56. Humanoids

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Humanoid robots selectively emulate 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, humanoid manipulation, 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.

56.1 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 (see Chap. 60, *Biologically Inspired Robots*). 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, humanoid robots have been developed as general-purpose mechanical workers, as entertainers, and as test-beds for theories from neuroscience and experimental psychology [56.1–3].

56.1.1 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. When automating a task that people perform, it is natural to consider the physical and intellectual mechanisms that enable a person to perform the task. 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 (see Chap. 54, *Domestic Robots*). For example, dishwashing machines bear little similarity to the manual dishwashing they replace.

56.1.2 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 [56.4]. Moreover, people are highly attuned to human characteristics, such as the sound of human voices and the appearance of human faces and body motion [56.5–7]. Infants show preferences for these types of stimuli at a very 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 narcissism 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 [56.8].

Popular works of fiction have frequently included influential portrayals of humanoid robots and manmade humanoid creatures. For example, Karel Čapek's science fiction play Rossum's Universal Robots (R.U.R.) is centered around the story of artificial people created in a factory [56.9]. This play from 1920 is widely believed to have popularized the term robot. Many other works have included explicit representations of humanoid robots, such as the robot Maria in Fritz Lang's 1927 film *Metropolis* [56.10], and the thoughtful portrayal of humanoid robotics by Isaac Asimov in works such as *The Caves of Steel* from 1954 [56.11]. 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.

56.1.3 Understanding Intelligence

Many researchers in the humanoid robotics community see humanoid robots as a tool with which to better understand humans [56.3,12]. Humanoid robots offer an avenue to test understanding through construction (*synthesis*), and thereby complement the careful *analysis* provided by researchers in disciplines such as cognitive science.

Researchers have sought to better emulate human intelligence using humanoid robotics [56.13]. Scientists, developmental psychologists, and linguists have found strong links between the human body and human cognition [56.14]. 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 [56.15]. Some of these researchers use humanoid robots that can physically explore the world in a manner similar to humans [56.16].

56.1.4 Interfacing with the Human World

Environments built for humans have been designed to accommodate human form and behavior [56.17,18]. 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 [56.19]. For example, humanoid robots and people could potentially collaborate with one another in the same space using the same

Fig. 56.1 The humanoid robot HRP-1S driving a backhoe (Courtesy of Kawasaki Heavy Industries, Tokyu Construction and 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

tools [56.20]. 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. 56.1 [56.21].

Mobility serves as another example. It is very difficult to create a tall wheeled robot with a small footprint that is capable of traversing stairs and moving over rough terrain. Robots with legs and human-like behavior could potentially traverse the same environments that humans traverse, such as the industrial plant shown in Fig. 56.2, which has stairs and handrails designed for human use [56.23]. In addition to mobility advantages, legs have the potential to help in other ways. For example, legs could enable a humanoid robot to

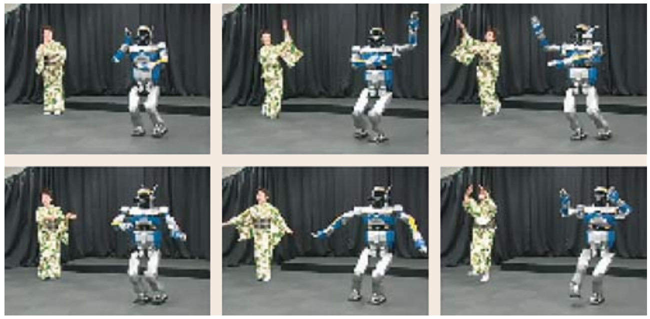

Fig. 56.3 The humanoid robot HRP-2 dancing with a human [56.22]. The human is a master of a traditional Japanese dance whose dancing was recorded by a motion-capture system, and transformed for use by the robot

change its posture in order to lean into something, pull with the weight of its body, or crawl under an obstacle [56.24, 25].

56.1.5 Interfacing with People

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. 58, *Social Robots that Interact with People*). 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 communications channels that already exist between people.

Similarly, people already have the ability to perform many desirable tasks. This task knowledge may

Fig. 56.2 HRP-1 operating in a mockup of an industrial plant (Courtesy of Mitsubishi Heavy Industries)

Fig. 56.4 Actroid (Courtesy of Kokoro), an android designed for entertainment, telepresence, and media roles

be more readily transferred to humanoid robots than to a robot with a drastically different body. This is especially true of cultural actions centered around the human form (Fig. 56.3).

56.1.6 Entertainment, Culture, and Surrogates

Humanoid robots are inherently appropriate for some applications. For example, many potential forms of entertainment, such as theater, theme parks, and adult companionship, would rely on a robot that closely resembles a human, see Fig. 56.4. For a humanoid robot to be an improvement over a wax figure or an animatronic historical character, it must be realistic in form and function.

People may one day wish to have robots that can 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 person. Along these lines, robotic prosthetics have a close relationship to humanoid robotics, since they seek to directly replace parts of the human body in form and function (Chap. 53, *Health Care and Rehabilitation Robotics*).

56.2 History and Overview

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 [56.27], Leonardo da Vinci designed a humanoid automaton in the late 15th century [56.28], and in Japan there is a tradition of creating mechanical dolls called Karakuri ningyo that dates back to at least the 18th century [56.29]. In the 20th century, animatronics became an attraction at theme parks. For example, in 1967 Disneyland opened its Pirate's of the Caribbean ride [56.30], 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 environment.

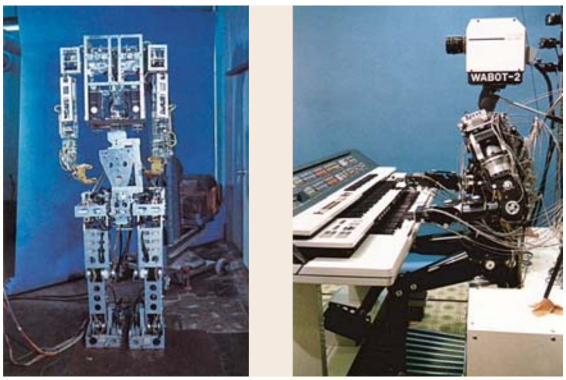

Fig. 56.5 WABOT-1 (1973) and WABOT-2 (1984) (Courtesy of Humanoid Robotics Institute, Waseda University)

Fig. 56.6 Honda P2 (180 cm tall, 210 kg), P3 (160 cm, 130 kg), and Asimo (120 cm, 43 kg) [56.26]. (Images courtesy of Honda)

In the second half of the 20th century, advances in digital computing enabled researchers to incorporate significant computation into their robots for sensing, 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 WABOT-1, developed by Ichiro Kato et al. at Waseda University in Japan in 1973 (Fig. 56.5).

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. 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 performance (see Fig. 56.6). 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* [56.13]. This project gave rise to an upper-body humanoid robot whose design was heavily inspired by the biological and cognitive sciences. Since the inception of the Cog project, many humanoid robotics projects with similar objectives have been initiated, and communities focused on developmental robotics, autonomous mental development (AMD [56.31]), and epigenetic robotics have emerged [56.32].

As of the early 21st century, many companies and academic researchers have become involved with humanoid robots, and there are numerous humanoid robots across the world with distinctive features.

56.2.1 Different Forms

Today, humanoid robots come in a variety of shapes and sizes that emulate different aspects of human form and behavior (Fig. 56.7). As discussed, the motivations that have driven the development of humanoid robots vary widely. These diverse motivations have lead to a variety of humanoid robots that selectively emphasize some human characteristics, while deviating from others.

Fig. 56.7 Kismet is an example of a humanoid head for social interaction

Fig. 56.8 The NASA Robonaut consists of an upper body placed on a wheeled mobile base

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 (see, for example, Fig. 56.8), and still others have an articulate and expressive face with arms, legs, and a torso. Clearly, this variation in form impacts the ways in which the robot can be used, especially in terms of mobility, manipulation, whole-body activities, and human–robot interaction.

56.2.2 Different Degrees of Freedom

Humanoid robots also tend to emulate some degrees of freedom in the human body, while ignoring others. Humanoid robots focusing on facial expressivity often incorporate actuated degrees of freedom in the face to generate facial expressions akin to those that humans can generate with their facial muscles. Likewise, the upper body of humanoid robots usually includes two arms, each with a one-degree-of-freedom (one-DOF) rotary joint at the elbow and a three-DOF rotary joint for the shoulder, but rarely attempt to emulate the human shoulder's ability to translate or the flexibility of the human spine [56.33, 34].

In general, humanoid robots tend to have a large number of degrees of freedom and a kinematic structure that may not be amenable to closed-form analysis due to redundancy and the lack of a closed-form inverse. This is in contrast to traditional industrial manipulators that are often engineered to have minimal redundancy (six DOFs) and more easily analyzed kinematic structures.

56.2.3 Different Sensors

Humanoid robots have made use of a variety of sensors including cameras, laser range finders, microphone arrays, lavalier microphones, and pressure sensors. Some researchers choose to emulate human sensing by selecting sensors with 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. 56.6, this is perhaps most evident in the use of cameras. Two to four cameras are often mounted within the head of a humanoid robot with a configuration 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 will 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 important 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.

56.2.4 Other Dimensions of Variation

Other significant forms of variation include the size of the robot, the method of actuation, the extent to which the robot attempts to appear like a human, and the activities the robot performs.

56.3 Locomotion

Bipedal walking is a key research topic in humanoid robotics (see also Chap. 16, *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.

56.3.1 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 [56.35]. As discussed in detail in Chap. 16, con-

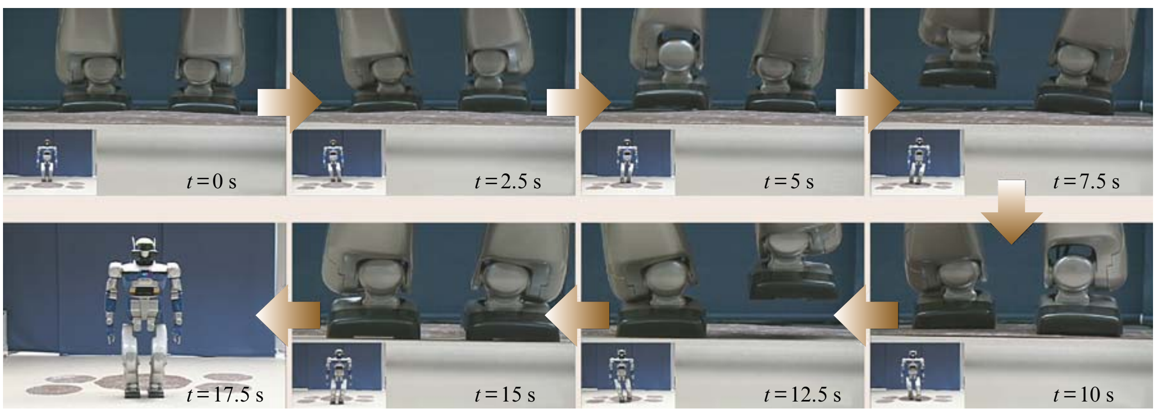

Fig. 56.9 HRP-2 walks on a slightly uneven surface

Fig. 56.10 These robots from Delft, MIT and Cornell (*left* to *right*) are designed to exploit their natural dynamics when walking [56.36]. (Image courtesy of Steven H. Collins)

Fig. 56.12 The humanoid robot HRP-2P getting up from a lying-down position

trol 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 motion patterns that make the robot dynamically stable while walking.

