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Humanoid Robot With Turnover Prevention and Self-Weight Compensation

Isamu Matsuo[a*], Toshihiko Shimizu[a], Yusuke Nakai[a], Masahiro Kakimoto[a], Yuki Sawasaki[a],

Yoshiki Mori[a], Takamasa Sugano[a], Shuhei Ikemoto[b], Takeshi Miyamoto[a]

[a]*Kobe City College of Technology, 8-3, Gakueni-Higashimachi, Nishi-ku, kobe-shi, Hyogo-ken, Japan*;
[b]*Osaka University, D536 1-3, Machikaneyama, Toyonaka, Osaka, Japan*

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We have developed a humanoid robot called Q-bot and denote its potential for operating convenience stores. The main feature of Q-bot is a small lightweight dual-armed crane with a universal vacuum gripper that holds its body for turnover prevention by vacuum force, by compensating for its weight. Also, the vacuum at the foot of the robot prevents Q-bot from falling over in response to the robot force of work such as drilling through a wall. The robot performs several functions, including dual-armed manipulation, omnidirectional movability, and adherence to uneven surfaces using arm- and foot mounted vacuum grippers. This study reports the development status of the robot and our experiment to prevent falling when the robot grips heavy objects while being adhered to the ground.

Keywords: humanoid robot, self-weight compensation, Universal Vacuum Gripper

1. Introduction

In recent years, with the decrease in the labor force in Japan, the labor shortage in the logistics and service industries has become serious. For logistics, We are exploring the Amazon Picking Challenge [1] and other robotic solutions [2–5]. In convenience stores, automation is being promoted for retail sales without a cashier, such as using Amazon Go's approach, but tasks, such as product stocking, disposal, and customer service, still require manual work. Therefore, the World Robot Summit 2018 held a competition called the Future Convenience-Store Challenge (WRS-FCSC),in which robots performed convenience-store operation.

Each company and university team developed a unique robot system to address tasks in three categories customer interaction, toilet cleaning, and stocking and disposal and competed according to its performance. Robots have been usually developed to have systems that integrate various sensors in the hardware, commonly combining robotic arms and an automated guided vehicle (AGV). In WRS-FCSC, there were many systems that contained single or double arm type robot arms and used the AGV technology. The robot moved to a specified position by the AGV and performed various tasks by holding and transporting multiple products with an end effector, such as a vacuum suction cup or chuck hand, attached to an arm. We expected that the next challenge in introducing robots into operation in a convenience store is associated with the task of holding and transferring heavy objects by small lightweight robots. For instance, it is necessary to transport, open, and release cardboard boxes filled with liquid bottles in narrow

*Corresponding author. Email: r113166@g.kobe-kosen.ac.jp

passages; because a carton of bottles weighing 10-24 kg must be carried from a truck to a narrow place, the work of transporting and unpacking is considered to be heavy labor at a convenience store. The aforementioned system in which a robot arm on the AGV is supposed to work within the payload of the robot is considered to be difficult to handle. More specifically, NEXTAGE (KAWADA Robotics, Inc.) has a one-arm payload of 3 kg and a dual-arm payload of 6 kg. Workers could load the cartons on the AGV; however, the labor supply for loading work would again be concerning. Besides, it is desirable to be able to use robots because the work involves not only transportation but also unpacking and product delivery. Therefore, it was essential to introduce a new device with a self-weight compensation function able to support the weight of the transported product at higher payloads. We looked into existing heavy goods transfer systems and cooperative robots[6] that can handle a heavy load.

For large goods transfer systems in factories, a forklift and an environment fixed crane are used. As shown in Fig. 1, massive objects can be transported by vehicles that are heavier than the objects. However, to have a sufficient body weight, such vehicle tend to be large. For example, environment fixed cranes include large jib cranes (ENDO KOGYO Co., Ltd.), arm balancers and vacuum balancers (KITO Corp.), powered arms (CKD Corp.), and ATOUN MODEL K (ATOUN Inc.), and others. These are systems[7] that reduce the burden on workers by using a self-weight guarantee mechanism that has a horizontally swingable arm and supports a heavy load in the vertical direction. At the same time, because of constraints such as having to install the machine using a dry bit and fix it in the environment., installation location is limited. Too, it may be difficult to install in existing stores. Heavy-duty transfer robots have been developed with industrial robot arms and for use as nursing robots, and rescue robots. However, it is difficult to operate in store industrial robots that exceed 20 kg in hand-held weight due to their size. For example, RS 030 N (Kawasaki Heavy Industry Inc.) weights 30 kg, but it is necessary to leave about 3 m of space around it for safety reason. In nursing care applications, robots such as RoNA (Star Technologies Inc.) can lift and transfer patients weighing about 130 kg. Howerer, although it has sufficient load capacity, it is necessary to increase the AGV weight as a counterweight to support the hand weight. The early Resyone bed (Panasonic Corporation) used a similar mechanism (before it became a combined bed and wheelchair as a result of user feedback).

