Humanoid Robots

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Definitions

- Humanoid robot (or simply ”humanoid”): It usually refers to a robot whose shape is close to that of humans. Its definition varies according to researchers, ranging from a dual-arm upper-body robot to a biped walker. In this chapter, an actuated human-size biped robot with arms and a head, designed to achieve some human capability is considered as a humanoid robot.
- Zero Moment Point (ZMP): Assuming the flat ground, the ZMP is defined as the point where the horizontal components of the moments applied to the body parts attached to the ground become zero.

Overview

This chapter is intended to provide a brief overview of humanoid robots, focusing on the human-size, bipedal type. Starting from its historical development and hardware progress, bipedal locomotion and whole-body motion planning and control are described as important aspects of making humanoid robots execute desired tasks. Wearable device evaluation and large-scale assembly are also introduced as promising applications of humanoid robots, and their expected future evolution is discussed.

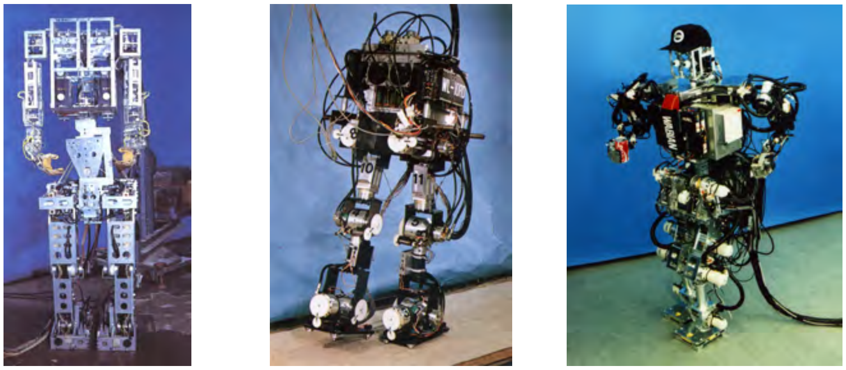
Introduction of Humanoid Robots

A typical list of applications of humanoids can be found in 2005 Hirukawa (2006), based on the results from national Humanoid Research Project (HRP) in Japan: 1) its human-like shape is useful, e.g., entertainment and human interaction; 2) it can use tools or machines designed for humans, e.g., operating power machines on dangerous construction sites; and 3) it can fit and work in environments designed for humans, e.g., inspections in damaged nuclear plants. The first application has been extended to the evaluation of devices for humans Omer et al (2008); Miura et al (2013) whereas the latter two have been intensively investigated, particularly in the DARPA Robotics Challenge (DRC) Pratt and Manzo (2013) Pfeiffer et al (2017), which is detailed in Section . In this way, research on humanoid robots is still growing in many aspects, motivated by realistic applications and the recent leaps of advancement in artificial intelligence (AI). This chapter is intended to invite readers to humanoid research by providing the required fundamentals. After outlining an historical overview of hardware development, various aspects of humanoid motion generation and control are presented: bipedal walking, whole-body motion planning and control, and motion imitation and optimization. Some of the above-mentioned applications are introduced before addressing future perspectives.

For further reading, some books dedicated to humanoid robots are recommended: a textbook for first learners Kajita et al (2014), a comprehensive reference book covering the entire research area of humanoid robots Goswami and Vadakkepat (2017), a book dedicated to humanoid motion planning Harada et al (2010), and the "Humanoid" chapter of the Handbook of Robotics 2 Siciliano and Khatib (2016).

