is always inside the foot support area. The adjustment only modifies the horizontal waist position of the key poses and the interpolated ones, for the adjusted motion to be as close as the original one (Fig. 67.32). The adjustment is automatically and immediately done every time a user has finished an edit operation so that the user can see the resulting motion.

67.5.3 Generating Whole-Body Motions with Various Tasks

The main purpose of the methods in previous section was to make the given coarse motion dynamically stable. One can think of a case the task is only given in an abstract manner, for instance reaching the end-effector in specified position and orientation in workspace, or aligning a camera axis in a direction. This section takes a step forward in order to generate automatically the motion to achieve the specified tasks by taking into account such constraints as balance, foot positions or joint limits at the same time. Generalized inverse kinematics technique with task priority and its extension is utilized as a key tool for local whole-body motion generation (Chap. 10).

The main particularities of humanoid robot from the viewpoint of inverse kinematics are the following: necessity of dynamic balancing, changing fixed root joint and floating base frame. Those issues should be dealt with appropriately depending on the task of the robot. Some extensions for more complex tasks including inequality constraints, footstep planning and dynamics are also mentioned at the last part of this section.

Dynamic Balancing and Walking

Some examples are shown the whole-body motion generation based on task priority generalized inverse kinematics. As shown in Chap. 10, this framework accomplishes first the task with the highest priority and then tries to achieve those with lower priority at the best in the null space of the higher-priority tasks.

Tasks are specified locally as a velocity in workspace, such as hand velocity to reach the target. The balance constraint can therefore be expressed as the velocity of the center of mass (COM). The ZMP-based pattern generator has the advantage that it outputs the velocity of the COM of dynamically stable walking motion from the reference ZMP trajectory, which can be easily integrated into this inverse kinematics framework by using COM Jacobian [67.97]. Figure 67.33 shows the whole-body reaching motion including a step to take a ball localized by a vision system [67.85]. The high priority is assigned to COM and foot motion to avoid falling in this example. As can be seen, the legs are used not only for stepping but also bending to reach a lower position in a manner coordinated with the upper body. The left arm moves backwards as the result of balancing task. Whole-body motions for manipulation of daily-life tools [67.84] or object pushing/lifting [67.98–100], and also for self-collision avoidance [67.101] have been implemented also based on a similar framework.

Another example is given in Fig. 67.34, VIDEO 595 and VIDEO 599 where the humanoid

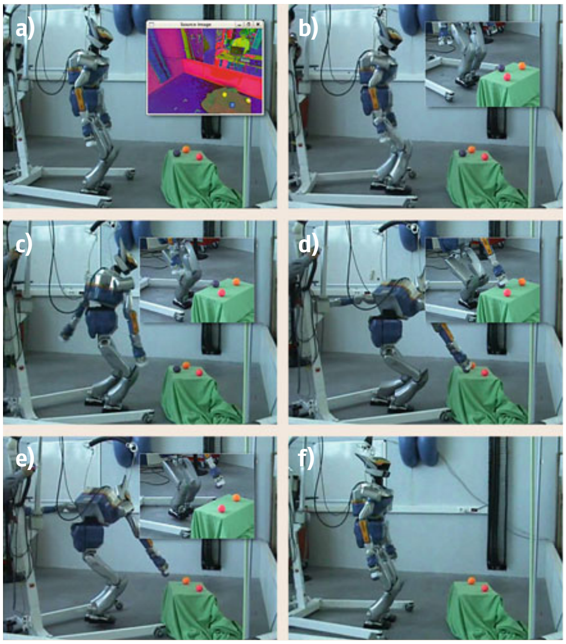


Fig. 67.33 (a–f) A whole-body grasping motion generated through task-priority generalized inverse kinematics (after [67.85]). Upper and lower bodies coordinate to achieve the desired grasping task while making a step and maintaining the balance