Controllers based on the ZMP criterion try to follow a planned sequence of contact states and are often unable to change the landing positions in real time in response to lost contact. Current ZMP-based bipedal walking algorithms have difficulty handling unexpected perturbations, such as might be encountered with uneven natural terrain (Fig. 56.9). Robots using ZMP differ from human locomotion in significant ways. For example, unlike people, robots using ZMP typically do not exploit the natural dynamics of their legs, or control the impedance of their joints.

Augmenting ZMP-based control is currently an active area of research. As will be discussed in Sect. 56.5 on whole-body activities researchers are working to integrate manipulation and bipedal locomotion. For example, when a robot walks while grasping a handrail, the contact could potentially increase the stability of the robot, but the ZMP criterion does not easily generalize to this task. So far, a generic and rigorous new criterion has not been established.

As an example of an alternative mode of bipedal locomotion, some running robots have used controllers based on an inverted pendulum model to achieve stable gaits. These methods change the landing positions to keep the robot dynamically stable [56.37]. More recently, 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. 56.10 [56.36]).

56.3.2 Falling Down

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 can control its falling motions in order to reduce the impact of touch down [56.38], al-

Fig. 56.11 Example of controlled falling-down motion

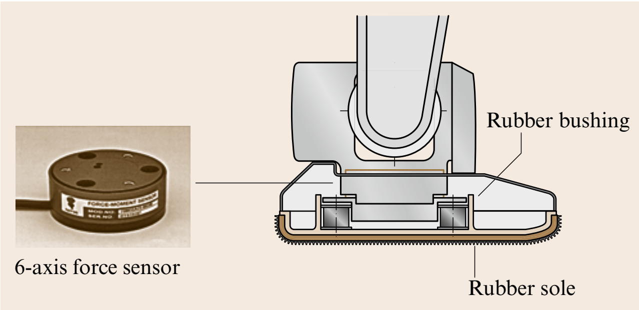

Fig. 56.13 Example of a humanoid foot structure for legged locomotion that uses compliance and force/torque sensing

Fig. 56.14 Asimo and artificial landmarks on the floor

though 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 [56.39]. Figure 56.11 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 [56.40] (Fig. 56.12).

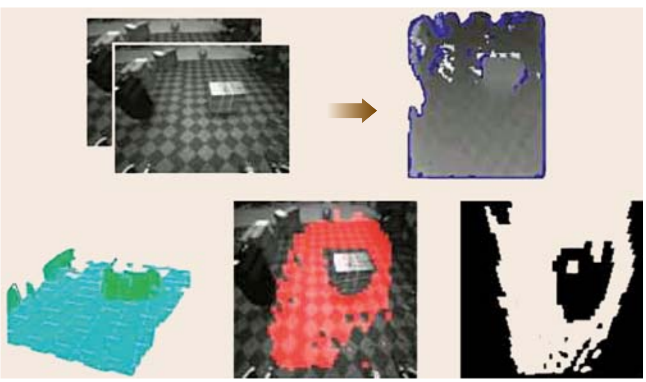

Fig. 56.15 Plane segment finder for detecting traversable floor area

56.3.3 Sensing for Balance

Bipedal walking needs to be robust to unexpected disturbances encountered during the execution of planned walking patterns. In these situations, walking can sometimes be stabilized with feedback control and appropriate sensing. 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. 56.13 in order to mitigate these problems. As with many other aspects of bipedal humanoid locomotion, foot design is currently an open problem.

56.3.4 Localization and Obstacle Detection

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. 56.14, Honda's Asimo uses a camera mounted on its lower torso that looks down at the floor to find artificial markers for position correction [56.41]. 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 vision have been utilized for this purpose. For example, the plane segment finder [56.42] developed by *Okada* et al. helps detect traversable areas. Figure 56.15 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 [56.43, 44].

56.4 Manipulation

Hands and arms are the main interfaces with which humans act on the world around them. Manipulation research within humanoid robotics typically focuses on the use of anthropomorphic arms, hands, and sensors to perform tasks that are commonly performed by people. Several chapters of the handbook relate to these goals, including Chap. 24 (*Visual Servoing and Visual Tracking*), Chap. 26 (*Motion for Manipulation Tasks*), and Chap. 28 (*Grasping*).

56.4.1 The Arm and Hand

The kinematics of humanoid robot arms emulate the human arm, which can be approximated by seven degrees of freedom (DOFs), with three at the shoulder, one at the elbow, and three at the wrist. The use of seven DOFs results in a redundant degree of freedom with respect to the six-DOF pose of the hand. To reduce mechanical complexity, humanoid robot arms sometimes have fewer than seven DOFs, for example, ARMAR-III and Justin have seven-DOF arms, Cog and Domo have six-DOF arms, and Asimo has five-DOF arms (Fig. 56.16) [56.45, 46].

Humanoid robot hands tend to vary more in their design (see Chap. 15, *Robot Hands*). 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 muscular control. If a robot hand is to be mounted on a robot arm, there are additional constraints in terms of the mass of the robot hand, since the hand sits at the end of the arm and must be efficiently moved in

Fig. 56.16 The humanoid robot Justin has two seven-DOF torque-controlled arms (DLR-Lightweight-Robot-III), and two 12-DOF hands (DLR-Hand-II). Justin's body is larger than a human's

Fig. 56.17 3-D object recognition by HRP-2 using versatile volumetric vision

Fig. 56.18 Using visual motion, Domo detects (*white cross*) the tips of tool-like objects it is rigidly grasping with error (*white circle*) comparable to the error achieved with hand labels (*black cross*)

space. Researchers have approximated the human hand with varying levels of accuracy, including the ACT hand, the 20-DOF Shadow Hand, the 12-DOF DLR-Hand-II, the 11-DOF Robonaut hand, the two-DOF Cog hand, and the one-DOF Asimo hand [56.47–50].

The ACT hand is an excellent representative of the high-fidelity end of the spectrum, since it emulates the bone structure, inertial properties, and actuation of the human hand in addition to the kinematics. Humanoid robot hands often include passive degrees of freedom. For example, one DOF of the two-DOF Cog hand controlled a multijointed power grasp, while the other controlled a multijointed two-fingered precision grasp. Studies indicate that many human grasps can be approximated with two degrees of freedom [56.53], so simplified hands may be sufficient to emulate a variety of human manipulation activities.

56.4.2 Sensing for Manipulation

Model-Based Vision

A common approach to visual perception for humanoid robots is real-time three-dimensional (3-D) object recognition and six-DOF pose estimation using models of the objects to be manipulated (see Chap. 23, *3-D Vision and Recognition*).

An example of this approach is provided by the versatile volumetric vision (VVV) system, which is an edge-based 3-D vision system developed by Tomita et al. [56.54]. The VVV system has been utilized to find and grasp objects during everyday manipulation tasks. Figure 56.17 shows a demonstration of the HRP-2 recognizing a beverage can on a table so that it can pick up the can and throw it into a trash can. This integrated system was demonstrated at Aichi EXPO 2005, where it enabled a human operator to control the HRP-2 humanoid robot in a semi-autonomous fashion with reduced effort [56.55]. The VVV system has also helped HRP-2 carry a table in cooperation with a human [56.56].

Other robots have used similar approaches. For example, Robonaut from the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) has used model-based vision to perform everyday manipulation tasks, such as tightening lug nuts on a wheel [56.57].

Feature-Based Vision

Another approach to visual perception for humanoid robots is feature-based vision. Encoding tasks in terms of task-relevant features, such as the tip of a tool or the contact surface of a hand, offers an alternative to approaches that use detailed 3-D models of objects. In order to generalize a task across different objects, only the task-relevant features need to be detected and mapped.

An example of this approach is provided by the humanoid robot Domo, which uses task-relevant features to perform everyday tasks such as pouring, stirring, and brushing. Domo detects features such as the opening of a container or the tip of a tool (Fig. 56.18) and then visually servoes these features with respect to one another in order to perform a task. Once the objects are in contact with one another, Domo uses force sensing and compliance to simplify tasks such as regrasping, inserting, and placing objects [56.52, 58].

Active Perception

Through action, robots can simplify perception. Humanoid robots have used this approach in ways that are reminiscent of human behavior. For example, a humanoid robot can reach out into the world to physically sense its surroundings (Fig. 56.19), or induce visual motion through physical contact so as to better estimate the extent of manipulable objects [56.59]. Similarly, a hu-

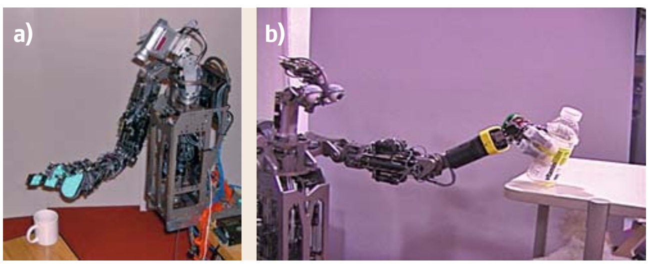

Fig. 56.19a,b The humanoid robots Obrero **(a)** and Domo **(b)** use passive compliance and force control to safely reach out into the world. Obrero haptically grasps an object [56.51]. Domo physically finds the shelf, and uses force control to let objects settle into place [56.52]

manoid robot can select postures that enable it to more easily view visual features that are relevant to the current task.

Force, Torque, and Tactile Sensing

When in contact with the world, force, torque, and tactile sensing are especially valuable (see Chap. 19, *Force and Tactile Sensors*), for example, as shown in the section on whole-body activities, force/torque sensing in the arms can be used to help a humanoid robot stay balanced while lifting or pushing an object for which an accurate model with friction coefficients and mass does not exist (Figs. 56.36 and 56.23). Likewise, many of the capabilities of the humanoid robots Cog, Domo, and Obrero depend on force, torque, and tactile sensing. As another example, the humanoid robot Justin from DLR uses torque sensing at all of its joints to perform Cartesian impedance control, which can implement virtual springs to coordinate bimanual manipulation of large objects (Fig. 56.16) [56.46].

