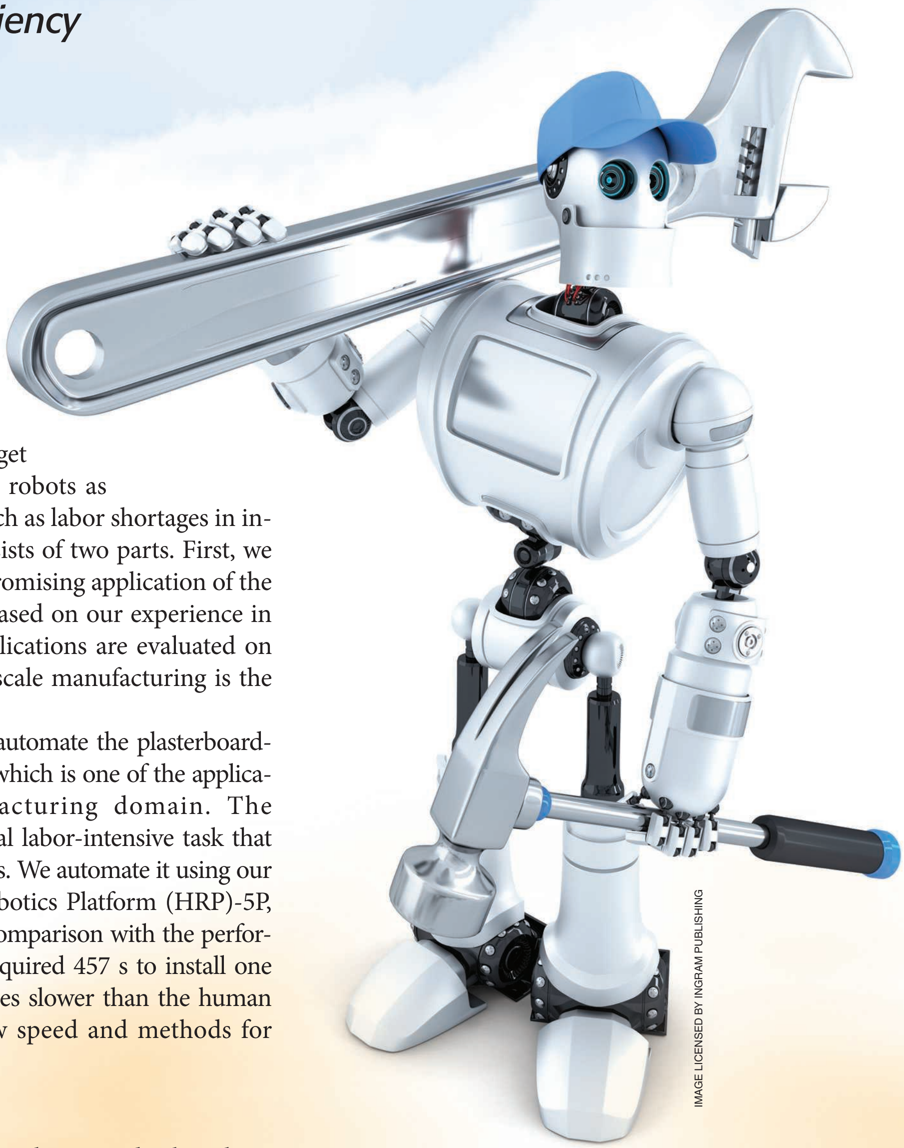
Toward Industrialization of Humanoid Robots

Autonomous Plasterboard Installation to Improve Safety and Efficiency



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Twenty-three years have passed since Honda unveiled its P2 robot in 1996. Even though extensive research has been conducted since then, humanoid robots have not been commercialized for practical applications. It is important to carefully select target applications to commercialize humanoid robots as soon as possible and solve social issues, such as labor shortages in industries and elderly care. This article consists of two parts. First, we discuss what we consider to be the most promising application of the commercialization of humanoid robots, based on our experience in their development. Several candidate applications are evaluated on four criteria, and we conclude that large-scale manufacturing is the most promising one.

Second, we introduce our approach to automate the plasterboard-installation process in house construction, which is one of the applications within the large-scale manufacturing domain. The plasterboard-installation process is a typical labor-intensive task that should not be performed by human workers. We automate it using our latest humanoid robot, the Humanoid Robotics Platform (HRP)-5P, and present the results accompanied by a comparison with the performance of human subjects. The HRP-5P required 457 s to install one sheet of plasterboard, and it was eight times slower than the human subjects. The major reasons for the slow speed and methods for improving it are discussed.

Potential Applications

Since Honda unveiled the P2 [1], numerous humanoid robots have been developed worldwide. The National Institute of Advanced Industrial Science and Technology (AIST), Tokyo, participated in the HRP from 1998 to 2002 and developed the HRP-2 [2] in collaboration with private companies. Since then, we have developed the HRP series, including the HRP-3 [3] and HRP-4C [4], and a few of them have been commercialized as research platforms (Figure 1).