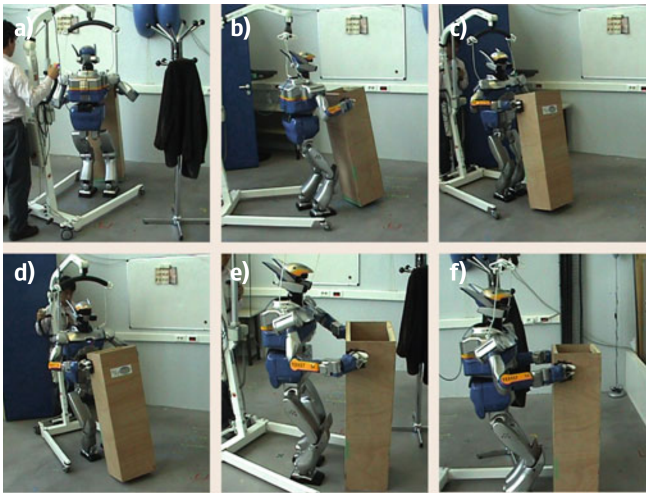


Fig.67.34a–f Experiments of whole-body *pivoting* manipulation. Starting from the initial position **(a)** with obstacle at right-hand side, the humanoid robot manipulates the object backwards away from the wall **(b)**. After switching motion direction to forward **(c)**, the robot continues to manipulate the object to the goal position by avoiding the obstacle (the hanger) **(d–f)** (VIDEO 595, VIDEO 599)

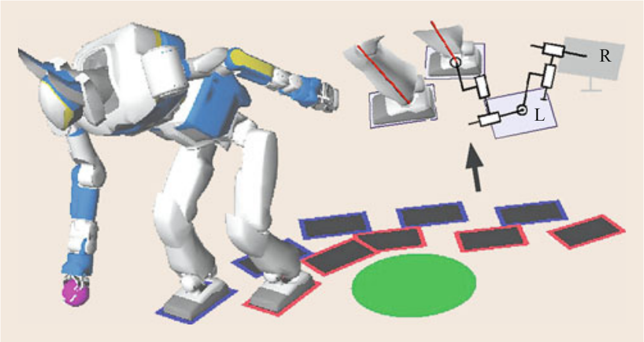


Fig. 67.35 Footstep planning modeled as a whole-body inverse kinematic problem (after [67.102]) (VIDEO 596, VIDEO 600)

execute *pivoting* manipulation to carry a bulky object without lifting [67.86]. In this case, a coarse path of the object towards its goal position is fist planned to compute the trajectory of the hands that perform the manipulation. Then foot positions are determined along the object path, from which the COM trajectory is derived using the dynamic walking pattern generator. Those tasks are provided to the inverse kinematics to generate the coordinated arm and leg motion for this complex manipulation. In addition to the dynamic balance, the change of the root joint is also considered to compute the whole-body motion when the support leg changes during walking. The same framework has been applied to a motion for catching a moving object during walking where the task of visual tracking by the end-effector is integrated with dynamic walking motion [67.103].

Floating base frame of a humanoid sometimes brings difficulties in determining the whole-body configuration from a specific abstract task specified in workspace. In the methods mentioned above, the goal configuration is derived as a result of repeated computation of local generalized inverse kinematics. However, there are often cases where goal whole-body configurations is first needed to be used popular motion planning techniques searching in configuration space such as sampling-based planning. Some methods that derive the goal configuration based on inverse kinematics can be useful for this purpose [67.90, 91, 104] or a precomputed reachability map that characterizes the capacity of reaching in discretized workspace around the robot [67.105, 106].

Extensions for Complex Tasks

The whole-body motion generation with tasks can be extended to cope with more complex tasks such as stepping and those expressed as inequality or dynamic constraints.

One extension particular to humanoid is incorporating stepping in the framework of whole-body generalized inverse kinematics. *Kanoun* et al. [67.102] introduced an augmented robot structure by introducing *virtual* planar links attached to a foot that represents footsteps as illustrated in Fig. 67.35, VIDEO 596 and VIDEO 600. This modeling makes it possible to solve the footstep planning as a problem of inverse kinematics, and also to determine the final whole-body configuration. After planning the footsteps, the dynamically stable whole-body motion including walking can be computed by using the method presented earlier.

Task-priority generalized inverse kinematics for redundant robots in Sect. 10.3 usually models tasks as equalities so that the operational points can achieve the desired velocity. However, tasks are sometimes given as inequalities: keeping the hand out of some area to avoid collisions or robot view obstruction, respecting joint limits, or maintaining the COM inside the foot support area. Inequality tasks have usually been transformed into more restrictive equality constraints through potential fields. A method for extending the task-priority inverse kinematics for those inequality tasks is proposed to remove this limitation based on a sequence of QP optimization [67.87]. This method searches for the optimal sets for the sequence of QPs by minimizing the error to the desired equality tasks in such a way that inequality ones can also be satisfied at a desired priority. This method allows the humanoid to perform such