The extent to which passive compliance and torque control should be integrated into humanoid robots is still an open issue (see Chap. 7, *Force Control*). Many humanoid robots have stiff joints that are well suited to position control, or perform force control using feedback from a force/torque sensor near the point of contact, such as the wrist or foot. However, even when a human attempts to maintain the position of her hand, the joints of her arm continue to exhibit significant compliance [56.60, 61] (Chap. 13, *Robots with Flexible Elements*).

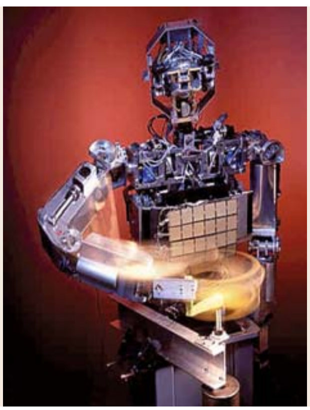

Fig. 56.20 The humanoid robot Cog used neural oscillators in conjunction with compliant force-controlled arms to perform a variety of everyday tasks with human tools, such as crank turning, hammering, and sawing. Photo by Sam Ogden

56.4.3 Rhythmic Manipulation

Many everyday tasks performed by humans involve rhythmic motions rather than discrete motions [56.62].

A good example of rhythmic humanoid manipulation was provided by Williamson, who demonstrated that central pattern generators (CPGs) in conjunction with compliant force-controlled arms can enable a humanoid robot to perform many everyday rhythmic manipulation tasks in a manner similar to humans (Fig. 56.20). His approach enabled the humanoid robot Cog to perform a variety of tasks without motion planning or model-based control. These tasks included hammering nails, sawing through wood, turning a crank at various orientations, turning cranks bimanually, playing with a slinky toy bimanually, and playing a snare drum [56.63]. The CPGs entrained on the natural dynamics of the robot's arm coupled to the environment. The output of the CPGs were used to control the set point of virtual springs in the joints, which were actuated with series elastic actuators (SEAs) [56.64].

Rhythmic motion can also be used as a basis for learning human-like manipulation tasks. For example, The humanoid robot DB has learned to perform rhythmic manipulation tasks, such as drumming, from human demonstration [56.65].

56.4.4 Cooperative Manipulation

Humanoid robots have potential advantages when working with humans to perform tasks cooperatively [56.20] (see Chap. 57, *Safety for Physical Human–Robot Interaction*). Humans typically have extensive experience cooperating with other humans to perform manual tasks. Humanoid robots have the potential to simplify this

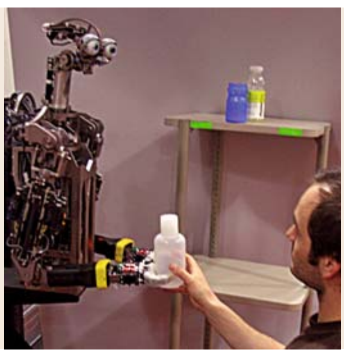

Fig. 56.21 Domo works with a human to place objects on a shelf [56.52]

form of human–robot interaction by closely matching a human counterpart during cooperative activities. For example, this can reduce the need for a human cooperator to learn how to interact with novel kinematic structures and sensing, and enable the robot and the human to use the same tools. Robonaut has been teleoperated to perform an insertion task in cooperation with a human [56.66]. Work with Domo has shown that people without prior experience readily interpret reaching cues and place an object in Domo's hand in a favorable pose (Fig. 56.21) [56.52, 67]. Likewise, as shown in the section on whole-body activities (Sect. 56.6), humanoid robots have the potential to help a person move large objects (Fig. 56.36).

Fig. 56.22 The humanoid robot DB learns to play air hockey against a human opponent through observation and practice. ©JST, ATR; Robot developed by SARCOS

56.4.5 Learning and Development

Humans are very successful at learning new manipulation tasks, and human infants progressively develop sophisticated manipulation abilities over the course of several years. Researchers within humanoid robotics have attempted to emulate these aspects of human intelligence.

Learning by demonstration is a common way for people to learn from one another. Since humanoid robots have a similar form to humans, and have been designed to perform similar tasks, learning by demonstration may have advantages for skill acquisition [56.68, 69] (see Chap. 59, *Robot Programming by Demonstration*). The humanoid robot ARMAR has a framework for learning bimanual tasks from demonstration, which has enabled ARMAR to open a container with a screw-on lid [56.70]. Researchers have also sought to integrate learning by demonstration with learning from exploration and motor primitives. For example, *Bentivegna* et al. have demonstrated methods that enable the humanoid robot DB to learn to play air hockey by observing a human opponent and practicing (Fig. 56.22) [56.71].

Biologically inspired approaches to humanoid manipulation are also common (see Chap. 62, *Neurorobotics: From Vision to Action*). Before contact, the hand must move through free space to a target. Researchers have worked to enable robots to develop reaching behaviors using methods inspired from infant development [56.15]. Likewise, researchers such as *Platt* et al. have created methods that enable a humanoid robot to learn to grasp everyday objects in order to perform common tasks, such as grasping grocery items and placing them in a bag [56.72].

56.5 Whole-Body Activities

The two previous sections have focused on humanoid locomotion and humanoid manipulation independently. This section looks at mobile manipulation using a full humanoid robot with both arms and legs. Researchers wish to enable these humanoids to perform tasks such as lifting and carrying a box (as shown in Fig. 56.23), climbing a ladder, or even playing a sport. This section provides a brief glimpse into several approaches to this challenging problem.

Unlike the industrial manipulators described in Chap. 42 (*Industrial Robotics*), or a humanoid that is rigidly fixed in place, a bipedal humanoid must be controlled so as to remain balanced while manipulating an object. Without actively maintaining stability, the robot could tip over and fall to the ground.

Moreover, a humanoid robot usually has many joints compared to a standard industrial manipulator. Humanoids are a kind of redundant robot as described in Chap. 11 (*Redundant Manipulators*). Consequently, there are many postures that can achieve a given pose of the robot's hand. Out of the possible configurations of the robot's body, many will result in the robot falling over.

Figure 56.24 shows an overview of several approaches to whole-body motion generation for humanoid robots. These methods decouple the problem

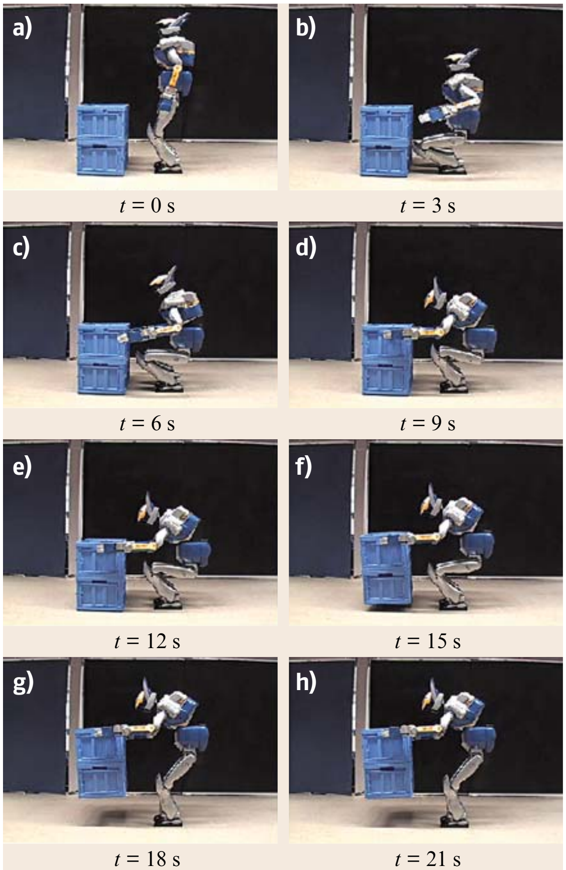

Fig. 56.23 Lifting an object while moving the waist to compensate for the load [56.73]

by computing a coarse movement and transforming it into a dynamically balanced movement. Then, during the whole-body activity, the humanoid uses a sensory feedback control system to stabilize its motion. If the generated motion pattern were perfect and the state of the world could be exactly anticipated in advance, this feedback might be unnecessary. However, it is very difficult, if not impossible, to make a perfect motion pattern during real-world situations, since models of the robot and the environment inevitably have errors, for example, surface conditions, such as friction and compliance, can be very important, yet difficult to anticipate (Chap. 27, *Contact Modeling and Sliding Manipulation*).

This section focuses on the first two parts of the process shown in Fig. 56.24: coarse motion generation and the conversion of coarse motions into detailed motions that enable whole-body activities.

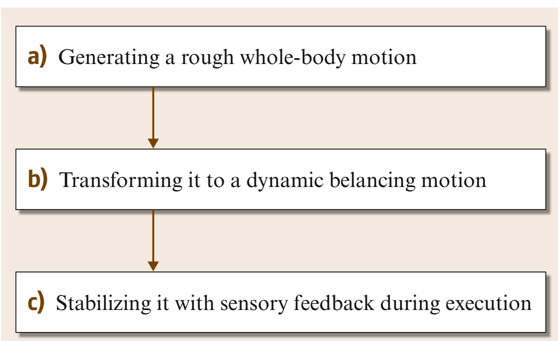

Fig. 56.24 Overview of motion-generation stages for a balancing robot

56.5.1 Coarse Whole-Body Motion

There are currently four prevalent ways to generate coarse whole-body motion:

1. Using a motion capture system
2. using a graphical user interface (GUI) offline
3. using a teleoperation interface in real time
4. using automatic motion planning

Using a Motion Capture System

Humanoid robots have a human-like shape and many researchers would like humanoid robots to perform tasks in a human-like way. Consequently, human motion is often used when generating the motion of a humanoid robot. Motion capture systems, such as those used by movie studios for special effects, are commonly used for recording human motion. Typically a human subject

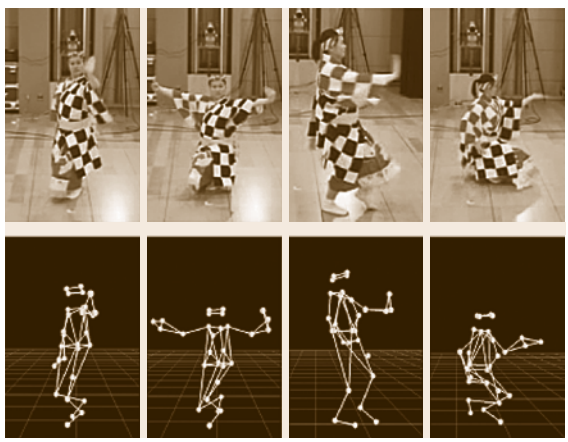

Fig. 56.25 An example of captured motion data for a Japanese folk dance [56.22]

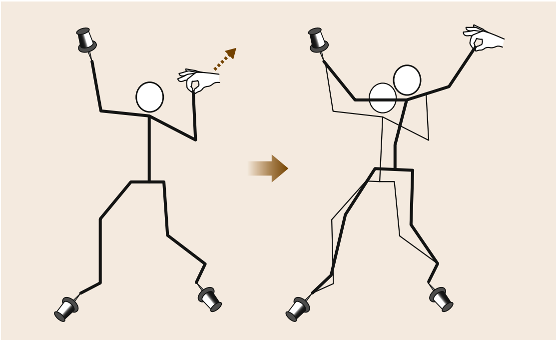

Fig. 56.26 The *pin-and-drag interface* for generating coarse movements [56.74]

performs actions while wearing easily detected markers on his or her body. The motion of these markers are recorded by cameras placed in the room, and software then infers the 3-D positions of these markers over time. Figure 56.25 shows an example: the captured motions of a woman performing a Japanese folk dance [56.22].