History and Hardware

Let us outline the history of humanoid robots. It is agreed that Japan was leading the research on humanoid robots until about the early 2000s, whereas now they are intensively studied almost everywhere in the world. The earliest academically reported humanoid is Kato's WABOT-1 (WAseda roBOT-1), which can walk in a quasi-static manner, recognize an object, and manipulate it using its hands Kato et al (1973) (Fig.1a). It is quite amazing to think that such a complete humanoid robot had already been developed more than 40 years ago (1973). In those early years, mainly because of immature technologies, many researchers did not believe the feasibility of humanoid robots, which were still regarded as science fiction. Some researchers continued to work on the dynamic walking of biped robots, together with hardware development. Takanishi and Yamaguchi developed WL (Waseda Leg, Fig. 1b) Takanishi et al (1990a) and WABIAN (WAseda BIpedal humANoid, Fig. 1c) Yarnaguchi and Takanishi (1997), a humanoid series (1991 and 1997, respectively) that can walk by ensuring dynamic stability through upper-body motions, based on the concept of zero moment point (ZMP) Vukobratović and Borovac (2004). Meanwhile, Honda R&D launched a secret project on humanoid robots in 1986, and revealed the P2 (second prototype model) Hirai et al (1998) humanoid robot in 1996, shown in Fig. 2a. The P2 is an autonomous humanoid that is 1.82 m tall and weighs 210 kg. It is capable of walking by wireless remote control, going up and down stairs, and pushing a cart. Its sudden release was



(a) WABOT (WAseda roBOT)-1: Humanoid Robotics Institute, Waseda University, Tokyo, Japan

(b) WL (Waseda Leg)-10RD (No.10 Refined Dynamic): Atsuo Takanishi Laboratory, Waseda University, Tokyo, Japan

(c) WABIAN (WAseda BIpedal humANoid): Atsuo Takanishi Laboratory, Waseda University, Tokyo, Japan

Fig. 1 Humanoid robots developed in Waseda University (courtesy of Waseda University).

a total surprise and a brutal shock to many researchers, but it had the positive impact of encouraging them to push humanoid research forward for realistic applications and to show that humanoids were no longer science fiction.

Soon afterwards, in Japan, the national Humanoid Research Project (HRP) Tanie and Yokoi (2003); Hirukawa et al (2004) was launched by Ministry of Economy, Trade and Industry (METI), Japan. The HRP project was led by National Institute of Advanced Industrial Science and Technology (AIST), with Honda R&D involved as a partner, among other private companies. Its goal was to develop a humanoid robot that could coexist in human society and collaborate with humans. In the meantime, Honda evolved their humanoid robot into P3 and finally the Advanced Step in Innovative Mobility (ASIMO), shown in Fig. 2b Takenaka et al (2009). ASIMO can hop and run, pour tea into a cup, and charge its own battery. The HRP project concluded in 2003 with HRP-2 Kaneko et al (2004) as the result of its hardware development, together with a number of applications like the teleoperated backhoe maneuver Yokoi et al (2003), and human-robot collaborative transportation Yokoyama et al (2003). The follow-up project to HRP produced hardware platforms such as HRP-3, with a tough structure for industrial use Kaneko et al (2008), and HRP-4C, with a closer shape to that of humans for entertainment use Kaneko et al (2009), as shown in Fig.3.

One important lesson from those projects is the importance of the platform. For instance, HRP-2 has been utilized in a number of different universities and research institutes, which allows sharing the development loads and results. The accompanying common software development platforms, often open-source ones like ROS and Gazebo Martinez and Fernndez (2013), YARP

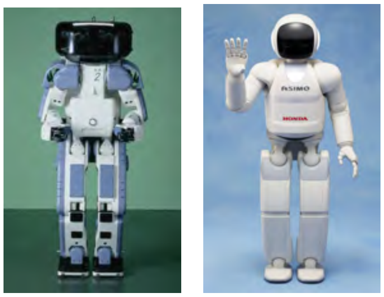

(a) P2 (b) ASIMO

Fig. 2 Humanoids developed by Honda R&D (courtesy of Honda R&D).

Metta1 et al (2006), and Choreonoid Nakaoka (2012) play an important role in results sharing by allowing researchers and engineers to exchange their software. For example, the installation of HRP-2 at the LAAS-CNRS, in France, triggered collaborative research on humanoid robots involving AIST and many European institutes through EU projects. This led to many joint publications. Since the mid-2000s, various humanoid robots have been developed, including WABIAN 2 Ogura et al (2006), iCub Metta et al (2008), HUBO Park et al (2005), and TORO Englsberger et al (2014), shown in Fig. 4, some of which are also used as research platforms for joint research.