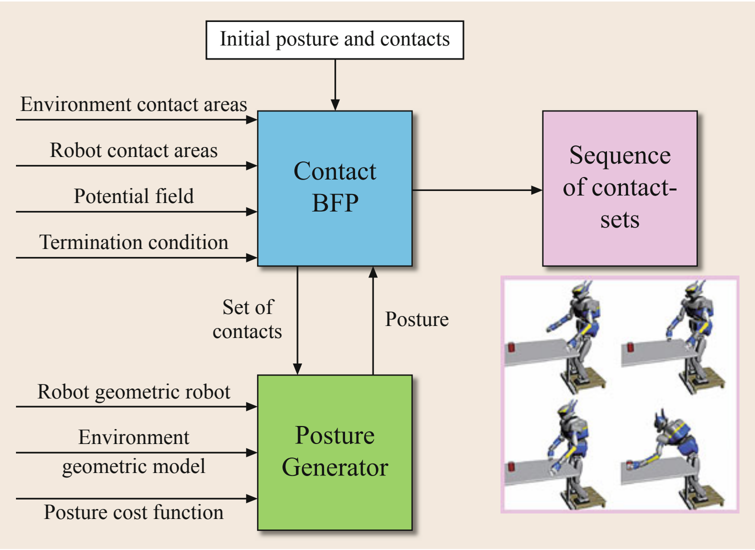


Fig. 67.36 Framework of contact motion planner composed of contact best-first-planner (BFP) and posture generator (after [67.107])

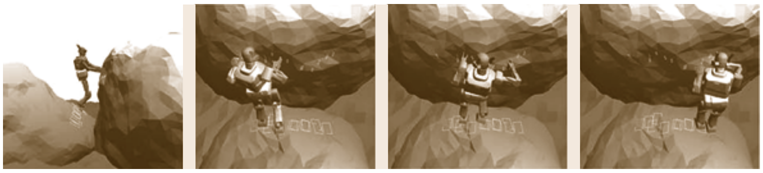


Fig. 67.37 A sequence of planned whole-body motion including multiple contacts on a irregular terrain (after [67.108])

a task of reaching its arm towards an object on the floor without obstructing its view.

This approach based on cascaded QP can be generalized to generate whole-body motions including dynamic equality and inequality tasks [67.109]. In addition to inverse kinematics considered so far, inverse dynamics is also integrated to the task-priority whole-body motion generation framework. By using this method, the dynamic balance can be addressed directly without converting the dynamic ZMP constraint into COM velocity via a pattern generator. This approach assumes a torque-controlled humanoid as opposed to position controlled ones that are often the case for platform currently used. However, dynamic whole-body motion generation with various tasks is being actively studied owing to not only recent progress of robot hardware [67.110] but also increasing interests on more complex tasks including multiple contacts presented in the next section.

67.5.4 Generating Motions Including Multiple Contacts

The whole-body motions presented so far basically supposes only the contacts between the humanoid's feet and the floor. Looking at our daily life however, contacts other than with feet occurs often, for example pass through narrow spaces or to support the body when reaching a distant place on the desk. Since a humanoid is high affinity to environments designed for humans, its application fields could be expanded by exploiting the contacts as much as possible rather than by avoiding them as is often the case in motion planning. This section addresses planning and control of whole-body motions with multiple contacts that have been intensively studied in recent years. The role of planner is to derive a global sequence of configuration with multiple contacts to reach the goal, whereas the controller generates dynamically stable motions to transit from one contact state to another.

Motion Planning for Multiple Contacts

Multicontact nongaited have been proposed that are applicable to legged robots including humanoids [67.107, 108, 112]. By defining a stance as a finite set of contacts between the robot and the environment, the planner generates a sequence of stances that can reach the goal. During the planning, possible transitions from a stance are explored by sampling another stance with a feasible and stable robot configuration, as shown in Fig. 67.36 [67.107]. Figure 67.37 shows a resultant locomotion planned using this planning method [67.108]. A more generalized framework is proposed to deal with multirobot and multiobject systems [67.113]. This

Fig. 67.38 Dynamic multicontact motion generated through global trajectory optimization (after [67.111], VIDEO 597)

generalization allows for a common description and treatment of locomotion and manipulation problems, either for a single robot or for multiple collaborating robots.