Fig. 56.27 An example of a whole-body motion generated using the pin-and-drag interface [56.74]

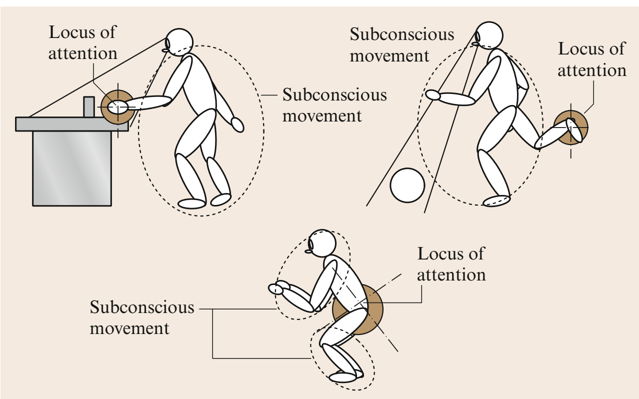

Fig. 56.28 While teleoperating a robot, the human operator can focus his or her attention on a small part of the humanoid robot. Automatic techniques can then take this coarse motion specification and automatically generate full motion specifications that meet important constraints, such as maintaining the robot's balance

This is a mature technology, so motions such as those shown in Fig. 56.25 can easily be obtained and then used as a reference for a humanoid's whole-body motion. Due to kinematic similarities, coarse kinematic motions can be transferred to a humanoid robot. However, due to dynamic differences, such as mass distributions and torque generation, captured motions may not be stable or feasible. Moreover, the task constraints and sensory feedback involved in a motion-captured activity may not be easily inferred, which can lead to robot motion that is similar in appearance, yet fails to achieve the goals of a motion.

Using a GUI Offline

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, the process would be tedious and inefficient. One approach to overcoming this issue is a *pin-and-drag* GUI interface, which can help the designer more efficiently control the motion of all the joints of a high degree of freedom humanoid [56.74]. Figure 56.26 outlines this interface. The user can pin links of the humanoid to desired locations. Then the software automatically generates natural movements of the humanoid's joints subject to these constraints, while the user drags other links. Figure 56.27 shows a whole-body movement generated by dragging the right hand up and down for four seconds while pinning the left hand, the toes, and the heels. This results in natural-looking movements for picking up an object. As with the motion capture system, this generated whole-body motion may not be directly applicable to a humanoid robot due to dynamics and modeling errors.

Using a Teleoperation Interface in Real Time

Given the complexity and potential instability of humanoid robots, every detail of a whole-body activity cannot be efficiently controlled by a human in real time. The teleoperation (Chap. 31, *Telerobotics*) of humanoid robots combines coarse motion control provided by a user with methods that generate effective full-body motions. Since teleoperation occurs in real time, the methods used to perform this transformation cannot rely on knowledge of future motion commands, and must be computationally efficient. This rules out the use of methods such as the autobalancer (described later), which requires an entire motion trajectory in order to globally optimize the conversion.

Fig. 56.29 An example whole-body motion generated by the RRT motion planning system [56.77]

Human motions are generated with a mixture of two kinds of motion: motions that require careful attention and motions that require little cognitive effort (Fig. 56.28). A similar division can be used when designing a teleoperation system for whole-body activities [56.75]. For example, in a manner similar to the previously discussed GUI interface, a human operator can control specific points on a humanoid robot's body in order to generate coarse motions. By reducing the aspects of the motion that the human operator must specify, he or she can control a humanoid robot to perform complex motions in real time using simple interfaces, such as joysticks or high-level commands [56.76].

Using Automatic Motion Planning

Motion capture, teleoperation, and GUI-based motion editing tools give the user interactive control over the robot's motions, but they can be time consuming to use. Fast path-planning techniques such as rapidly exploring random trees (RRT) [56.79] can compute collision-free full-body motions for humanoid robots automatically [56.77] (see Chap. 5, *Motion Planning*, and Chap. 26, *Motion for Manipulation Tasks*). Given geometric models of the humanoid and the environment, an initial posture, and a goal posture, the planning system automatically searches for a collision-free whole-body motion that moves the humanoid from the initial posture to the goal posture (Fig. 56.29). This type of method can also search for statically stable postures that smoothly interpolate between the initial and goal posture, and explicitly include other constraints based on the dynamics.

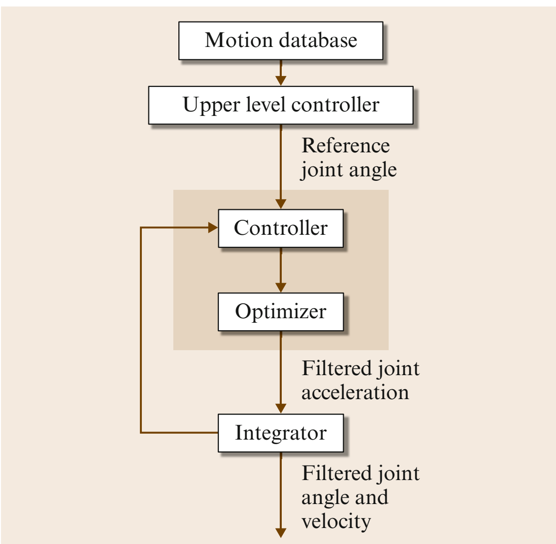

Fig. 56.30 Dynamics filter system diagram [56.78]

56.5.2 Generating Dynamically Stable Motions

The methods presented in Sect. 56.5.1 can be useful when generating coarse whole-body motions for a humanoid robot. 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 two example techniques for converting coarse motions to dynamically-stable motions: the dynamics filter, and the autobalancer (other methods such as strict trunk motion computation used in the motion generation system for waseda bipedal humanoid (WABIAN) [56.80] are also possible).

Dynamics Filter

The dynamics filter proposed by *Yamane* and *Nakamura* [56.78] can convert a physically infeasible motion into a feasible one for a given humanoid. This consists of a controller and optimizer as shown in Fig. 56.30.

The controller calculates reference joint accelerations by using local and global feedback loops with respect to the given coarse motions and the current state of the humanoid model. The optimizer calculates joint accelerations that minimize the difference between the reference joint acceleration and the current joint acceleration under the given contact constraints, such as floor friction and contact force feasibility. Figure 56.31 shows motion-captured data of a human walking and the resulting, physically feasible motion produced by the dynamics filter. The motions look similar, but the contact conditions for the feet have been modified to be physically feasible.

Autobalancer

The autobalancer calculates all joint angles at every sample in time by solving a quadratic programming op-

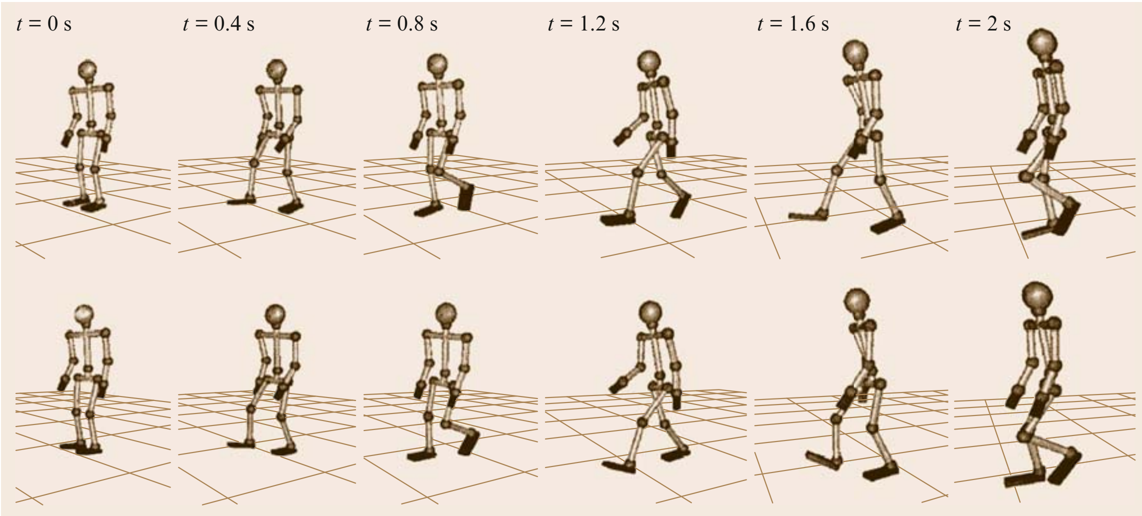

Fig. 56.31 An example of motions converted by the dynamics filter [56.78]; the top row shows the original coarse planned movements, and the lower row shows the modified movements that meet necessary constraints

timization problem in order to convert a given motion to a balanced one [56.81]. This method is not suitable for a motion in which dynamic balancing is dominant, such as during walking motions. However, this approach can be effective for a motion in which static balancing is dominant, such as when the humanoid is standing. The autobalancer can sometimes generate a walking motion if the robot can move slowly enough to minimize the influence of the dynamics while still maintaining stability [56.81].

The autobalancer calculates a whole-body motion based on the following concepts.

1. Fix the center of gravity (CoG) on the vertical axis which passes through a point in the support polygon of the humanoid;
2. Keep inertia moments around the CoG at acceptable values in order to satisfy the balancing conditions.