However, when the Great Earthquake hit the Tohoku area of Japan and caused severe accidents in the Fukushima Daiichi nuclear power plants, those humanoid robots could neither search for buried victims in the rubble nor perform critical operations to replace humans in radioactive environments. This tragedy drove researchers in humanoid robots to orient toward humanitarian activities,


(a) HRP-2 (b) HRP-3 (c) HRP-4C (Cybernetic Human)

Fig. 3 Humanoid robots developed at AIST.

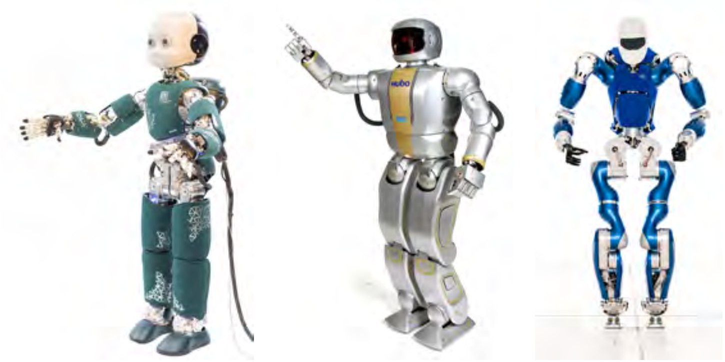

(a) iCub (b) HUBO-2 (c) TORO

Fig. 4 Humanoid robots developed around the world: (a) iCub (courtesy of IIT-Istituto Italiano di Tecnologia), (b) Hubo (courtesy of the Humanoid Robot Research Center, KAIST-Korea Advanced Institute of Science and Technology), and (c) the torque-controlled humanoid robot TORO, developed at DLR (courtesy of the DLR-German Space Agency).

especially disaster response. The DRC competition was launched against this backdrop Pratt and Manzo (2013). In the competition, participant robots are required to complete such tasks as driving a vehicle, opening a door, rotating a valve, using a tool, going over rough terrain, and climbing stairs within a limited amount of time. As a result, remarkable progress has been made in a short time. This can be attributed to the effect of competition, which mobilizes a huge mass of people, in addition to the distribution of a common platform, as mentioned earlier, this time the hydraulically actuated Atlas humanoid robot Cass (2013). The DRC also boosted the development of new humanoid hardware, e.g., Valkyrie by NASA Radford et al (2015) and DRC-Hubo Lim et al (2015); Jeong et al (2015), which continue to evolve in terms of hardware and control software.

As of 2017, after the DRC, research on humanoid robots is still very active for applications related not only to disaster response but also to large-scale manufacturing, as mentioned in Section of this Chapter.

Key Research Findings

Bipedal Walking

Humanoid robots have evolved along with the progress in bipedal walking. The WABOT-1 Kato et al (1973) can perform quasi-static biped walking, namely a stable walking motion that always keeps the total center of mass (COM) projected on the ground, inside a support polygon formed by the outer contour of the foot (or feet) touching the ground. Obviously, this becomes very slow, unlike natural human walking. The significant difference is that natural human walking is a dynamic motion, where stability is maintained by taking into account the inertial force caused by acceleration. Because the COM can go outside the support polygon during dynamic walking, the ZMP Vukobratović and Borovac (2004) is used as the stability criterion.

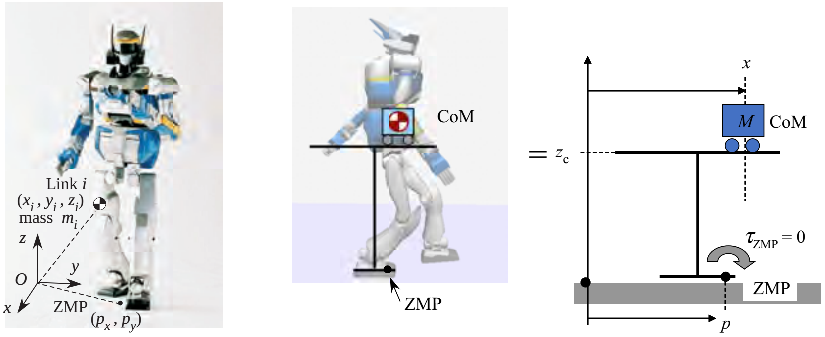
The definition of ZMP is given earlier in this Chapter. By modeling each humanoid link i as a concentrated mass whose position and mass are (x_i, y_i, z_i) and m_i, respectively as shown in Fig. 5a, the position of the ZMP (p_x, p_y) can be written as Takanishi et al (1985, 1990a); Vukobratović and Borovac (2004)