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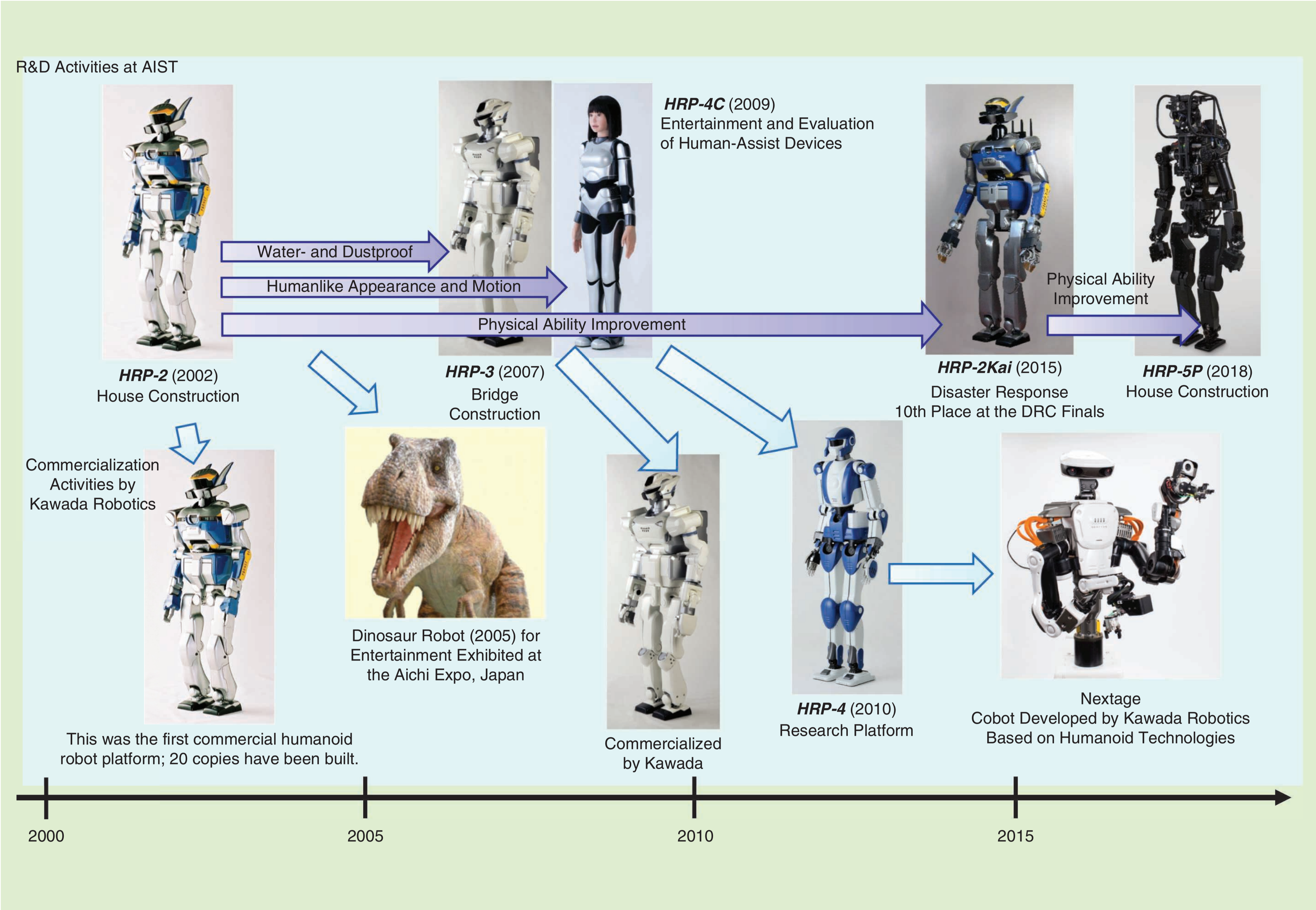

Figure 1. The humanoid–robot development history at the AIST, including the HRP-2, HRP-3, HRP-4C, HRP-4, HRP-2Kai, and HRP-5P. A few of the HRP models were commercialized as research platforms. DRC: DARPA Robotics Challenge.

Even though more than 20 years have passed since the P2 was unveiled, no humanoid robot has been commercialized for practical applications, except as a research platform.

One of the advantages of humanoid robots is that they can move in an environment designed for humans without changing it. Additionally, they can use tools and vehicles designed for humans because of their anthropomorphic body structure. However, a humanoid robot must have recognition and physical abilities comparable with those of a human to exploit that advantage; such a humanoid robot does not exist. A humanoid robot is not required if we can modify an environment so that a robot can work in it using its limited recognition and physical abilities. In that case, using a robot designed for the modified environment is a reasonable solution. We believe that the commercialization of humanoid robots has not been realized because of this technical immaturity.

There are numerous tasks that cannot be performed by conventional robots and can only be completed by human workers. We believe that humanoid robots are a promising solution to automate them. To boost the commercialization of humanoid robots, we believe that it is important to first select an appropriate application based on its technical difficulty, market size, and so on. Then, the technology can be improved while commercializing the humanoid robot within its scope, and the range of appropriate applications can be extended. This article considers which application should be realized first and concludes that it is large-scale manufacturing. Based on that conclusion, we select the plasterboard-installation task and automate it by utilizing our latest humanoid robot.

Humanoid Applications

The AIST has conducted trials for the commercialization of humanoid robots with Kawada Robotics, Tokyo, as shown in Figure 1. The HRP-2 was operated by voice commands from a human coworker, and it carried and installed a panel by collaborating with that person [6]. The HRP-3 was teleoperated and performed a small part of a bridge-construction task [3]. After those trials, we developed the HRP-4C for an entertainment application [7] since its technical difficulty was lower compared with other applications. After the Great East Japan Earthquake in 2011, we worked on the development of a disaster-response humanoid robot [8]. Based on our experiences, we evaluated several applications to select the most promising one for humanoid robots.