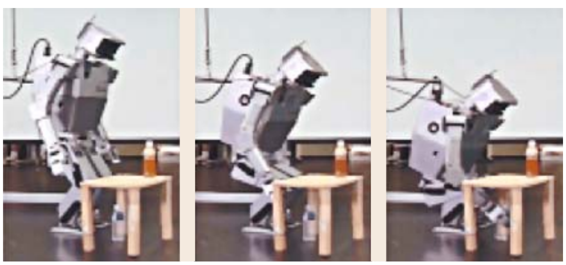

Fig. 56.32 The humanoid robot H7 executes a motion generated by the autobalancer [56.77]

Acceptable values for the moments are obtained by using constraints that keep the ZMP in the support polygon and keep the angular momentum generated by the moments close to zero over a given length of time. This problem can be handled as a quadratic programming optimization that minimizes errors between the given reference motion and the calculated motion given the constraints on the position of the CoG and the generated moments. The autobalancer solves this problem over every sampling period. Figure 56.32 shows the humanoid robot H7 executing a whole-body motion that resulted from using the autobalancer to transform the automatically planned coarse motions shown in Fig. 56.29 [56.77].

56.5.3 Generating Whole-Body Motions from Operational Point Motions

The example GUI and teleoperation interface described previously, enable a person to control the motions of particular points on a robot. Similarly, many automated control systems have been designed to control particular points on a robot, such as the end effector [56.82] (see Chap. 26, *Motion for Manipulation Tasks*). In order to control a real or simulated humanoid robot, these coarse motions must be converted to whole-body motions.

The computational efficiency and causality of this conversion is important. Teleoperation requires real-time methods, and human interfaces benefit from interactive control that provides real-time feedback.

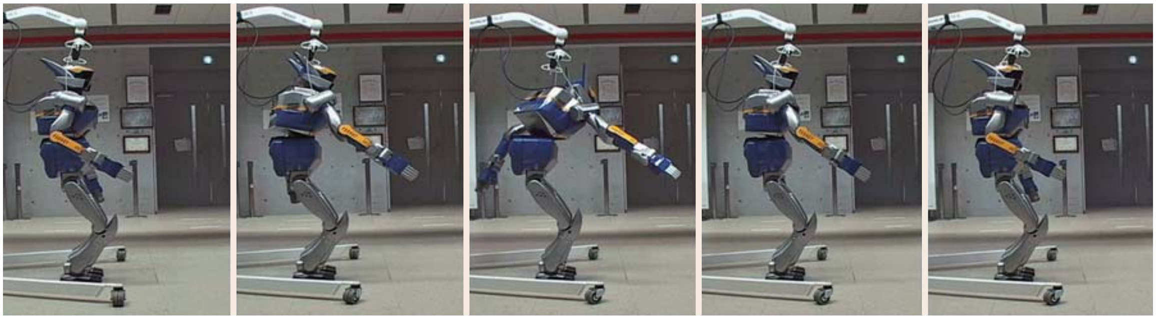

Fig. 56.33 Forward reaching motion with balance [56.75]

Likewise, the autonomous control of real robots with nontrivial dynamics requires real-time methods. Many approaches have been developed to generate whole-body motions from operational point motions in real time, two examples of which follow.

Resolved Momentum Control

Kajita et al. proposed a framework for whole-body control based on the linear and angular momentum of the entire robot [56.85]. Intuitively, one can think of the robot as a single rigid body whose linear and angular momentum is to be controlled. For example, the center of mass of the robot might be commanded to move at a fixed height above the ground. 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.

Neo et al. adapted this framework to generate whole-body motions from operational point motions specified by a human operator [56.75, 76]. The human operator can control the foot motion, the overall motion of the humanoid robot, or the motion of a hand at any time by switching the mode of operation. The whole motion-generation system then computes joint velocities that meet the desired motions and additional constraints.

Reaching tasks performed by the humanoid HRP-2 provide an example of this type of operation [56.86]. Figure 56.33 shows snapshots of the robot's movement with the operator controlling only the velocity of the right hand in order to perform a horizontal reaching motion. The robot automatically moves other joints, such as its torso, in order to stay balanced while the operator solely controls the hand.

Coordinating Constraints, Tasks, and Postures

Dynamic stability is very important during whole-body activities. However, humanoid motion is often subject to many simultaneous objectives that may be in competition with one another. *Sentis* and *Khatib* proposed a framework that enables a humanoid robot to perform motions that simultaneously meet prioritized objectives in real time [56.87], and *Park* and *Khatib*

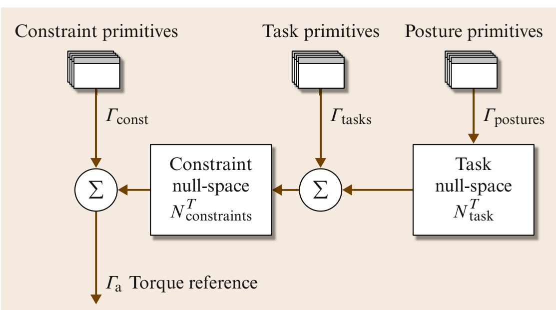

Fig. 56.34 A control hierarchy is established using null-space projections [56.83]

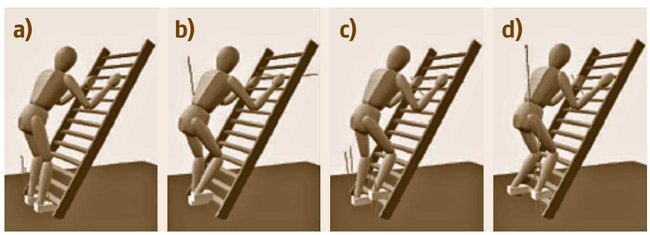

Fig. 56.35a–d Climbing a ladder. **(a)** The robot begins to climb; it has contacts on both hands and feet. **(b)** The right foot is then controlled to move up one step. **(c)** Next, the center of mass is controlled to move to the right in order to maintain balance with two hands and the right foot. **(d)** The left foot is then controlled to move up one step [56.84]

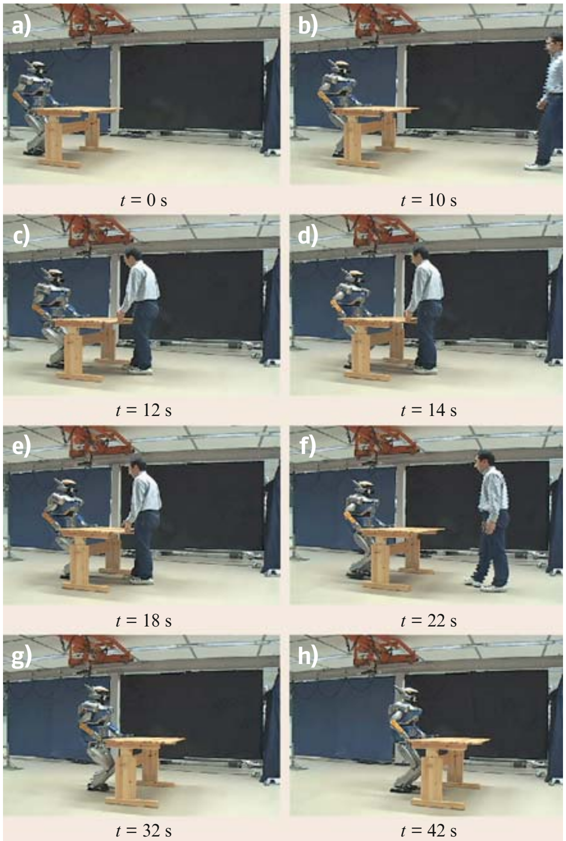

Fig. 56.36 Example of pushing manipulation and cooperation [56.88]

have augmented this approach to handle contact with the environment [56.84]. With these methods many controllers can be coordinated, and each controller can specify different objectives, such as a desired trajectory for a particular point on the robot.

This coordination of controllers uses three distinct control categories: constraint handling, operational tasks, and postures. A control hierarchy handles conflicting scenarios among these three categories of controllers. Constraint primitives, such as joint limits, have the highest priority and the posture primitives have the lowest priority. One advantage of the posture primitives is that they can control redundant degrees of freedom in a consistent way.

To achieve this control hierarchy, operational tasks are projected into the constraint null space, and postures are projected into the task null space followed by the constraint null space (Fig. 56.34). Unlike resolved momentum control, which generates joint velocities, all of these controllers generate joint torques. When calculating these torques, the controllers use models of the dynamics of the robot and the environment.

A ladder-climbing behavior tested in simulation demonstrates this framework for control (Fig. 56.35). In this example, the desired trajectories for the center of mass, the hands, and the feet are specified in advance. When the simulation is run, the whole-body control system generates joint torques that seek to meet these coarse motion specifications, which results in the simulated robot climbing the ladder. While climbing, the simulated robot successfully resists unexpected disturbances.

Research into methods for the coordination of controllers for humanoid robots is an active area of research, for example, *Mansard* et al. have used a *stack of tasks* to organize prioritized controllers, including a visual servoing controller and a grasping controller, to enable a real HRP-2 robot to visually grasp a pink ball while walking [56.89].

56.5.4 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

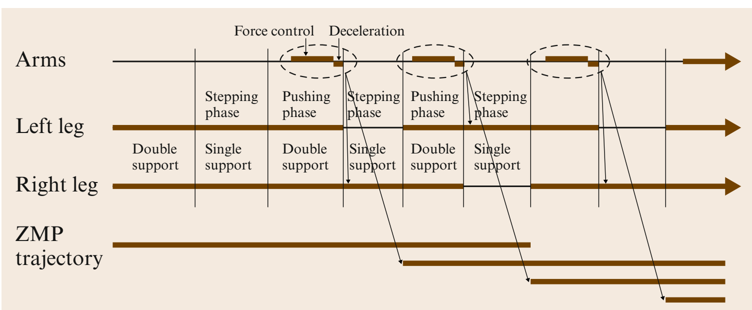

Fig. 56.37 Time chart of force-controlled pushing manipulation

the conventional ZMP property defined by the center of pressure of the supporting feet [56.90]. 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 has 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 [56.91]. 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 [56.92]. Researchers have also developed specialized methods for generating stable robot motion while an object is being manipulated [56.88, 90, 93–95].

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 [56.73, 90, 93, 96]. Figure 56.23 shows an experimental result of carrying an object that weighs 8 kg [56.73]. 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 [56.88].

One approach to this activity is to have the robot push the object during the double support phase of walking, when both feet are in contact with the floor. A timing chart of this strategy for force-controlled pushing is shown in Fig. 56.37. During the pushing phase, the robot pushes the object while controlling the reaction forces applied at the hands. In the stepping phase, the step length is set to match the distance the object has been pushed in the pushing phase. The desired ZMP trajectory is recalculated and connected to the current ZMP trajectory. The trajectory of the center of gravity is also recalculated in order to realize this ZMP trajectory.

Figure 56.36 shows an experimental result for this approach [56.88]. 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.

56.6 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.

56.6.1 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 [56.97].