$$\begin{aligned} p_x &= \frac{\sum m_i(-z_i\ddot{x}_i + x_i(\ddot{z}_i + g))}{\sum m_i(\ddot{z}_i + g)} \\ p_y &= \frac{\sum m_i(-z_i\ddot{y}_i + y_i(\ddot{z}_i + g))}{\sum m_i(\ddot{z}_i + g)} \qquad (1) \end{aligned}$$

where g is the gravity in $-z$ direction. These equations can estimate the ZMP with a practical precision, although they neglect the effect of the inertia tensor of each link whose contribution to the total motion is sufficiently small.

Dynamic walking control using this ZMP is widely known as an established method. The basic approach is to compute stable bipedal motion after deriving the reference ZMP trajectory to follow the desired footsteps. Takanishi et al. proposed a method for tracking the target ZMP using a Fourier transform to model the upper-body cyclic motion Takanishi et al (1990b). Honda P2 and other following robots are controlled based on "ground reaction force (GRF) control" and "model ZMP control" Hirai et al (1998). When the robot is about to tip over, GRF control is used to recover its posture. But if the recovery is not sufficient, model ZMP control is used to accelerate the upper-body and achieve the desired ZMP. Nishiwaki et al. proposed an online walking pattern generation method based on the fast computation of a partial trajectory to follow the desired ZMP Nishiwaki et al (2002); Nishiwaki and Kagami (2009).

Kajita et. al Kajita et al (2003a, 2014) applied preview control, regarded as model predictive control (MPC) without constraints on the optimization, to compute a dynamic walking motion from the desired ZMP trajectory based on a simplified linear inverted pendulum model (LIPM). By modeling the distributed concentrated masses into



(a) (b)

Fig. 5 (a) Robot model including link structure and ZMP related to Eq. (1) (b) Table-cart model representing the relationship between COM and ZMP in Eq. (2) Kajita et al (2003a).

a table-cart model with a single-point mass and constant height, as illustrated in Fig. 5b, Eq. (1) becomes

$$\begin{aligned} p_x &= x - \frac{z_c}{g}\ddot{x} \\ p_y &= y - \frac{z_c}{g}\ddot{y} \end{aligned} \tag{2}$$

where (x, y) is the total COM and z_c is the constant height of the waist. As a result, preview control allows the COM velocity to be generated online by taking into account the future evolution of the ZMP through preview control, which results in smoother walking motions. This method is generalized based on an optimization technique Wieber (2008) to bind the ZMP in a designated area within the support polygon. Although the LIPM is quite a simple model, it has been demonstrated that a practical dynamic walking pattern can be generated through preview control. If some upper-body motion occurs simultaneously during walking, its effect is computed with a dynamic filter Yamane and Nakamura (2003) to adjust the resultant walking motion computed by the preview control scheme. For instance, shifting the waist position during walking can maintain the stability of the original dynamic walking pattern Kajita et al (2003a, 2014).

Although we have mainly presented a well-established bipedal walking pattern generator based on the ZMP, other criteria have been proposed for stability analysis and pattern generation. Among them are the capture point Pratt et al (2006) and the divergent component of motion (DCM) Takenaka et al (2009); Englsberger et al (2013), which can be applied to push recovery and walking motion generation on 3D terrain. The capture point is the ground position in which to place the next footstep in order to come to a complete stop, whereas the DCM is its generalized concept in 3D space. In this way, the biped motion generation technique is still evolving to adapt to various terrains in a robust and reactive manner.