Evaluation Criteria

We used the following criteria to evaluate several applications:

- *Necessity for humanoids*: If a task can be carried out by a robot that was designed for it, using the robot is more reasonable than opting for a versatile humanoid robot, because the cost of the robot is lower than that of the humanoid robot. We should select a task that can be performed by human workers but that they should not undertake because of a harsh working environment, heavy physical burden, and so on.
- *Technical difficulty*: Ideally, it should be possible to use humanoid robots in any applications in which humans are working. However, if the technical difficulty of an application is extremely high compared to the current technology level, it will require considerable time to develop a robot that can complete the task. We consider the required autonomy level, prior knowledge about the working environment and tasks, and the required safety level as the major factors of technical difficulty. A high autonomy level, less prior knowledge, and a high safety level increase the technical difficulty.
- *Market size*: If a few robots are sufficient for an application, the market size will remain small. As a result, it is difficult to launch and maintain businesses based on those applications, and technological evolution will not occur.
- *Cost restriction*: Since a humanoid robot has an anthropomorphic body, it inevitably contains numerous joints, and its cost is higher than that of a specialized robot. Commercialization, such as for personal use, becomes highly difficult if the cost restriction is extremely stringent.

Disaster Response

- *Necessity for humanoids (limited)*: In recent years, several sediment disasters, volcanic eruptions, and earthquakes occurred in Japan. In such situations, robots are used to prevent secondary disasters. Drones have already been deployed to inspect affected areas from the air immediately after a disaster. However, initial inspections on the ground and the removal of landslides and rubble are carried out by humans because heavy machines cannot be used before rescuers search for victims. Remote-controlled heavy machines are used during the disaster-recovery phase. However, it would be helpful if a humanoid robot could operate multiple kinds of normal heavy machines. Since a humanoid robot is suited to working in environments designed for humans, it is appropriate for use at chemical, biological, radiological, nuclear, and explosive disaster sites. However, the necessity for humanoids at other disaster sites is limited.
- *Technical difficulty (autonomy: low; prior knowledge: less; safety: low)*: The required autonomy level is low because disaster-response robots are generally teleoperated. The prior knowledge is limited because we cannot determine what is happening at disaster sites in advance. The required safety level is low because, in numerous cases, there are no humans at disaster sites.
- *Market size (small)*: It is difficult to expect a large market size because disaster-response robots are used only after catastrophes. That constraint applies to all disaster response robots, not only humanoid robots.
- *Cost restriction (low)*: The cost restriction is not expected to be excessive because the social importance of disaster response is quite high.

Infrastructure Maintenance

- *Necessity for humanoids (limited)*: In recent years, aging social and industrial infrastructures have become an urgent issue in Japan. Robots are expected to be deployed because of a shortage of manpower and the risk related to many construction tasks. Drones and arm robots have been developed to inspect bridges and tunnels. Since the inspection targets are diverse and complex, there are locations that are difficult for conventional robots to access. A few types of inspections involve touching objects and using tools to hit them. A humanoid robot would be useful in those cases if it could perform the inspections using tools designed for humans. There are vertical ladders and narrow passages in industrial plants, and human workers move through them using their entire body. Those environments are difficult for conventional robots to navigate. A humanoid robot would be particularly useful in such places thanks to its anthropomorphic body. Since numerous robots have been developed for infrastructure maintenance, the remaining applications suited exclusively to humanoid robots are limited.

- *Technical difficulty (autonomy: high; prior knowledge: rich; safety: low)*: The required autonomy level is high because robots are expected to inspect infrastructures autonomously. The prior knowledge is rich because the inspection work is repeated in the same environment, and robots can use maps of the area. The required safety level is low since robots can reach locations that are difficult for humans to access.
- *«Market size (medium)*: A medium market size can be expected because there is a large number of aging infrastructures.
- *Cost restriction (low)*: The cost restriction is low because infrastructure maintenance is managed by large, private companies and public institutions.

Decommissioning

- *Necessity for humanoids (sufficient)*: The use of humanoid robots at decommissioning sites is reasonable because those places are designed for human workers.
- *Technical difficulty (autonomy: low; prior knowledge: rich; safety: low)*: The required autonomy level is low since teleoperation is acceptable. The prior knowledge is available as a CAD model. The required safety level is low because cooperation with human workers is not required.
- *Market size (small)*: The number of required robots is extremely small. Therefore, the market size is small, and launching and maintaining businesses through this application will be difficult.
- *Cost restriction (low)*: The cost restriction is low because decommissioning is an extremely important task, and it is undertaken by larger electricity companies.

Entertainment

- *Necessity for humanoids (sufficient)*: An anthropomorphic body is meaningful for entertainment and attracts people.
- *Technical difficulty (autonomy: low; prior knowledge: rich; safety: low)*: The necessary autonomy level is low because entertainment robots repeat predefined scenarios through which they obtain prior knowledge. The required safety level is low because the stage where the robots move is typically separated from the spectators' seats.
- *Market size (small)*: Even if we could create extremely good entertainment robots, the number of them would be limited. The market size will remain small.
- *Cost restriction (medium)*: The cost restriction is not high because entertainment robots are operated by private companies.