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 (see Chap. 58, *Social Robots that Interact with People*).

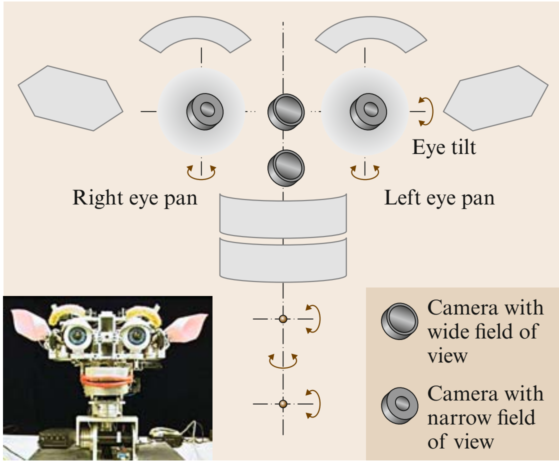

Fig. 56.38 On Kismet, foveal vision was implemented using cameras in the eyes, and peripheral vision used unobtrusive cameras on the head [56.97]. This achieved good expression of locus of attention, while simplifying the process of differentiating egomotion from motion of objects (since the head moved 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

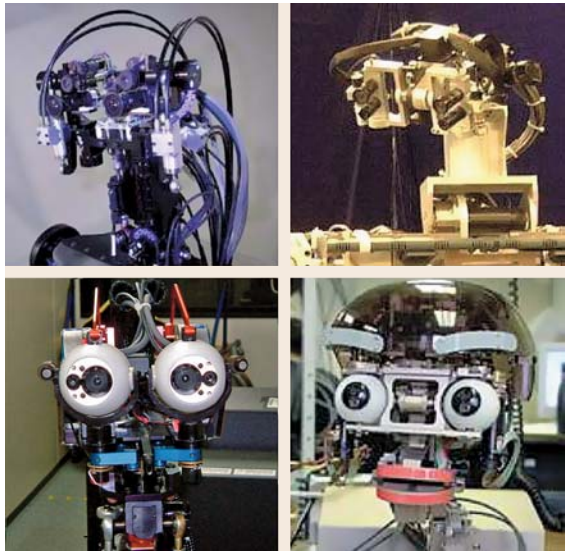

Fig. 56.39 The heads of humanoid robots come in many forms. A popular arrangement is to have two cameras per *eye*, as a crude approximation of foveal and peripheral vision in humans. *Top left*: biomimetic oculomotor control investigated on DB [56.98]. *Top right*: Cog's head [56.99]. *Bottom left*: the double-camera arrangement can be arranged in a less-double-barreled appearance (see *Ude* et al. [56.100] for more examples and an analysis) ©ATR; Humanoid head developed by ATR and SARCOS. *Bottom right*: the Infanoid robot [56.101]

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 non-human-like camera arrangement that simplified some forms of perception (Fig. 56.38).

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. 56.39). 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 [56.102].

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. 56.40. These 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.

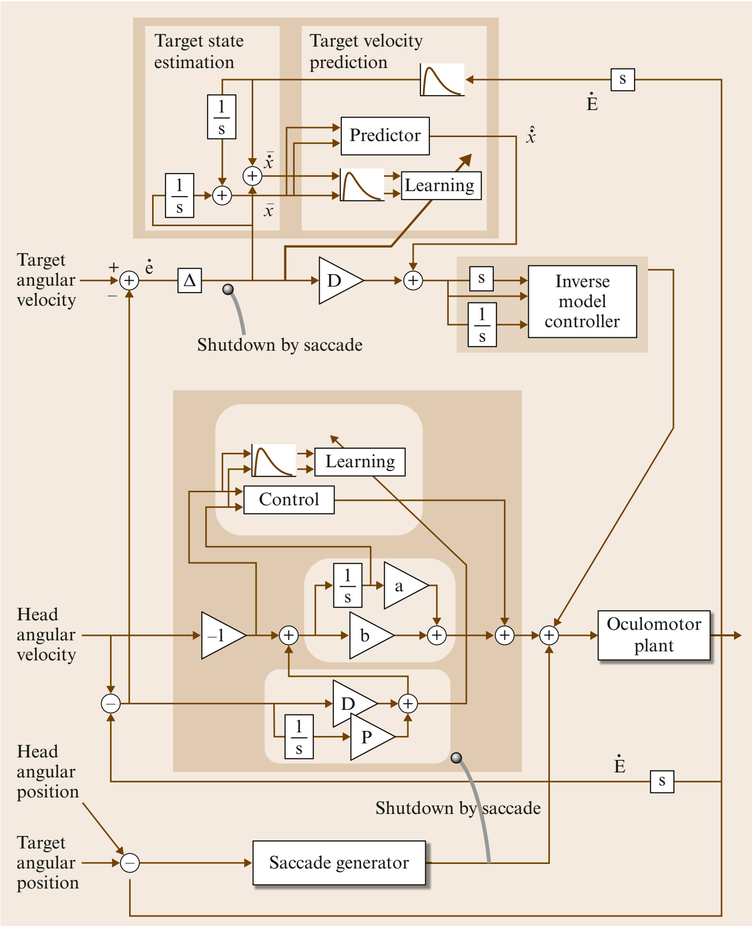

Fig. 56.40 A biomimetic control model [56.103], that integrates saccading, smooth pursuit, the vestibular-ocular reflex (VOR), and the optokinetic response (OKR). Smooth pursuit and VOR/OKR commands are summed, with periodic corrections to errors in position made by saccades

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, 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.

56.6.2 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. 56.41. 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 functions on a humanoid are not yet robust, and are active areas of research.

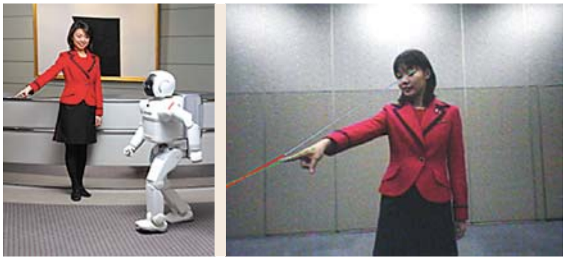

Fig. 56.41 Asimo recognizing a pointing gesture during a reception task

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 [56.104]. 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

Fig. 56.42 HRP-2 recognizing speech with background noises (TV sound)

Fig. 56.43 HRP-2 recognizing face and gaze direction for communication via eye contact

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 [56.105].

Multimodal Perception

Sound-source separation can be achieved by beam forming. In order to perform beamforming effectively,

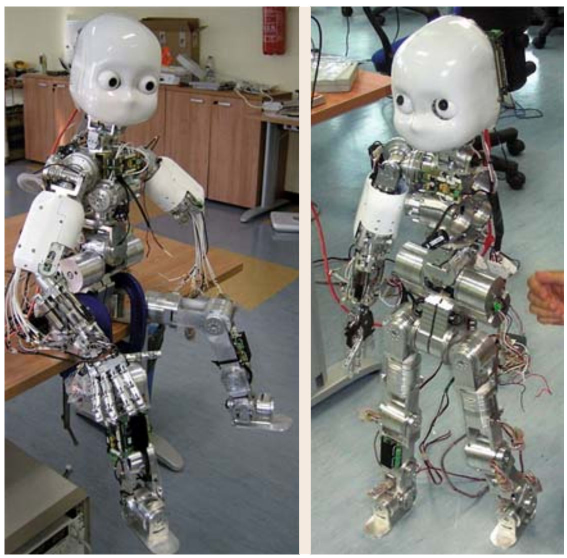

Fig. 56.44 The iCub robot [56.16], an infant-like robot that serves as an open humanoid platform for cognitive and neuroscience research

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 [56.106]. Figure 56.42 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 [56.105]. Multimodal interaction with these functions has also been demonstrated by HRP-2, as shown in Fig. 56.43.

56.6.3 Alternative Models for Human–Robot Communication

Humanoid robots typically use methods for perception and interaction that are similar to those found in fields such as computer vision and dialogue systems. There is also a subfield called *epigenetic* or *developmental* robotics that attempts to form an explicit bridge between robotics and human studies, such as psychology and neuroscience [56.107, 108]. Much of the research within this subfield deals with human-like perception and interaction using humanoid robots, such as the iCub shown in Fig. 56.44.

56.7 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 humanoids depend. Additionally, this chapter thoroughly references work within the humanoid robotics community and related communities. Consequently, the reader should be able to use this chapter as a high-level overview of the field from which to explore specific areas of humanoid robotics.

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. Humanoids have already gained a foothold in the marketplace as robots for entertainment through competitions and toys (e.g., Robo-One and RoboSapien). Time will tell whether consumers prefer robots with human-like qualities. For example, if service robots are to have two, high-degree-of-freedom arms and articulated sensing mechanisms, a human-like form may be a desirable configuration. Given the special properties of humanoid robots, they seem likely to at least fill a niche in the world of the future. Whether or not humanoids become a dominant form for robots may depend on the extent to which they can compete against specialized robots that are better suited to particular tasks, and human labor, which in some ways already meets the ultimate goals of humanoid robotics.

References

56.1 H. Inoue, S. Tachi, Y. Nakamura, K. Hirai, N. Ohyu, S. Hirai, K. Tanie, K. Yokoi, H. Hirukawa: Overview of humanoid robotics project of METI, Proc. 32nd Int. Symp. Robot. (ISR) (2001)

56.2 Y. Kuroki, M. Fujita, T. Ishida, K. Nagasaka, J. Yamaguchi: A small biped entertainment robot exploring attractive applications, Proc. IEEE Int. Conf. Robot. Autom. (ICRA) (2003) pp. 471–476

56.3 C.G. Atkeson, J.G. Hale, F.E. Pollick, M. Riley, S. Kotosaka, S. Schaal, T. Shibata, G. Tevatia, A. Ude, S. Vijayakumar, M. Kawato: Using humanoid robots to study human behavior, IEEE Intell. Syst. **15**(4), 46–56 (2000)

56.4 K.F. MacDorman, H. Ishiguro: The uncanny advantage of using androids in social and cognitive science research, Interact. Stud. **7**(3), 297–337 (2006)

56.5 V. Bruce, A. Young: *In the Eye of the Beholder: The Science of Face Perception* (Oxford Univ. Press, Oxford 1998)

56.6 R. Blake, M. Shiffrar: Perception of human motion, Annu. Rev. Psychol. **58**, 47–73 (2007)

56.7 J.F. Werker, R.C. Tees: Influences on infant speech processing: Toward a new synthesis, Annu. Rev. Psychol. **50**, 509–535 (1999)

56.8 D. Hanson, A. Olney, I.A. Pereira, M. Zielke: Upending the uncanny valley, Nat. Conf. Artif. Intell. (AAAI '05), Pittsburgh (2005)