Whole-body Motion Planning and Control

So far, together with online biped walking pattern generation, whole-body motion planning, and control has been intensively studied. It deals with all kinds of combined motions generated by the overall robot body, including biped locomotion mainly coming from the lower limbs. If we look at human motions, we naturally use combined movements of our body parts in an efficient manner to achieve a desired goal. For example, if you want to pick up an object under a table, you might bend your knees and extend your hand toward the object while maintaining your balance and avoiding collision with the table. Whole-body motion generation enables a humanoid to perform such motions, and it includes two main elements: planning and control. The former obtains a global "path," a discrete set of configurations (robot position and posture), from the initial position to the goal. The latter provides a local method for allowing the humanoid to perform a "trajectory" that is a continuous transition of the angles of each joint, transformed from the planned path. In the previous example, the path corresponds to the rough idea of reaching the object while avoiding collision and the trajectory is the actual motions generated by our limbs.

Since the 1990s, sampling-based motion planning techniques Latombe (1991); Choset et al (2006); LaValle (2006) have enjoyed drastic progress in solving the path planning of high degree-of-freedom (DOF) robotic systems, along with the rapid growth of computing power. The method consists of randomly sampling robot configurations and connecting them to compose a collision-free path from initial to goal configurations. Sampling-based motion planning has been applied to humanoid robots since the early 2000s by taking advantage of its capacity to deal with high DOF systems. Given that sampled whole-body configurations do not necessarily satisfy the stability conditions, several methods have been proposed that utilize a dynamic filter to obtain stable configurations Kuffner et al (2002), overlaying the planned whole-body manipulation motion onto a dynamically stable walking path Yoshida et al (2008) or sampling configurations in the workspace for tasks to project onto feasible humanoid postures Dalibard et al (2009); Berenson et al (2011). Recently, multi-contact motion planning has been studied more and more intensively in order to extend the field of activities Hauser et al (2005); Escande et al (2006, 2013). This technique allows for the planning of humanoid motions, supporting a humanoid's body with multiple contacts between environments and not only the feet but also the arms and other body parts, to overcome a rough terrain, climb a ladder, or get into a narrow space. Because the selection of contact points has infinite possibilities, those proposed methods generate a sequence of contact points that accompany whole-body postures based on some heuristics that evaluate feasibility and stability. Once this contact sequence is planned, a whole-body controller handles trajectory generation, and control for the humanoid to perform the planned path.

For recent research developments, readers are referred to dedicated books that survey related work Harada et al (2010); Goswami and Vadakkepat (2017). Some software frameworks are also available that facilitate motion planning for humanoid robots, such as MoveIt! Chitta et al (2012), OpenRAVE Diankov and Kuffner (2008), HPP Mirabel et al (2016), and OMPL Sucan et al (2012).

After planning feasible paths, a trajectory, along with the time that it is sent to the robot as the control input, should be generated. Because the planned path is often a discrete sequence of configurations, sometimes with reduced DOF, it is necessary to transform it to a trajectory for every actuated DOF, usually each joint, through such techniques as interpolation or whole-body motion generation. Local methods like prioritized inverse kinematics (IK) using the pseudo-inverse of the Jacobian can be applied to resolve various tasks and constraints on priorities Nakamura (1991); Siciliano and Slotine (1991); Yoshida et al (2008). Here tasks can be specified in a workspace like extending a hand and grasping an object, directing a camera in a particular direction, or performing leg motions such as stepping or walking. Velocity-based IK control can be extended, including other whole-body tasks. Sugihara developed a method to compute the "COM Jacobian" Sugihara and Nakamura (2002) so that the balancing motion with COM could be integrated into IK for whole-body motions. Resolved momentum control is another local method Kajita et al (2003b) for whole-body control. After deriving the desired linear/angular momentum for the desired tasks, the method allows automatic computation of each body part's motion. Recently, methods have been proposed for a task-priority IK framework to include inequalities that describe constraints such as the COM inside the support polygon or gazing inside an interested area Kanoun et al (2009, 2011). Figure 6 shows the result of whole-body motion generation based on this framework: the robot reaches the target, keeping its hand from entering its view as much as possible to avoid obstructing its vision.