Device Evaluation

- *Necessity for humanoids (sufficient)*: In recent years, several assistive devices have been developed to support humans performing labor-intensive tasks and for people whose physical capability is diminished. Those devices are generally evaluated by humans. However, their evaluations depend on feelings, and it is difficult to assess them in a quantitative manner. Since a humanoid robot has an anthropomorphic body, trials have been conducted using such a robot as a quantitative evaluator of such devices [9]. The necessity for humanoids is sufficient because an anthropomorphic body is required.
- *Technical difficulty (autonomy: low; prior knowledge: rich; safety: low)*: The required autonomy level is low because the robots repeat predefined motions. They can access the prior knowledge about motions and environments. The required safety level is low because there is no interaction between the robots and humans.
- *Market size (small)*: The market size will remain small because the number of required robots is limited.
- *Cost restriction (medium)*: The cost restriction is not high because the robots are bought by companies that develop assistive devices.

Daily Life Support

- *Necessity for humanoids (sufficient)*: The necessity for humanoids is sufficient because the interiors of homes are designed for humans.
- *Technical difficulty (autonomy: high; prior knowledge: less; safety: high)*: Because the number of devices for this application is quite high, teleoperating robots is not reasonable, and they are expected to perform tasks autonomously. Hence, the autonomy level is high. Obtaining prior knowledge is difficult since every home has a different environment that changes every day. An extremely high safety level is necessary to coexist with babies and pets.
- *Market size (large)*: Commonly people have particularly demanding expectations for daily life support robots. A significantly large market size can be expected because the number of users would be considerable.
- *Cost restriction (high)*: The cost restriction is extremely high because the users are general consumers.

Large-Scale Manufacturing

- *Necessity for humanoids (sufficient)*: Large-scale manufacturing involves building structures, such as homes, commercial buildings, airplanes, and ships, having construction sites that differ significantly from conventional factories, as shown in Figure 2. In conventional factories, robots are fixed to the ground, and the target products are served by conveyor belts. By contrast, at the manufacturing sites of large structures, robots must move around as they perform tasks. They must have mobility and manipulation functions. In addition, the inside of the target product does not necessarily have flat floors where wheeled robots can move. Hence, the necessity of humanoids is sufficient.

- *Technical difficulty (autonomy: high; prior knowledge: rich; safety: medium)*: Since the robots for this application are used to compensate for shortages of manpower, they are expected to work autonomously. The required autonomy level is high. Prior knowledge is available because the target products are designed using CAD. The existence of CAD models reduces difficulties in mapping and localization. The required safety level is medium since the robots must share a working environment with humans, although the employees are educated about the situation.
- *Market size (medium)*: We can expect a medium market size because there are numerous airplane and ship factories and construction sites of homes and commercial buildings.
- *Cost restriction (medium)*: The cost restriction is not high because the robots would be operated by private companies.

The Most Promising Application

A comparison of the previously discussed applications is given in Table 1. The items shown in bold face represent the factors that make commercialization difficult. There is no application without difficulty. The necessity for humanoids is considered to be limited if a working environment is accessible not only for humanoid robots but for other robots. The market size is viewed as small if an application does not require a large number of robots. The cost restriction is determined to be high if the users are consumers. The evaluation results are based on the nature of the applications, and it is difficult to change them through R&D. By contrast, technical difficulties can be solved through investigation. Large-scale manufacturing is the only application that does not present challenges related to the necessity for humanoids, market size, and cost restriction. That is why we believe it is the most promising application for humanoid robots.

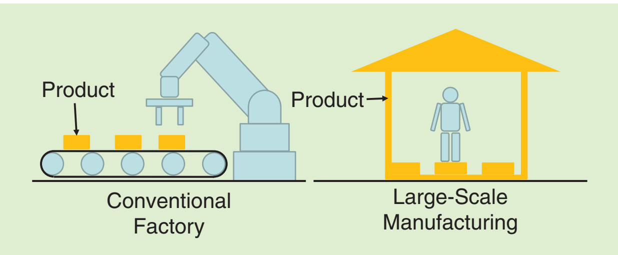

Figure 2. A comparison between conventional factories and large-scale manufacturing. Conventional factories are designed for robots, and the robots are fixed to the ground. A robot for large-scale manufacturing must move around and perform tasks for the product under construction.

Table 1. The humanoid robot applications results.

	Necessity for Humanoids	Technical Difficulty: Autonomy	Technical Difficulty: Prior Knowledge	Technical Difficulty: Safety	Market Size	Cost Restriction
Disaster response	**Limited**	Low	**Less**	Low	**Small**	Low
Infrastructure maintenance	**Limited**	**High**	Rich	Low	Medium	Medium
Decommissioning	Sufficient	Low	Rich	Low	**Small**	Low
Entertainment	Sufficient	Low	Rich	Low	**Small**	Medium
Device evaluation	Sufficient	Low	Rich	Low	**Small**	Medium
Daily life support	Sufficient	**High**	**Less**	**High**	Large	**High**
Large-scale manufacturing	Sufficient	**High**	Rich	Medium	Medium	Medium

Construction Work

The construction domain, which includes large-scale manufacturing, is an example of the most promising application area for humanoid robots. In 2010, the number of workers in Japan's construction industry was 4.47 million. That number was 32.6% smaller than its peak in 1995. It is estimated that the total will decrease to 2.94 million in 2020. Robot technologies must compensate for the shortage of manpower.

Private companies have developed robots to automate some construction processes. Construction Robotics, Victor, New York, [10] developed two robots, the Material Unit Lift Enhancer (MULE) and Semi-Automated Mason (SAM). MULE is a lift-assist robot for handling and placing heavy materials, while SAM is a brick-laying robot. Advanced Construction Robotics, Allison Park, Pennsylvania, [11] developed an autonomous rebar-tying robot, and Doxel AI, Redwood City, California, [12] and SiteAware, Tel Aviv, Israel, [13] have developed quality-monitoring systems. Doxel uses a drone to monitor construction progress from the air, and SiteAware employs a crawler robot. Some construction companies in Japan are trying to use the SpotMini [14] from Boston Dynamics, Waltham, Massachusetts, for a similar purpose.