The output of the planner is a sequence of statically stable contact stances that can be executed through quasi-static motions. In order to generate fast but dynamically stable motions, a global optimization approach has been proposed [67.111]. This method parameterizes joint trajectory by B-Spline function to convert the infinite trajectory problem to semi-infinite one so that optimization technique can be applied. The whole-body motion is generated through nonlinear optimization to minimize square torque and execution time, by taking into account such constraints as joint torque limits and dynamic multiple contact stability. As a result, the generated motion is much faster than quasi-static ones. An example of resultant motion is shown in Fig. 67.38 and VIDEO 597. Trajectory optimization approach can also be applied for lifting of a very heavy object by generating a weight-lifting motion by always respecting physical constraints [67.114].

Even though the feasibility of multicontact motions like in Fig. 67.38 have been validated with experiments, the optimization process is time-consuming and cannot cope with errors or disturbances during execution. It is therefore necessary to build a controller that ensures execution of multicontact whole-body motions.

Stability Measure for Motion with Multiple Contacts

Before discussing controller, it is worth mentioning first dynamic stability measure for non coplanar contacts and its usage. Although the ZMP is well-known dynamic stability criteria, it can only be applied to contacts on a flat plane. Stability margin for mobile robots [67.118] is only applicable for static gait for legged robots. A generalized version of ZMP (GZMP) has therefore been proposed [67.119] by extending the ZMP by considering interaction forces other than floor-feet contacts. The stable region for multiple contacts can be obtained by considering the infinitesimal displacement and the moment about the edges of the convex hull of the supporting points. *Hirukawa* et al. proposed another criterion called contact wrench sum (CWS), which is the sum of the gravity and the inertia wrench applied to the COG of the robot. The humanoid is stable if it is inside the polyhedral convex cone of the contact wrench between the feet of a robot and its environment [67.115, 120]. Based on this criterion, walking

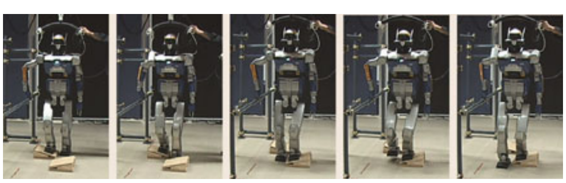


Fig. 67.39 Walking on a rough terrain using a support of arm on a handrail (after [67.115])

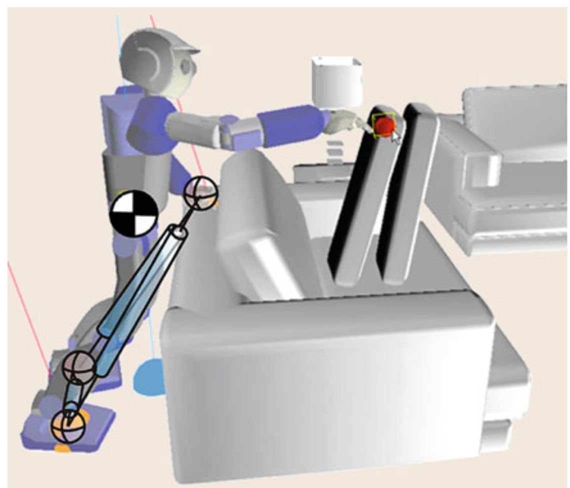


Fig. 67.40 Real-time simulation of a multicontact behavior with user-enabled interactive control of the robot's right hand. A virtual linkage model is overlaid capturing the internal force behaviors acting between supporting bodies (after [67.116])

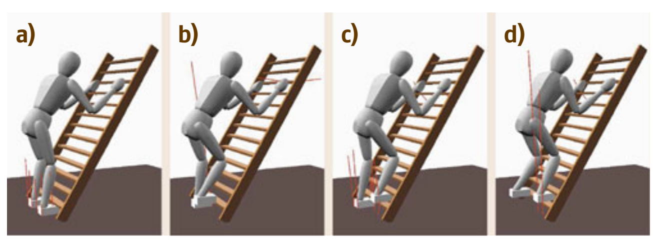


Fig.67.41a–d A digital figure climing a ladder by using whole-body controller with task priority with multiple contacts (after [67.117])

Fig. 67.42 Snapshots from multicontact planning and control of HRP-2 ingress in a car (after [67.121]). From the initial posture, supported on the steering handle and the seat by an arm, the robot finally succeeds in entering the car

on a rough terrain by supporting a handrail has been performed (Fig. 67.39).

Controlling Whole-Body with Multiple Contacts

The execution of the multicontact motions presented earlier by a humanoid requires the control based on sensor feedback to absorb unexpected disturbance or modeling errors.