The aforementioned IK scheme can be generalized as a least-square method to solve more complex motion generation problems. Especially in order to cope with the dynamic constraints involving forces or torques in the case of locomotion on non-flat terrain, which sometimes require multiple contacts with body parts other than feet, more generally applicable optimization techniques represented by quadratic programming are now frequently used Bouyarmane et al (2012); Saab et al (2013); Erez et al (2013); Lengagne et al (2013); Escande et al

Fig. 6 Hierarchical inverse kinematics, including inequality constraints. Humanoid HRP-2 has the high-priority task of reaching the ball on the ground under a low-priority constraint that forces it to put its hand outside of the box region as much as possible but not block its view, which can be described as an inequality. The constraint is respected until it is finally violated to achieve the high-priority reaching task Kanoun et al (2009).

(2014); Kuindersma et al (2016). The desired tasks are described as an evaluation function in quadratic form, including joint accelerations together with constraints including whole-body dynamics and inequalities such as joint torque limits, collision avoidance, and contact constraints. The resultant motions are often described by joint accelerations, which can be executed by position-controlled humanoids through integration, or directly through torque control by torque-controlled humanoids like TORO Englsberger et al (2014). Figure 7 shows the results of ladder climbing Vaillant et al (2016) based on the multi-contact motion planning and control method already described.

Examples of Application

Humanoid robots are still under development and are not yet applied in everyday life or to industrial usage. However, they are making steady progress, showing us some glimpse of the practical uses that leverage their features. As mentioned in Section , after the five-year HRP in Japan Tanie and Yokoi (2003); Hirukawa et al (2004), Hirukawa anticipated three main application directions for humanoid robots: 1) the shape itself is useful, 2) the tools for humans can be used as they are, and 3) the social environments for humans can be used as they are Hirukawa (2006). For direction 1), typical applications that take advantage of human shape are entertainment and the digital archiving of intangible cultural assets. For example, the “cybernetic human” HRP-4C Kaneko et al (2009) has been utilized as a dancer or a master of ceremonies in event shows. Another example is the digital archiving of traditional cultures that are in danger of disappearing owing to a lack of successors. Nakaoka et al. demonstrated that the humanoid robot HRP-2 could reproduce the dynamic human motions of traditional Japanese folk dance Nakaoka et al (2005), which illustrates one possible use of using a humanoid as an instructor of various traditional cultures by archiving and reproducing motions. Integrated with human behavior recognition, communication applications for solitary people and remote monitoring can be considered in this category. For directions 2) and 3), several applications including plant maintenance and machine tele-operation in hazardous environments as well as home management were demonstrated in the HRP project. Although the project showed several possibilities, concrete applications were still unclear.

After repeated natural disasters such as earthquakes and hurricanes, and the severe accidents in the nuclear power plants at Fukushima, the need for disaster response robots has been clearly recognized. With this kind of ultimate goal, several closer applications for humanoids are emerging. First, as an application of direction 2) using products designed for humans, the evaluation of wearable devices is being studied instead of human subjects Omer et al (2008); Miura et al (2013). This is done by devising a humanoid robot that has a shape and structure close to those of a human to reproduce various measured users’ motions based on a technique called retargeting, which transforms the human motions into humanoid motions Ayusawa et al (2015); Ayusawa and Yoshida (2017).