56.9 K. Čapek's: *R.U.R. (Rossum's Universal Robots), A Play in Introductory Scene and Three Acts* (eBooks, Adelaide 2006), translated into English by D. Wyllie

56.10 *Metropolis*, directed by Fritz Lang (DVD) (Kino Video, 1927)

56.11 I. Asimov: *Caves of Steel* (Doubleday, Garden City, New York 1954)

56.12 B. Adams, C. Breazeal, R.A. Brooks, B. Scassellati: Humanoid robots: A new kind of tool, IEEE Intell. Syst. **15**(4), 25–31 (2000)

56.13 R.A. Brooks, L.A. Stein: Building brains for bodies, Auton. Robot. **1**(1), 7–25 (1994)

56.14 R.W. Gibbs Jr.: *Embodiment and Cognitive Science* (Cambridge Univ. Press, Cambridge 2006)

56.15 M. Lungarella, G. Metta: Beyond gazing, pointing, and reaching: A survey of developmental robotics, Proc. Third Int. Workshop Epigenet. Robot. (2003) pp. 81–89

56.16 G. Metta, G. Sandini, D. Vernon, D. Caldwell, N. Tsagarakis, R. Beira, J. Santos-Victor, A. Ijspeert, L. Righetti, G. Cappiello, G. Stellin, F. Becchi: The RobotCub project – an open framework for research in embodied cognition, Proc. IEEE-RAS Int. Conf. Humanoid Robot. (2005)

56.17 E. Grandjean, K. Kroemer: *Fitting the Task to the Human*, 5th edn. (Routledge, London 1997)

56.18 W. Karwowski: *International Encyclopedia of Ergonomics and Human Factors*, 2nd edn. (CRC, Boca Raton 2006)

56.19 R. Brooks, L. Aryananda, A. Edsinger, P. Fitzpatrick, C. Kemp, U.-M. O'Reilly, E. Torres-Jara, P. Varshavskaya, J. Weber: Sensing and manipulating built-for-human environments, Int. J. Humanoid Robot. **1**(1), 1–28 (2004)

56.20 W. Bluethmann, R. Ambrose, M. Diftler, S. Askew, E. Huber, M. Goza, F. Rehnmark, C. Lovchik, D. Magruder: Robonaut: A robot designed to work with humans in space, Auton. Robot. **14**(2-3), 179–197 (2003)

56.21 K. Yokoi, K. Nakashima, M. Kobayashi, H. Mihune, H. Hasunuma, Y. Yanagihara, T. Ueno, T. Gokyuu, K. Endou: A tele-operated humanoid operator, Int. J. Robot. Res. **22**(5–6), 593–602 (2006)

56.22 S. Nakaoka, A. Nakazawa, K. Yokoi, H. Hirukawa, K. Ikeuchi: Generating whole body motions for a biped humanoid robot from captured human dances, IEEE Int. Conf. Robot. Autom. (2003) pp. 3905–3910

56.23 K. Yokoi, K. Kawauchi, N. Sawasaki, T. Nakajima, S. Nakamura, K. Sawada, T. Takeuchi, K. Nakashima, Y. Yanagihara, K. Yokohama, T. Isozumi, Y. Fukase, K. Kaneko, H. Inoue: Humanoid robot applications in HRP, Int. J. Human. Robot. **1**(3), 409–428 (2004)

56.24 B. Thibodeau, P. Deegan, R. Grupen: Static analysis of contact forces with a mobile manipulator, Proc. IEEE Int. Conf. Robot. Autom. (ICRA'06) (2006) pp. 4007–4012

56.25 J. Gutman, M. Fukuchi, M. Fujita: Modular architecture for humanoid robot navigation, Proc. 5th IEEE-RAS Int. Conf. Humanoid Robot. (2005) pp. 26–31

56.26 K. Hirai, M. Hirose, Y. Haikawa, T. Takenaka: The development of Honda Humanod Robot, IEEE Int. Conf. Robot. Autom. (1998) pp. 1321–1326

56.27 M.E. Rosheim: *Robot Evolution: The Development of Anthrobotics* (Wiley, New York 1994)

56.28 M.E. Rosheim: *Leonardo's Lost Robots* (Springer, Berlin, Heidelberg 2006)

56.29 T.N. Hornyak: *Loving the Machine: The Art and Science of Japan's Robots* (Massachusetts Institute of Technology, Cambridge 2006)

56.30 J. Surrell: *Pirates of the Caribbean: From the Magic Kingdom to the Movies* (Disney, New York 2005)

56.31 J. Weng, J. McClelland, A. Pentland, O. Sporns, I. Stockman, M. Sur, E. Thelen: Autonomous mental development by robots and animals, Science **291**(5504), 599–600 (2001)

56.32 J. Zlatev, C. Balkenius: Why "epigenetic robotics"?, Proc. First Int. Workshop Epigenet. Robot. Model. Cognit. Dev. Robot. Syst., ed. by C. Balkenius, J. Zlatev, H. Kozima, K. Dautenhahn, C. Breazeal (Lund Univ. Press, Lund 2001) pp. 1–4

56.33 Y. Sodeyama, I. Mizuuchi, T. Yoshikai, Y. Nakanishi, M. Inaba: A shoulder structure of muscle-driven humanoid with shoulder blades, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS'05) (2005) pp. 4028–4033

56.34 I. Mizuuchi, M. Inaba, H. Inoue: A flexible spine human-form robot-development and control of the posture of the spine, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS'01), Vol. 4 (2001) pp. 2099–2104

56.35 M. Vukobratović, J. Stepanenko: On the stability of anthropomorphic systems, Math. Biosci. **15**, 1–37 (1972)

56.36 S.H. Collins, A.L. Ruina, R. Tedrake, M. Wisse: Efficient bipedal robots based on passive-dynamic walkers, Science **307**, 1082–1085 (2005)

56.37 M.H. Raibert: *Legged Robots That Balance* (MIT Press, Cambridge 1986)

56.38 K. Nagasaka, K. Kuroki, S. Suzuki, Y. Itoh, J. Yamaguchi: Integrated motion control for walking, jumping and running on a small bipedal entertainment robot, IEEE Int. Conf. Robot. Autom. (2004) pp. 3189–3194

56.39 K. Fujiwara, F. Kanehiro, S. Kajita, K. Kaneko, K. Yokoi, H. Hirukawa: UKEMI: falling motion control to minimize damage to biped humanoid robot, IEEE Int. Conf. Robot. Autom. (2002) pp. 2521–2526

56.40 H. Hirukawa, S. Kajita, F. Kanehiro, K. Kaneko, T. Isozumi: The human-size humanoid robot that can walk, lie down and get up, Int. J. Robot. Res. **24**(9), 755–769 (2005)

56.41 Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, K. Fujimura: The intelligent ASIMO: system overview and integration, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS'02) (2002) pp. 2478–2483

56.42 K. Okada, S. Kagami, M. Inaba, H. Inoue: Plane segment finder: Algorithm implementation and applications, Proc. Int. Conf. Robot. Autom. (ICRA'01) (2001) pp. 2120–2125

56.43 K. Sabe, M. Fukuchi, J.-S. Gutmann, T. Ohashi, K. Kawamoto, T. Yoshigahara: Obstacle avoidance and path planning for humanoid robots using stereo vision, Proc. Int. Conf. Robot. Autom. (ICRA'04) (2004)

56.44 J. Gutman, M. Fukuchi, M. Fujita: Real-time path planning for humanoid robot navigation, Proc. Int. Joint Conf. Artif. Intell. (2005) pp. 1232–1238

56.45 T. Asfour, K. Regenstein, P. Azad, J. Schroder, A. Bierbaum, N. Vahrenkamp, R. Dillmann: ARMAR-III: An integrated humanoid platform for sensory-motor control, Proc. 6th IEEE-RAS Int. Conf. Humanoid Robot. (2006)

56.46 C. Ott, O. Eiberger, W. Friedl, B. Bäuml, U. Hillenbrand, C. Borst, A. Albu-Schäffer, B. Brunner, H. Hirschmüller, S. Kielhöfer, R. Konietschke, M. Suppa, T. Wimböck, F. Zacharias, G. Hirzinger: A humanoid two-arm system for dexterous manipulation, Proc. IEEE-RAS Int. Conf. Humanoid Robot. (2006) pp. 276–283

56.47 M. Vande Weghe, M. Rogers, M. Weissert, Y. Matsuoka: The ACT hand: Design of the skeletal structure, Proc. 2004 IEEE Int. Conf. Robot. Autom. (ICRA '04) (2004)

56.48 L.Y. Chang, Y. Matsuoka: A kinematic thumb model for the ACT hand, Proc. IEEE Int. Conf. Robot. Autom. (ICRA '06) (2006) pp. 1000–1005

56.49 C. Lovchik, M.A. Diftler: The robonaut hand: A dexterous robot hand for space, Proc. Int. Conf. Robot. Autom. (ICRA) (1999) pp. 907–912

56.50 M.J. Marjanović: Teaching an Old Robot New Tricks: Learning Novel Tasks via Interaction with People and Things. Ph.D. Thesis (MIT, 2003)

56.51 L. Natale, E. Torres-Jara: A sensitive approach to grasping, Sixth Int. Conf. Epigenet. Robot., Paris (2006) pp. 20–22

56.52 A. Edsinger, C.C. Kemp: Manipulation in human environments, Proc. IEEE/RAS Int. Conf. Humanoid Robot., Genoa (2006)

56.53 M. Santello, M. Flanders, J.F. Soechting: Postural hand synergies for tool use, J. Neurosci. **18**(23), 10105–10115 (1998)

56.54 F. Tomita, T. Yoshimi, T. Ueshiba, Y. Kawai, Y. Sumi, T. Matsushita, N. Ichimura, K. Sugimoto, Y. Ishiyama: R&D of versatile 3D vision system VVV, Proc. IEEE Int. Conf. SMC, Vol. 5 (1998) pp. 4510–4516

56.55 K. Yokoi, N.E. Sian, T. Sakaguchi, H. Arisumi, E. Yoshida, Y. Kawai, K. Maruyama, T. Yoshimi, O. Stasse, S. Kajita: Humanoid Robot HRP-2 No.10 with human supervision, Proc. Int. Symp. Robot. (ISR'05) (2005)

56.56 K. Yokoyama, H. Handa, T. Isozumi, Y. Fukase, K. Kaneko, F. Kanehiro, Y. Kawai, F. Tomita, H. Hirukawa: Cooperative works by a human and humanoid robot, Proc. Int. Conf. Robot. Autom. (ICRA'03) (2003) pp. 2985–2991