Khatib et al. extended their framework of operational space approach that enables a humanoid robot to perform motions that simultaneously meet prioritized objectives in existence of multiple contacts [67.116, 117]. A torque-based approach for the control of internal forces is suggested and integrated into the framework for whole-body prioritized multitasking, thus enabling the unified control of COM maneuvers, operational tasks, and internal-force behavior (Fig. 67.40). Figure 67.41 shows an example of multicontact behavior on a real-time simulator. *Hyon* et al. proposed another approach of passivity-based controller that can adapt to unknown external forces applied to arbitrary contact points without sensing the contact forces by using a torque-controlled robot [67.122].

Another real-time controller based on linear QP optimization has been proposed for whole-body motion with multiple contacts [67.121, 123]. The motion is constrained by the free-floating whole-body dynamics of the humanoid robot without using a reduced model such as inverted pendulum since the motions we aim at are more general than bipedal walking. The optimization process also incorporates such constraints as nonsliding condition, actuation torque limits, contact forces within friction cones, and avoidance of undesirable self-collisions and collisions with the environment. Taking a target contact stance and also necessary sensory information as its input, the controller can compute feedback control commands to execute the whole-body motion with multiple contacts in real time, on less than 100 Hz control loop. Figure 67.42 shows a simulation result of complex motion of a humanoid entering into a car based on the control method.

67.6 Morphological Communication

Humans evaluate each others' state through body posture and movement. It is quite natural to extend this form of communication to include robots that share our morphology.

67.6.1 Expressive Morphology and Behavior

Humanoids can communicate with people through expressive morphology and behavior. As with people, humanoid robots integrate communicative and noncommunicative functionality. For example, the arms and hands of a robot can reach and grasp, but also point and gesture. Heads for humanoid robots are an especially important example of these overlapping roles, and have had an important impact on humanoid robotics and robotics in general [67.124].

The head of a humanoid robot has two main functions:

- To orient directional sensors as needed for the purposes of perception, while leaving the main body free to meet other constraints such as maintaining balance and gait. Cameras and sometimes microphones are usefully oriented in this way.
- To strike expressive poses, along with the rest of the body. Even if a robot head is not intended to be expressive, it will be interpreted as being so by humans – particularly as a cue to the robot's presumed locus of visual attention. It is also possible to deliberately engineer an approximate *face* that can be an important line of communication with humans (Chap. 72).

Locus of Attention

Eyes can be one of the most expressive components of a humanoid robot. For humans, eye movements are both expressive and important for sensing. Humanoid robots have the option to factor these two roles by moving eyes that are only for display, and using sensors placed elsewhere. Most humanoid robots, however, use head-mounted servoed cameras that play both expressive and sensory roles. These mechanisms exhibit different degrees of biological realism, for example, the Kismet head captured many of the expressive components of human eye movements, while having a nonhuman-like camera arrangement that simplified some forms of perception (Fig. 67.43).

Many humanoid robots use biologically inspired, foveated vision systems, which provide a wide field of view with low detail, combined with a narrow field of view with high detail (Fig. 67.44). With appropriate control strategies to fixate the narrow field of view on task-salient regions detected in the wide field of view, these robots achieve a practical compromise between resolution and field of view. Additionally, the configuration of the eyes communicates the robot's locus of attention in an intuitive way. Many systems use four cameras, with a narrow- and wide-angle camera for each of the robot's eyes, but some researchers have also used special-purpose space-variant cameras modeled after the space-variant receptor densities in the human eye [67.125].

The eye movements of some humanoids are modeled explicitly after human eye movements. An example of a model of this kind is shown in Fig. 67.45. These

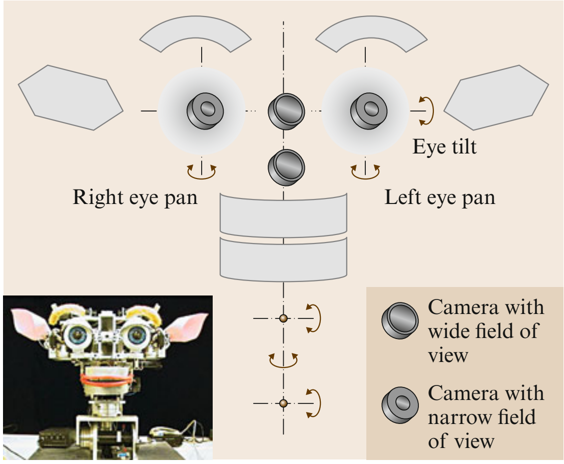


Fig. 67.43 On Kismet, foveal vision was implemented using cameras in the eyes, and peripheral vision used unobtrusive cameras on the head (after [67.124]). This achieved good expression of locus of attention, while simplifying the process of differentiating egomotion from motion of objects (since the head moved less frequently and more slowly than the eyes). This is an example of a partial decoupling of expressive and functional concerns, showing that many different levels of humanoid *fidelity* are possible

bio-inspired approaches to active vision typically have four types of visual behavior:

Saccades. These are high-velocity movements to fixate a new target or *catch up* with a fast-moving target. From a control point of view, these movements are *ballistic* (at least in humans) – once initiated, they continue without responding to changing stimuli.

Smooth Pursuit. These are movements to continuously track a moving target. They apply at low velocities. These movements respond constantly to visual feedback about the target's location. A fast-moving target may also trigger small saccades.

VOR and OKR. The vestibulo-ocular reflex and optokinetic response work to stabilize the direction of gaze in the presence of movement of the head and body, using inertial and visual information respectively.

Vergence. This movement drives the relative angle of the two eyes so that the same target is centered in both. This only applies to two-eyed systems that have this freedom of motion. For conventional stereo algorithms,

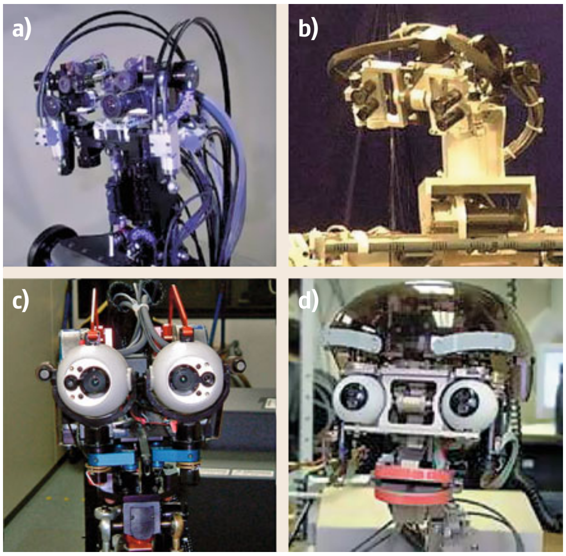


Fig. 67.44a–d The heads of humanoid robots come in many forms. A popular arrangement is to have two cameras per *eye*, as a crude approximation of foveal and peripheral vision in humans. **(a)** Biomimetic oculomotor control investigated on DB (after [67.126]). **(b)** Cog's head (after [67.127]). **(c)** The double-camera arrangement can be arranged in a less-double-barreled appearance (after [67.128]; see *Ude* et al. [67.128] for more examples and an analysis) ATR; Humanoid head developed by ATR and SARCOS. **(d)** The Infanoid robot (after [67.129])