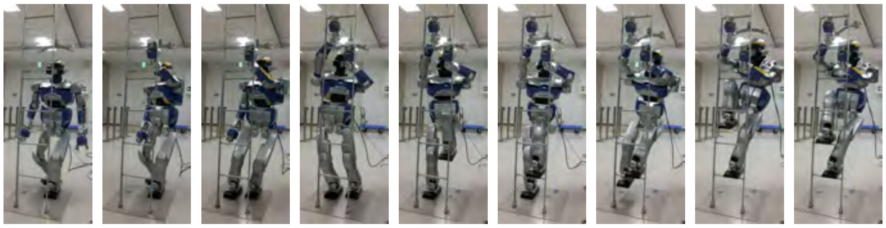
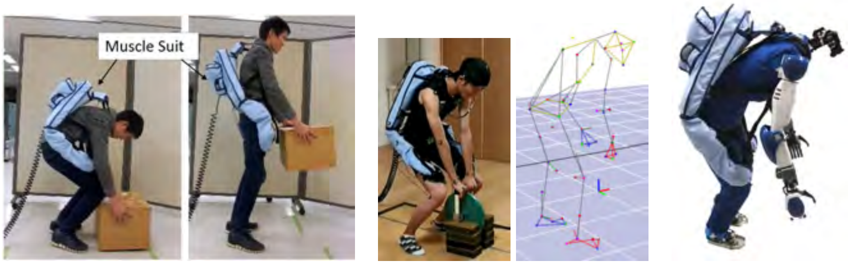


Fig. 7 Ladder climbing by the humanoid HRP-2. First, the left arm grasps a rung, the right leg is brought near the ladder, and the right arm grasps the upper rung. Then, the left leg is raised onto the first rung from the bottom, and the right leg is raised onto the second rung to lift the robot from the ground Vaillant et al (2016).

This application is expected to bring several advantages to solving issues with human experiments: quantitative evaluation of the supportive effect as opposed to subjective questionnaires, clearing heavy ethical procedures and high repeatability in situations close to real use. Figure 8 shows an example of such an application, in which the humanoid robot HRP-4 wears a powerful wearable supportive "Muscle Suit" Kobayashi et al (2009) device and evaluates its supportive torque Ito et al (2017).

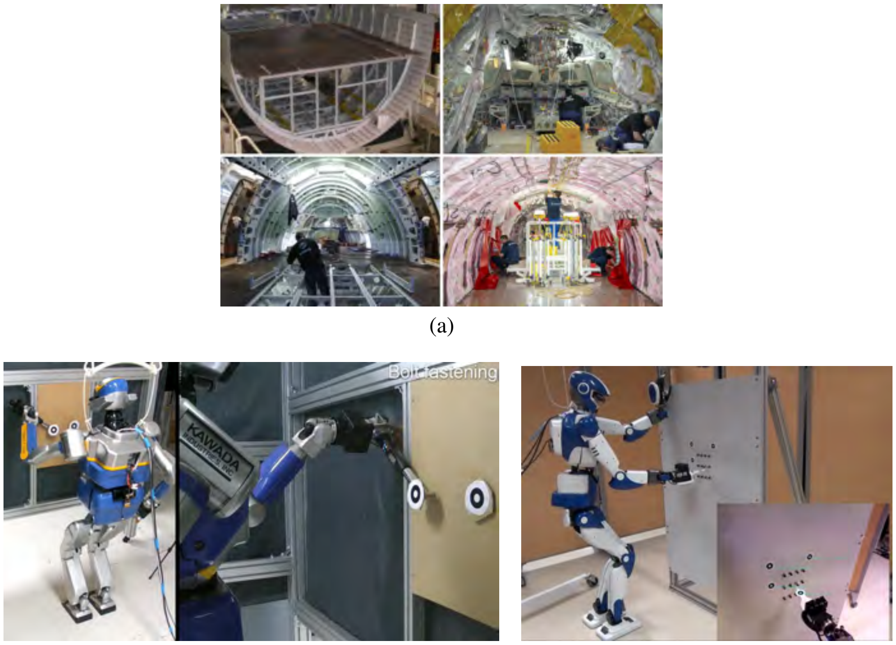
As a closer application in direction 3) of working in human environments as they are, an "industrial humanoid" in large-scale manufacturing is investigated more and more intensively in recent years. An exemplar case is airplane manufacturing, which is much less automated in that many of the assembly processes are still done manually compared with the automobile industry. Human workers are often need to do tedious and repetitive tasks in confined environments sometimes forcing very difficult postures, which may lead to serious physical disorders, as shown in Fig. 9a. Humanoid robots are expected to execute such jobs to relieve human workers from those "non-added-value"



(a) (b) (c)