It is reasonable to develop a specialized robot using existing technologies to automate a process for a short period. However, we believe that a versatile robot, for example, a humanoid robot, is more suitable. If we consider developing robots that are specialized for every process, a large number of them will be necessary. That approach works well for mass production in conventional factories. For example, we can place products on a conveyor belt, arrange robots along the conveyor, and have the robots work in parallel. However, the production rate for large-scale structures is much lower than it is for mass-produced goods, such as cars, and conveyor belts cannot carry bulky objects. If we develop special robots for every process, only a few of them can work at once, and most of them will not be used most of the time, which is very inefficient.

Aiming to automate the construction process, we focused on plasterboard installation, which involves cutting the material into the necessary sizes, picking it up, carrying it to a wall or ceiling, and screwing it into place. The size of a common plasterboard is 1,820 mm × 910 mm × 9.5 mm, and a sheet weighs roughly 11 kg. We chose this process to be our trial since its automation is expected and it has many factors that are unfavorable for human workers:

- *Weight*: A plasterboard is heavy, and humans can develop backaches from carrying it.
- *Ergonomics*: While installing a plasterboard onto a ceiling, a human must maintain a looking-up posture, which is ergonomically unsafe.
- *Boredom and repetition*: A plasterboard must be fixed by many screws.
- *Danger*: While installing a plasterboard onto a ceiling, a human needs to climb up and down a stepladder, which can be dangerous.

Two private companies, Shimizu, Tokyo, and Sekisui House, Osaka, Japan, have also realized the importance of process automation and developed robots specialized in the plasterboard-installation process [15], [16].

The HRP-5P

To automate the process, we used our latest humanoid robot, the HRP-5P [5], which was designed to handle large, heavy construction materials, such as plasterboard. Table 2 provides its brief specifications, and Figure 3 shows its software architecture. The system runs on two onboard computers (CPU: Intel Core i7-5557U, 3.1 GHz; memory: 32 GB) and one remote-terminal computer (CPU: Intel Core i7-6900K, 3.2 GHz; memory: 64 GB) connected to the onboard computers by a wireless local area network (LAN). The motor drivers and force-torque sensors are connected by ethernet for control-automation technology (EtherCAT), and an inertial measurement unit (IMU) is connected according to Electronic Industries Alliance standard RS422 to onboard computer number 1. Communication with the hardware components, joint control, and whole-body motion control is performed by real-time threads. Cameras, a MultiSense device, and an red-green-blue-depth (RGB-D) camera are connected to onboard computer number 2, which also executes the sensor reading, position/orientation detection of the LentiMark [17], and visual odometry, which processes stereo images at 10 Hz. The remote-terminal computer executes back-end services, such as simultaneous localization and mapping (SLAM) and the motion and footstep planning, and two graphical user interfaces, Choreonoid [18] and RViz. Those components were implemented using two middleware platforms, OpenRTM and Robot Operating System (ROS), and constitute a distributed software system. The robotic tasks are described in Python and implemented by a task-sequencer system [19].

Plasterboard Installation

We prepared a mock-up of a house construction site, as illustrated in Figure 4, and realized autonomous plasterboard installation with the HRP-5P through the procedures shown in Figure 5 (a video is available at https://www.youtube.com/watch?v=fMwiZXxo9Qg.)

Table 2. The brief specifications of the HRP-5P.

Dimension	Measurement
Height	1,830 mm
Weight (including batteries)	101 kg
Degrees of freedom	37
Neck	2
Arm (×2)	8
Hand (×2)	2
Trunk	3
Leg (×2)	6

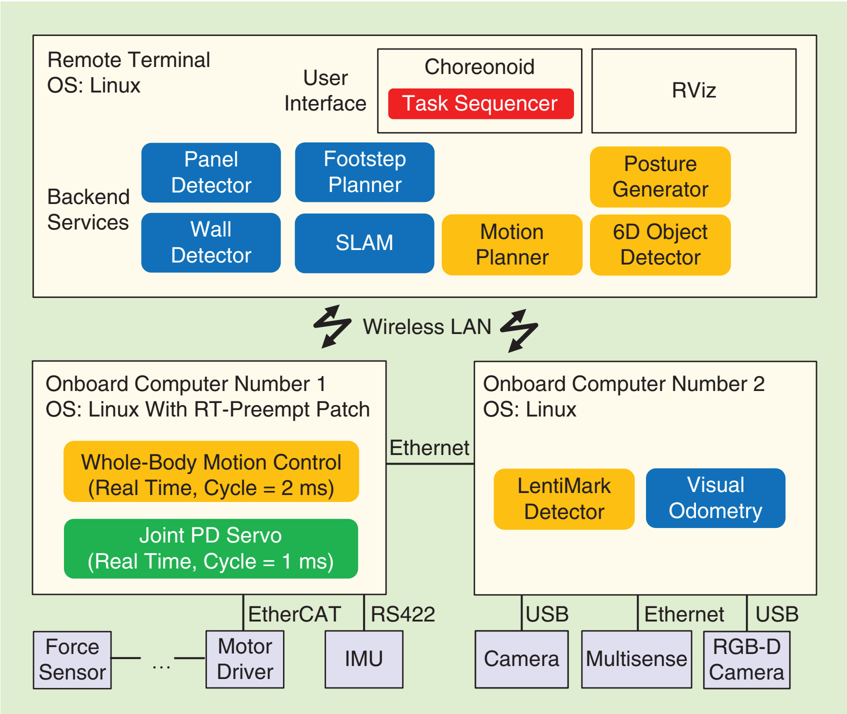

Figure 3. The HRP-5P's software architecture. Orange and blue represent the robotic technology (RT) components and ROS nodes, respectively. Green indicates a stand-alone process. OS: operating system; PD: proportional-derivative.