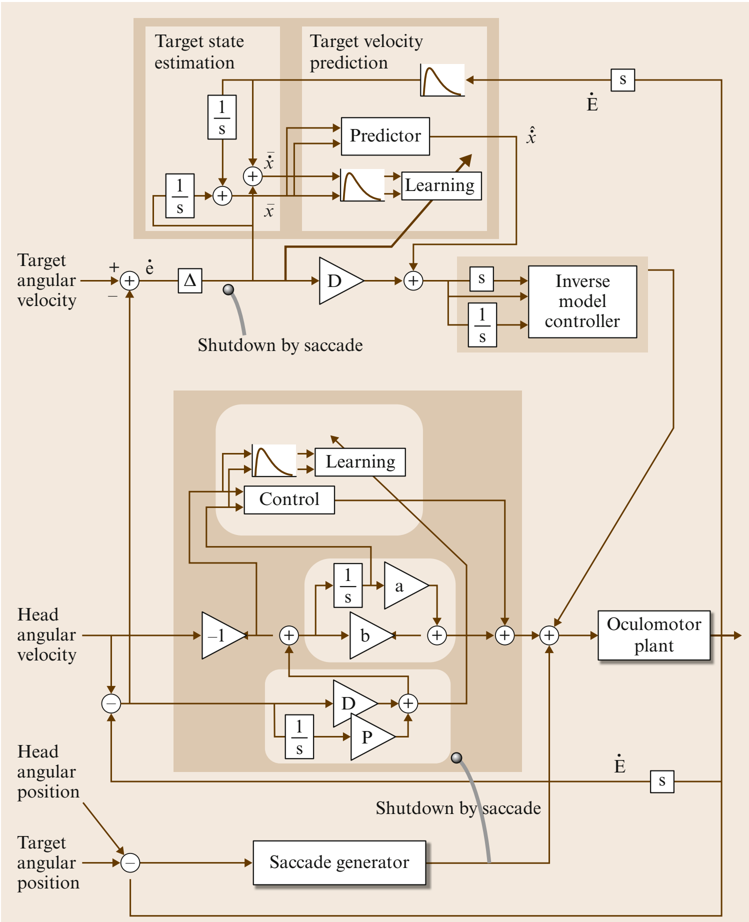


Fig. 67.45 A biomimetic control model (after [67.130]), that integrates saccading, smooth pursuit, the vestibular-ocular reflex (VOR), and the optokinetic response (OKR). Smooth pursuit and VOR/OKR commands are summed, with periodic corrections to errors in position made by saccades

vergence is a disadvantage, since the algorithms are simplest when the cameras remain parallel. Other algorithms are possible, but it is currently quite common not to use vergence.

67.6.2 Interpreting Human Expression

The interpretation of human expression is essential for many forms of natural human communication that could be valuable for humanoid robots.

Posture and Expression

The recognition and interpretation of the location and pose of humans is important, since humanoids are often expected to work in human environments. Algorithms for the following functions have been incorporated in various humanoids:

- Person finding
- Person identification
- Gesture recognition
- Face pose estimation.

ASIMO has used these functions to perform a prototypical reception task as shown in Fig. 67.46. The robot can find and identify a person, then recognize gestures such as *bye-bye*, *come here*, and *stop*, which are utilized for performing reception tasks. In general, such func-

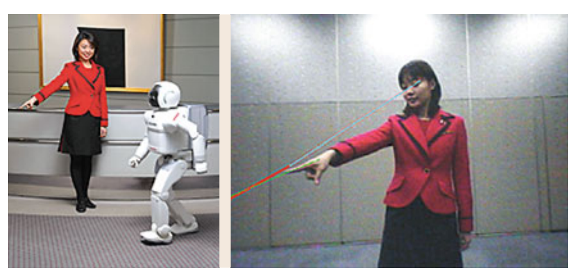


Fig. 67.46 ASIMO recognizing a pointing gesture during a reception task

tions on a humanoid are not yet robust, and are active areas of research.

Speech Recognition

Speech is a natural, hands-free mode of communication between humans, and potentially between robots and humans. Speech recognition is a popular interface utilized for commanding a humanoid, and many off-the-shelf packages are now available. However the use of microphones embedded in the robot is problematic, because general-purpose speech recognition software is usually optimized for utterances captured by a microphone that is close to the speaker. In order to achieve sufficient recognition performance in natural interaction situations between a humanoid and a human new methods for speech recognition are being investigated. These methods compensate for sources of noise, such as the robot's motors and air flow in the environment, by using multiple microphones and multimodal cues [67.131]. However, at the time of writing researchers often circumvent these issues by using a headset, lavalier, or handheld microphones.

Auditory Scene Analysis

In order to attain more-sophisticated human–robot interaction, researchers have been developing methods for computational auditory scene analysis on a humanoid robot. The objective of this research is to understand an arbitrary sound mixture including nonspeech sounds and voiced speech, obtained by microphones embedded in the robot. Beyond speech recognition, this also involves sound-source separation and localization.

As for sound recognition, sound categories such as *coughing*, *laughing*, *beating by hand*, *adult's voice*, and *child's voice* have been shown to be recognizable using maximum-likelihood estimation with Gaussian mixture models. This function has been utilized during interactions between the HRP-2 and a human [67.132].

Multimodal Perception

Sound-source separation can be achieved by beam forming. In order to perform beamforming effectively, sound-source localization is essential. Vision can be utilized for finding the talker within the field of view. *Hara* et al. used a camera and an eight-channel microphone array embedded in the head of HRP-2, and succeeded in speech recognition in the presence of multiple sound sources by using sound source separation [67.133]. Figure 67.47 shows a scenario in which speech recognition is taking place with television (TV) sound playing in the background.