Fig. 8 Evaluation of assistive device using a humanoid. (a) pneumatically powered assistive device "Muscle Suit," (b) measurement and analysis of human lifting motion using a motion capture system, and (c) the humanoid HRP-4 wearing the evaluation device and reproducing the measured motion.

tasks so that they can concentrate on more creative and intelligent tasks. Unlike disaster response, the advantage of this application is that we usually have information about the environment, for example, CAD data of the assembled airplane, which allows the humanoid to localize itself based on sensory information, such as visual stimuli. The European Commission Horizon 2020 project COMANOID (Collaborative humanoid) and AIRBUS-CNRS-JRL Joint Research Program envision the development of technologies enabling humanoid robots to execute nut fastening and circuit breaker testing Pfeiffer et al (2017); Bolotnikova et al (2017) (Fig. 9b, c). This area of application is not limited to aircraft but can be applied to shipyards, or plant construction and maintenance. Now that a number of platforms are being proposed by companies in pursuit of human-size "industrial humanoid" platforms Kakiuchi et al (2017); Yoshiike et al (2017); Tellez et al (2008), we can expect that humanoids will be utilized for realistic applications in the near future, together with progress in humanoid capabilities, as mentioned in this chapter. Home servicing applications could also be considered by augmenting their interaction capacity through the development of this type of collaborative and interactive humanoid robot.



(a)

(b)

(c)

Fig. 9 Possible applications of humanoids in large-scale assembly. (a) shop floors of airplane assembly: the cargo area, cockpit, and upper area in two different phases of assembly/installation, where humans are working in difficult postures; use cases involving (b) a repetitive test of circuit-breakers Bolotnikova et al (2017); and (c) nut fastening using tools Pfeiffer et al (2017).

Future Directions for Research

This chapter provided a brief overview of humanoid robots, from the historical aspects, development of hardware and software, and their applications, focusing on human-size biped humanoids. As mentioned in this chapter, humanoid robotics is an active domain that is growing and making considerable advances. Until recently, despite tremendous progress, there is still room for further evolution. Robotics is already a research field requiring the integration of various technologies, such as perception, intelligence, and motion generation, and humanoid robots are the most demanding owing to their complexity.

Humanoid robots need to incorporate most of the perceptual technologies: recognition of environments using vision and laser, and auditory signal, tactile and force information. In particular, the last one currently requires considerable improvement for the future development of humanoids. Physical interactions with environments and humans are the most lacking capacity in current humanoid robots. Although intensive efforts are being made using tactile sensors in iCub amd M. Fumagalli et al (2011) or torque control Englsberger et al (2014), for instance, current humanoid robots are still rigid and insensitive, far from the fine and compliant physical interactions that humans can perform. This is also closely related to the evolution of actuation technology. New compliant actuators are being awaited that have efficiencies and capacities that are equivalent to our muscles and can completely replace the combination of electric motors and mechanical gears commonly used in humanoids. Concerning hardware, robustness is also a critical issue: “rigid” humanoid robots are vulnerable to damage, especially when they fall. Robustness in hardware and control is therefore essential. Soft robotics Albu-Schäffer et al (2008); Majidi (2013) has been attracting attention for decades, and we can expect breakthroughs through interdisciplinary research that also involves materials and biological sciences. Obviously, control techniques should also be investigated to exploit the progress in perception and actuation. These developing technologies are altogether the key drivers toward the high-performance industrial humanoid robots mentioned earlier that can execute dexterous tasks in an autonomous way, collaborating with human workers when necessary.

Last but not least, the intelligence to cope with humanoids’ complex physical embodiments and environments is of course indispensable. In this chapter, we focused on humanoid research, but recent remarkable advancements in AI, especially deep learning, can naturally go very well with humanoids. Advanced intelligence is necessary everywhere they go: understanding and analyzing their surroundings, making decisions to accomplish required tasks, and interacting with humans and environments in an adaptive manner. Synergetic interdisciplinary research is required more than ever to push humanoid technology toward its applications in the real world, so that humanoids can be integrated as the best partners of humans in near future.

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