First, the robot plans and executes its footsteps to approach the workbench [Figure 5(a)]. It, then, detects the plasterboard using an image and a point cloud and computes its position with respect to the plasterboard. If the position is out of the acceptable region, the robot steps to adjust it. Once its standing position is in the acceptable region, the robot places its hands on the plasterboard and approaches the workbench. Then, it leans over the workbench, stretches its arms forward, hooks its fingers to the edge of the board, and slides the sheet [Figure 5(b)]. After returning to an upright posture and stepping back, it pulls out the board [Figure 5(c)]. The robot rotates the board by pushing down on the nearest edge with its right hand and holding it with both arms [Figure 5(d)]. Then, the robot picks up the board and rotates it 90° [Figure 5(e)]. Owing to its high-power joints and arm configuration, the HRP-5P can handle large and heavy objects, such as the plasterboard.

While picking up and rotating the board, the robot must grasp the sheet by hooking its fingertips because it has a kinematic limitation. To grasp the board firmly by cramping it with all of its fingers, the robot puts the board down and picks it back up before carrying it to the wall. While carrying the board, the robot's field of view is obstructed, and its feet slip because of the heavy load. Even in that situation, the robot can plan and adjust its footsteps so that it can reach the expected position by localizing its position in its memorized 3D map [20] [Figure 5(g)].

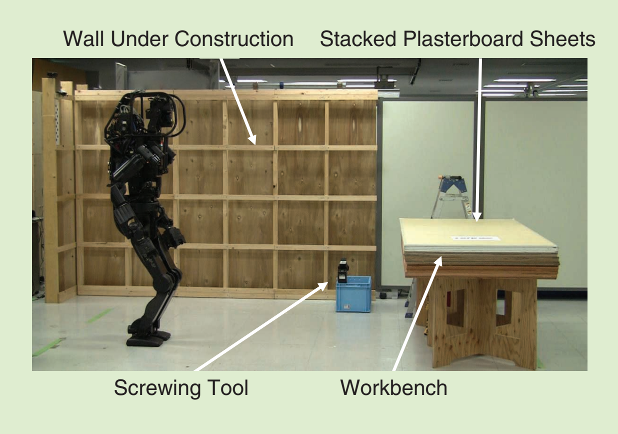

Figure 4. The mock-up of a house construction site.

Figures 6 and 7 present snapshots of RViz and Choreonoid, respectively, taken when the robot begins to carry the board. The dark yellow region in Figure 6 shows the floor area where the robot can walk, and the 3D map is displayed by voxels colored according to their height. The object-detection results are shown at the top, and an image obtained from the head camera is shown at the lower right. Figure 7 also shows the user interface of the task-sequencer system, which was used to operate the robot manually when the automatic execution stopped because of errors.

After placing the board on the floor, the robot picks up a screwing tool from a box with its right hand while pushing on the board with its left hand [Figure 5(h)]. The robot measures the tool's position by detecting the LentiMark on the implement through a camera in its right-hand palm [Figure 5(i)]. Since the board is not fixed yet, the robot inserts screws at the middle height while applying pressure to the board [Figure 5(j)]. Then,