When integrated with speech recognition, vision can also help resolve the ambiguities of speech. For instance, the ambiguity of demonstrative pronouns such as *this* or *that* can sometimes be resolved by recognizing pointing gestures. Similarly, the face and gaze direction can be used to realize communication via eye contact, so that the humanoid only replies when a human is looking at it and talking to it [67.132]. Multimodal interaction with these functions has also been demonstrated by HRP-2, as shown in Fig. 67.48.

67.6.3 Physical Interaction and Developmental Robotics

Humanoid robots typically use methods for perception and interaction that are established in fields such as computer vision and dialogue systems. There is also an emerging research field called developmental robotics or epigenetic robotics in which human-like perception and interaction abilities are obtained through physical interaction with the real environments including humans [67.134–136]. In developmental robotics, researchers aim at studying the developmental mechanisms, architectures and constraints that allow life-long and open-ended learning of new skills and new knowledge in embodied machines. Much of the research in this field utilizes humanoid robots, such as the iCub shown in Fig. 67.36. As in human children, learning is expected to be cumulative and of progressively in-

Fig. 67.47 HRP-2 recognizing speech with background noises (TV sound)

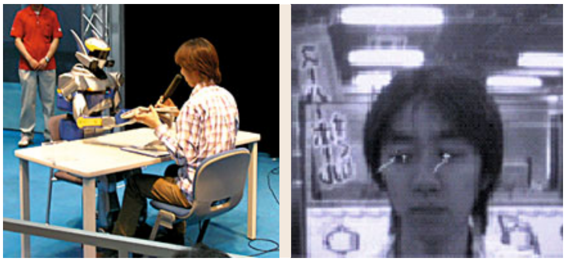


Fig. 67.48 HRP-2 recognizing face and gaze direction for communication via eye contact

creasing complexity, and to result from self-exploration of the world in combination with social interaction. The typical methodological approach consists in starting from theories of human development elaborated in fields such as developmental psychology, cognitive science, neuroscience, developmental and evolutionary biology, and linguistics, then to formalize and implement them in robots. The experimentation of those models in robots allows researchers to confront them with reality, and as a consequence developmental robotics also provides feedback and novel hypothesis on theories of human development.

67.7 Conclusions and Further Reading

Because of the integrative nature of humanoid robotics, this chapter has avoided details and formalisms and liberally cross-referenced other chapters within the handbook that can provide the reader with deeper coverage of many of the areas of robotics on which humanoid robots depend. Additionally, this chapter references work within the humanoid robotics community and related communities.

Humanoid robotics is an enormous endeavor. The emulation of human-level abilities in a human-like robot serves as a grand challenge for robotics, with significant cultural ramifications. The motivations for humanoid robotics are as deep as they are diverse. From the earliest cave drawings, humanity has sought to represent itself. Robotics is one of the most recent mediums for this ongoing fascination. Besides this deep societal motivation, humanoid robots offer unique opportunities for human–robot interaction, and integration into human-centric settings.

Over the last decade, the number of humanoid robots developed for research has grown dramatically, as has the research community. Humanoid robots have already gained a foothold in the marketplace as robots for entertainment and research (e.g., the Robo-One competition and the NAO from Aldebaran). Given the special properties of humanoid robots, they seem likely to further increase in number as their capabilities improve and their costs go down. Robots with human characteristics, and technologies related to humanoid robotics, also appear destined to proliferate. Will human-scale, legged robots with human form become commonplace, as so often imagined by science fiction? Only time will tell.

Video-References

VIDEO 594 3-D collision-free motion combining locomotion and manipulation by humanoid robot HRP-2
available from http://handbookofrobotics.org/view-chapter/67/videodetails/594

VIDEO 595 Whole-body pivoting manipulation
available from http://handbookofrobotics.org/view-chapter/67/videodetails/595

VIDEO 596 Footstep planning modeled as a whole-body inverse kinematic problem
available from http://handbookofrobotics.org/view-chapter/67/videodetails/596

VIDEO 597 Dynamic multicontact motion
available from http://handbookofrobotics.org/view-chapter/67/videodetails/597

VIDEO 598 3-D collision-free motion combining locomotion and manipulation by humanoid robot HRP-2 (experiment)
available from http://handbookofrobotics.org/view-chapter/67/videodetails/598

VIDEO 599 Regrasp planning for pivoting manipulation by a humanoid robot
available from http://handbookofrobotics.org/view-chapter/67/videodetails/599

VIDEO 600 Footstep planning modeled as a whole-body inverse kinematic problem (experiment)
available from http://handbookofrobotics.org/view-chapter/67/videodetails/600

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