56.57 E. Huber, K. Baker: Using a hybrid of silhouette and range templates for real-time pose estimation, Proc. ICRA 2004 IEEE Int. Conf. Robot. Autom., Vol. 2 (2004) pp. 1652–1657

56.58 A. Edsinger, C.C. Kemp: Two arms are better than one: A behavior-based control system for assistive bimanual manipulation, Proc. 13th Int. Conf. Adv. Robot. (ICAR) (2007)

56.59 P. Fitzpatrick, G. Metta: Grounding vision through experimental manipulation, Phil. Trans. R. Soc. Math. Phys. Eng. Sci. **361**(1811), 2165–2185 (2003)

56.60 V. Zatsiorsky: *Kinetics of Human Motion* (Human Kinetics, Champaign 2002)

56.61 M. Darainy, F. Towhidkhah, D.J. Ostry: Control of hand impedance under static conditions and during reaching movement, J. Neurophysiol. **97**, 2676–2685 (2007)

56.62 S. Schaal, D. Sternad, R. Osu, M. Kawato: Rhythmic arm movement is not discrete, Nat. Neurosci. **7**, 1136–1143 (2004)

56.63 M. Williamson: Robot Arm Control Exploiting Natural Dynamics. Ph.D. Thesis (Massachusetts Institute of Technology, Cambridge 1999)

56.64 G. Pratt, M. Williamson: Series elastic actuators, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS-95), Pittsburg, Vol. 1 (1995) pp. 399–406

56.65 A. Ijspeert, J. Nakanishi, S. Shaal: Learning rhythmic movements by demonstration using nonlinear oscilators, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS2002) (2002) pp. 958–963

56.66 J. Glassmire, M. O'Malley, W. Bluethmann, R. Ambrose: cooperative manipulation between humans and teleoperated agents, Haptics **00**, 114–120 (2004)

56.67 A. Edsinger, C.C. Kemp: Human-robot interaction for cooperative manipulation: Handing objects to one another, Proc. 16th IEEE Int. Symp. Robot Human Interact. Commun. (RO-MAN) (2007)
56.68 S. Schaal: Is imitation learning the route to humanoid robots?, Trends Cognit. Sci. **3**(6), 233–242 (1999)
56.69 A. Billard, M.J. Mataric: A biologically inspired robotic model for learning by imitation, Proc. Fourth Int. Conf. Auton. Agents, ed. by C. Sierra, M. Gini, J.S. Rosenschein (ACM, Barcelona 2000) pp. 373–380
56.70 R. Zollner, T. Asfour, R. Dillmann: Programming by demonstrastion: Dual-arm manipulation tasks for humanoid robots, IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS) (2004)
56.71 D.C. Bentivegna, A. Ude, C.G. Atkeson, G. Cheng: Learning to act from observation and practice, Int. J. Humanoid Robot. **1**(4), 585–611 (2004)
56.72 R. Platt, A. Fagg, R. Grupen: Re-using schematic grasping policies, Proc. IEEE-RAS Int. Conf. Humanoid Robot. (2005)
56.73 K. Harada, S. Kajita, H. Saito, M. Morisawa, F. Kanehiro, K. Fujiwara, K. Kaneko, H. Hirukawa: A humanoid robot carrying a heavy object, Proc. IEEE Int. Conf. Robot. Autom. (2005) pp. 1724–1729
56.74 K. Yamane: *Simulating and Generating Motions of Human Figures* (Springer, Berlin, Heidelberg 2004)
56.75 E.S. Neo, K. Yokoi, S. Kajita, K. Tanie: A framework for remote execution of whole body motions for humanoid robots, IEEE-RAS Int. Conf. Humanoids (2004) pp. 58–68
56.76 E.S. Neo, K. Yokoi, S. Kajita, F. Kanehiro, K. Tanie: A switching command-based whole-body operation method for humanoid robots, IEEE/ASME Trans. Mechatron. **10**(5), 2569–2574 (2005)
56.77 J.J. Kuffner, K. Nishiwaki, S. Kagami, M. Inaba, H. Inoue: Motion planning for humanoid robots under obstacle and dynamic balance constraints, IEEE Int. Conf. Robot. Autom. (2001) pp. 692–698
56.78 K. Yamane, Y. Nakamura: Dynamics filter-concept and implementation of online motion generation for human figures, IEEE Trans. Robot. Autom. **19**(3), 421–432 (2003)
56.79 J.J. Kuffner, S.M. LaValle: RRT-Connect: An efficient approach to single-query path planning, IEEE Int. Conf. Robot. Autom. (2000) pp. 995–1001
56.80 J. Yamaguchi, E. Soga, S. Inoue, A. Takanishi: Development of a bipedal humanoid robot – control method of whole body cooperative dynamic biped walking –, IEEE Int. Conf. Robot. Autom. (1999) pp. 369–374
56.81 S. Kagami, F. Kanehiro: AutoBalancer: An online dynamic balance compensation scheme for humanoid robots, Workshop Algorithmic Found. Robot. (2000) pp. 79–89
56.82 O. Khatib: A unified approach to motion and force control of robot manipulators: The operational space formulation, Int. J. Robot. Autom. **3**(1), 43–53 (1987)
56.83 L. Sentis, O. Khatib: A whole-body control framework for humanoids operation in human environments, IEEE Int. Conf. Robot. Autom. (2006) pp. 2641–2648
56.84 J. Park, O. Khatib: Contact consistent control framework for humanoid robots, IEEE Int. Conf. Robot. Autom. (2006) pp. 1963–1969
56.85 S. Kajita, F. Kanehiro, K. Fujiwara, K. Harada, K. Yokoi, H. Hirukawa: Resolved momentum control: Humanoid motion planning based on the linear and angular momentum, IEEE/RSJ Int. Conf. Intell. Robot. Syst. (2003) pp. 1644–1650
56.86 K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa: Humanoid Robot HRP-2, IEEE Int. Conf. Robot. Autom. (2004) pp. 1083–1090
56.87 L. Sentis, O. Khatib: Synthesis of whole-body behaviors through hierarchical control of behavioral primitives, Int. J. Humanoid Robot. **2**(4), 505–518 (2005)
56.88 K. Harada, S. Kajita, F. Kanehiro, K. Fujiwara, K. Kaneko, K. Yokoi, H. Hirukawa: Real-time planning of humanoid robot's gait for force controlled manipulation, Proc. IEEE Int. Conf. Robot. Autom. (2004) pp. 616–622
56.89 N. Mansard, O. Stasse, F. Chaumette, K. Yokoi: Visually-Guided Grasping while Walking on a Humanoid Robot, IEEE Int. Conf. Robot. Autom. (ICRA'07) (2007)
56.90 K. Harada, S. Kajita, K. Kaneko, H. Hirukawa: Pushing manipulation by humanoid considering two-kinds of ZMPs, Proc. IEEE Int. Conf. Robot. Autom. (2003) pp. 1627–1632
56.91 K. Harada, S. Kajita, K. Kaneko, H. Hirukawa: Dynamics and balance of a humanoid robot during manipulation tasks, IEEE Trans. Robot. **22-3**, 568–575 (2006)
56.92 H. Hirukawa, S. Hattori, K. Harada, S. Kajita, K. Kaneko, F. Kanehiro, K. Fujiwara, M. Morisawa: A universal stability criterion of the foot contact of legged robots – Adios ZMP, Proc. IEEE Int. Conf. Robot. Autom. (2006) pp. 1976–1983
56.93 Y. Hwang, A. Konno, M. Uchiyama: Whole body cooperative tasks and static stability evaluations for a humanoid robot, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (2003) pp. 1901–1906
56.94 T. Takenaka: Posture Control for a Legged Mobile Robot, Japanese Patent 10230485 (1998)
56.95 K. Inoue, H. Yoshida, T. Arai, Y. Mae: Mobile manipulation of humanoids – real-time control based on manipulability and stability –, Proc. IEEE Int. Conf. Robot. Autom. (2000) pp. 2217–2222
56.96 T. Takubo, K. Inoue, K. Sakata, Y. Mae, T. Arai: Mobile manipulation of humanoid robots – control method for CoM position with external force –,

Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (2004) pp. 1180–1185

56.97 C. Breazeal, A. Edsinger, P. Fitzpatrick, B. Scassellati, P. Varchavskaia: Social constraints on animate vision, IEEE Intell. Syst. **15**, 32–37 (2000)

56.98 T. Shibata, S. Vijayakumar, J. Conradt, S. Schaal: Biomimetic oculomotor control, Adapt. Behav. **9**, 189–208 (2001)

56.99 B. Scassellati: *A Binocular, Foveated Active Vision System*, Vol. AIM-1628 (MIT, Cambridge 1998)

56.100 A. Ude, C. Gaskett, G. Cheng: Foveated vision systems with two cameras per eye, Proc. IEEE Int. Conf. Robot. Autom., Orlando (2006)

56.101 H. Kozima: Infanoid: A babybot that explores the social environment. In: *Socially Intelligent Agents: Creating Relationships with Computers and Robots*, ed. by K. Dautenhahn, A.H. Bond, L. Canamero, B. Edmonds (Kluwer Academic, Amsterdam 2002) pp. 157–164

56.102 F. Berton, G. Sandini, G. Metta: Anthropomorphic Visual Sensors. In: *The Encyclopedia of Sensors*, Vol. X, ed. by M.V. Pishko, C.A. Grimes, E.C. Dickey (American Scientific, Valencia 2005) pp. 1–16

56.103 T. Shibata, S. Schaal: Biomimetic gaze stabilization based on feedback-error-learning with nonparametric regression networks, Neural Netw. **14**(2), 201–216 (2001)

56.104 P. Heracleous, S. Nakamura, K. Shikano: Simultaneous recognition of distant-talking speech to multiple talkers based on the 3-D N-best search method, J. VLSI Signal Process. Syst. Archive **36**(2–3), 105–116 (2004)

56.105 J. Ido, Y. Matsumoto, T. Ogasawara, R. Nisimura: Humanoid with interaction ability using vision and speech information, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS'06) (2006)

56.106 I. Hara, F. Asano, H. Asoh, J. Ogata, N. Ichimura, Y. Kawai, F. Kanehiro, H. Hirukawa, K. Yamamoto: Robust speech interface based on audio and video information fusion for humanoid HRP-2, Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS'04) (2004) pp. 2402–2410

56.107 M. Lungarella, G. Metta, R. Pfeifer, G. Sandini: Developmental robotics: a survey, Connect. Sci. **15**(4), 151–190 (2003)

56.108 B. Scassellati, C. Crick, K. Gold, E. Kim, F. Shic, G. Sun: Social development, Comput. Intell. Mag. (IEEE) **1**(3), 41–47 (2006)