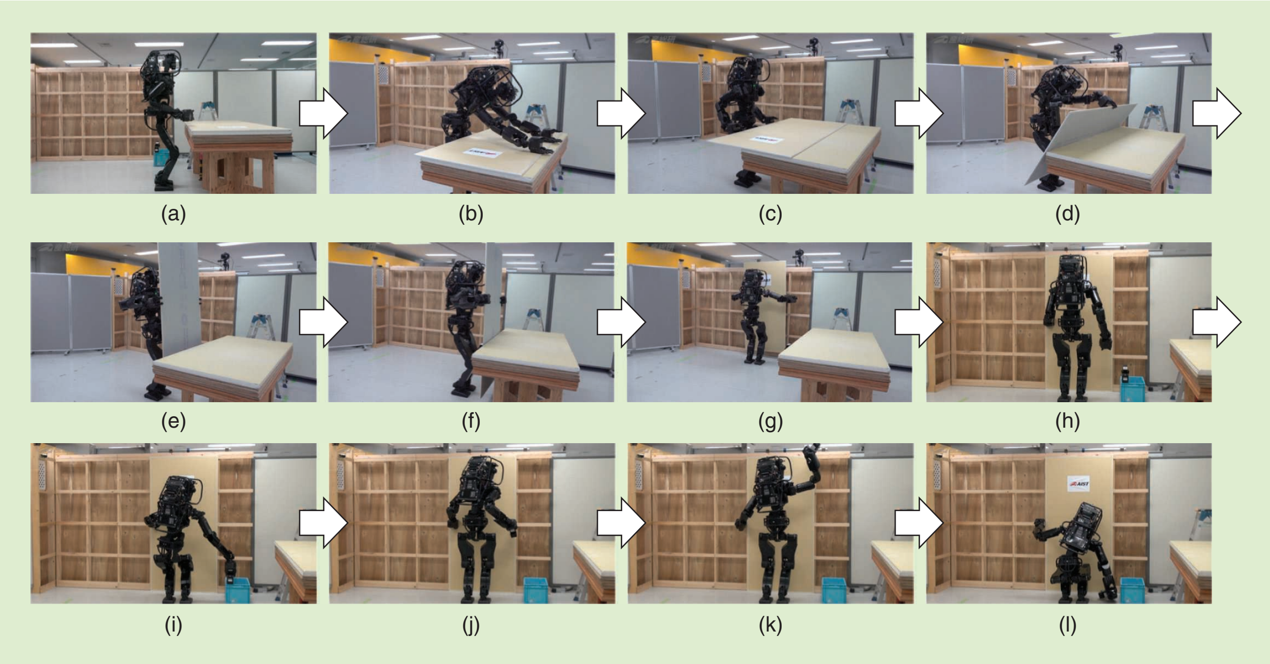

Figure 5. Snapshots of the plasterboard installation. (a) Approach the workbench. (b) Slide the board on top. (c) Pull out the board. (d) Push down and rotate the board. (e) Pick up and rotate the board. (f) Regrasp and carry the board. (g) Put down the board. (h) Push the board with the left hand. (i) Pick up the tool. (j) Screw the middle position. (k) Screw the top corner. (l) Screw the bottom corner.

the robot releases the board and holds a horizontal bar to resist the reaction forces of screwing [Figure 5(k)]. While holding the horizontal bar, the robot applies screws from the top to the bottom of the board [Figure 5(l)].

Discussion

Figure 8 shows the commands that the robot executed while it conducted the task. Each box indicates what time a command started and ended. Pink, purple, light blue, light green, dark green, and navy boxes represent walking, motion generation, reaching, looking, hand opening/closing, and manipulation-motion commands, respectively. The task took approximately 8 min to execute, as seen in Figure 5, and the commands consumed 13.4, 39.1, 7.9, 9.9, 6.9, and 9.9% of the total time, respectively.

Although robots that are specialized in the task of plasterboard installation already exist, as mentioned earlier, their technical details have not been released. To the best of our knowledge, there is no other humanoid robot that has tackled the same task. To evaluate the performance of our robot, we compared it with human subjects. We asked five people to do the following tasks:

- execute the task in two different procedures, the first being the same one that the HRP-5P used and the second being each subject's natural method
- execute the task three times for each procedure
- execute the task without hurrying.

The human subjects were Japanese male robotics researchers, not professional construction workers. We divided the task into four segments, as shown in Figure 8. Segment 1 included the tasks that involved approaching the workbench and placing the board for regrasping. Segment 2 included regrasping the board and placing it in front of the wall. Segment 3 involved pushing the board and picking up the tool, and segment 4 incorporated screwing the middle position and standing up after placing the tool in the box. We recorded the human motions and measured the total time required and the times for each segment. The results appear in Table 3. The times for the three executions of each procedure by each subject were averaged.

The averages for the HRP-5P–like and natural procedures were 57 and 34 s. All of the human subjects used nearly the same procedure as their natural one. The major difference between the HRP-5P–like and natural procedures was that the human subjects did not put the board back down before they regrasped it. They began carrying the board immediately after picking it up. That cut 10 s from segment 1 and 7 s from segment 2, which involved the regrasping and picking up. The 6-s difference in segment 4 is difficult to explain since the procedures used were the same. One possible reason could be that the humans had to recall the HRP-5P's motions to execute them similarly.

The task-execution time of the HRP-5P was 459 s, which was eight times slower than the subjects' time. Even if we consider that robots can work 24 h a day, that was too slow and could be attributed to several major factors, some of which are as follows.

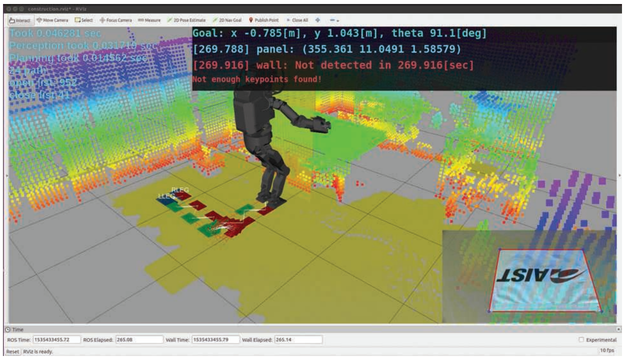

Figure 6. The 3D map and planned footsteps displayed on RViz.

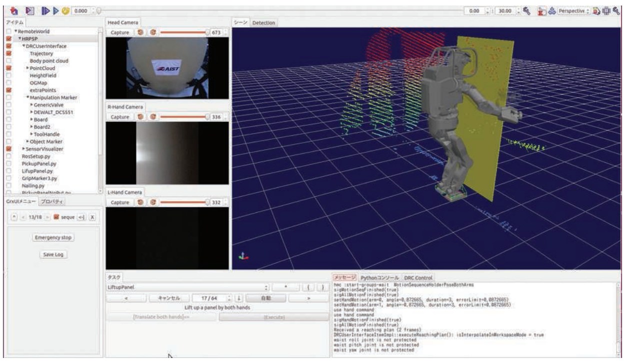

Figure 7. The task-sequencer user interface implemented on Choreonoid.

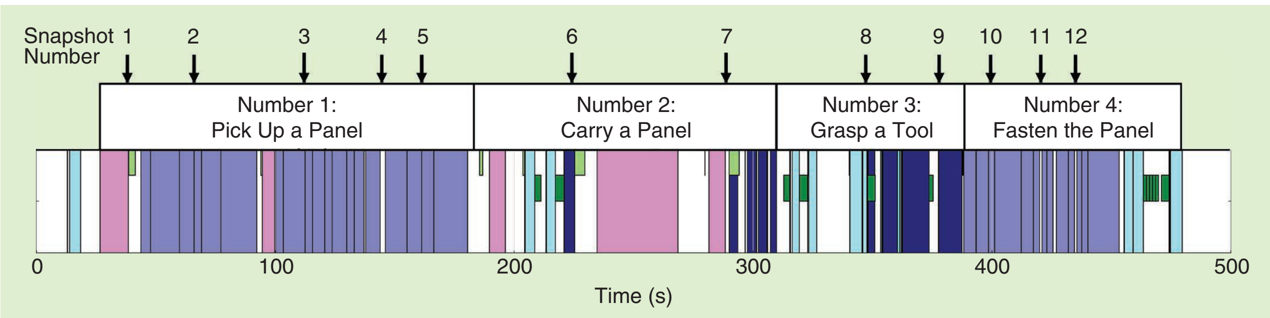

Figure 8. The time chart of the commands executed during the installation of one plasterboard. Pink: walking; purple: motion generation; light blue: reaching; light green: looking; dark green: hand opens/closes; and navy: manipulation.

Table 3. The HRP-5P's results compared with those of human subjects, measured in seconds.

Procedure			Number 1	Number 2	Number 3	Number 4	Total
HRP-5P–like	HRP-5P		161	158	47	93	459
	Human	A	24	16	2	33	76
		B	14	13	3	23	54
		C	11	11	2	23	48
		D	18	15	2	25	62
		E	13	9	3	19	45
		Average	16	13	2	25	57
	HRP-5P/human average		10	12	17	4	8
Natural	Human	A	8	8	2	28	47
		B	4	5	1	19	31
		C	6	5	3	18	32
		D	7	8	2	21	38
		E	5	3	1	11	22
		Average	6	6	2	19	34
	HRP-5P/human average		26	25	23	5	13

The HRP-5P is much slower than human subjects even when it uses the same task-execution procedure. Moreover, human subjects can execute tasks faster because they can use the methods that feel the most natural.

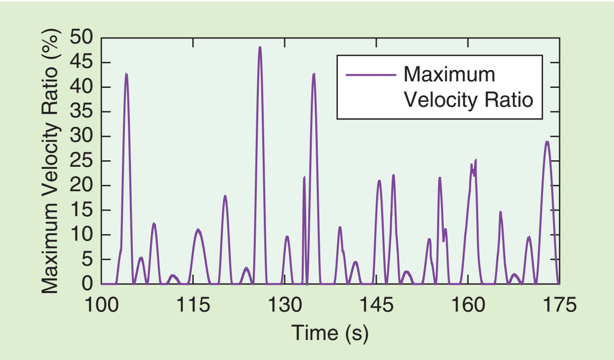

Figure 9. The maximum joint-velocity ratio while pulling out, pushing down, picking up, and putting down the board. From the hardware point of view, there is room for speeding up. The motions consist of short movements that start and finish with zero joint velocities.

Motion generation while standing: The motion generation command is the most time-consuming one. It produces a standing motion using whole-body-prioritized inverse kinematics. There are two major reasons for the slowness. The first is that the center of mass is always constrained above its support polygon. Figure 9 shows the maximum joint-velocity ratio while pulling out, pushing down, picking up, and putting down the board. A joint-velocity ratio compares the absolute joint velocity to its upper limit. The maximum joint-velocity ratio is the maximum value of the joint-velocity ratios for all of the joints. The maximum value in Figure 9 is lower than 50%, which implies that, from the hardware point of view, there is room to speed up. However, if we simply increase the speed of the motions, the robot will fall down since the center of mass would be constrained above its support polygon. To speed up the movements, we need to improve our motion generator to consider motion dynamics. The other reason for the slowness is that each motion consists of short movements that start and finish with zero joint velocities, as seen in Figure 9. Much time is consumed while deaccelerating to a stop and accelerating again. Such motions are easy to design and test since we can incrementally create and evaluate each short movement independently. To speed them up without losing their advantages, we need to realize an automatic method of continuously and efficiently executing the short motions.

Walking speed: In this study, we used walking speed of 1 km/h, which is much slower than that of humans. The speed was chosen because the visual-odometry function, which runs at 10 Hz, loses visual features if the robot walks faster. To achieve a faster walking speed, the running frequency of the visual odometry must be improved or a view-direction control, which mitigates rapid scene changes, must be added.

Conclusions

In this article, we compared several humanoid applications based on four criteria to find one that would be the most appropriate to use as a trial. We decided on large-scale manufacturing since it does not have any major difficulties that cannot be solved through R&D. Commercializing humanoid robots in that area will lead to an ecosystem in which humanoid technology can continue to improve. After that system has been created, we can apply humanoid robots to other applications that are very important for society but have a small market. Daily life support is an application that is commonly expected to develop, but it is the most difficult to execute from the technical point of view and, thus, may be achieved at a later time.

Based on our conclusion, we chose a plasterboard-installation task from the large-scale manufacturing domain for the first trial. It is a typical task that should not be executed by human workers. We realized its autonomous execution by using our latest humanoid robot, the HRP-5P. We compared its performance with that of human subjects and found that its task-execution speed was significantly slow. We discussed the major reasons for that slowness and how to improve the speed. Addressing those measures is a part of our future work.

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