Rescue robots with limbs that can negotiate stairs [8, 9] have been developed that have sufficiently high degrees of freedom that they can hold at least 11 kg in weight while maintaining balance, as can a human being. Also mimicking human activity, robots have been used for ladder elevating, gripping and conveying of construction panel, and nailing operations using tools. On the other hand, posture stability control with two legs is important. When carrying heavy objects in a store, the existing method in which the robot's body is fixed to the environment is preferable from the viewpoint of safety. That is, it is necessary for the robot to be able to be fixed to the environment as needed so that it can be small and yet lift a heavy object without falling over. We saw the need to have a small robot that can grip and transport heavy objects and be fixed to its surroundings as needed so that it does not fall over.

Therefore, in this research, we developed Q-bot a compact, lightweight, heavy-duty humanoid robot that also has a fall prevention mechanism.

2. Q-bot

The main feature of the Q-bot is the adhesion mechanism of the sole. As shown in Fig. 1, industrial robots need a certain amount of weight to transport objects comparable to their mass. Despite its light mass, Q-bot is designed to achieve the weight compensation by the adhesion force of the sole at the time of receiving the object to be held, because that is when the moment load is greatest. After that, Q-bot moves the heavy load to the trunk to reduce the moment load and transports it to a specified place by the omnidirectional movement mechanism. Also, Q-bot uses foot adhesion to fix the body to the environment and avoid falls. Too, it can reduce the reaction force from a wall when working against it and can still operate stably.

Unlike a factory, a convenience store does not prepare a wide passage or a shelf or product placement with robots in mind. Therefore we thought through in-store robot falls due to stumbling while holding an object or by contact with a store visitor (Fig. 2(a) and 2(b)). As a result, we equipped the lower part of the main body of Q-bot with a Universal Vacuum gripper (UVG)[10] to prevent falls. We also included in the design self-weight Compensation and the means to reduce the reaction force from an encounter with a wall (Fig. 2(c)) such as to enable stable work on a wall. In addition, we used a humanoid robot rather than an industrial robot to smooth communication between a customer and a robot, and we developed a life-sized robot to apply it in an existing convenience store. Fig. 3 shows the overall appearance of the robot, and Table 1 shows the Q-bot's main dimensions and apparatus.

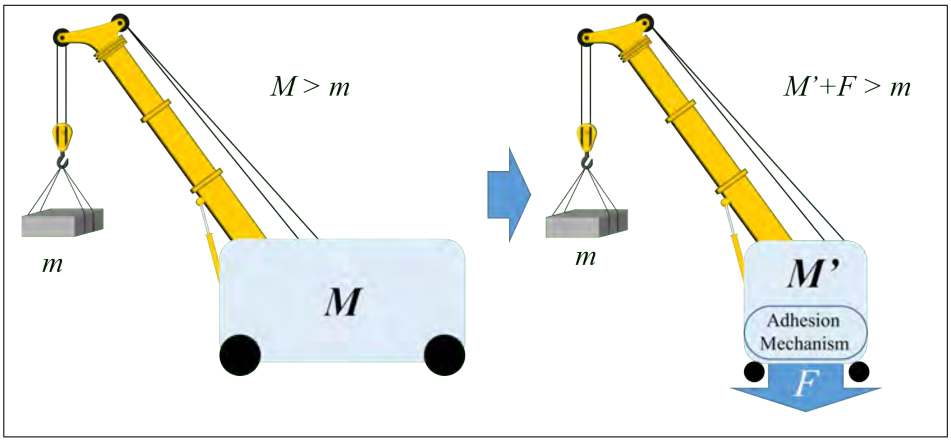
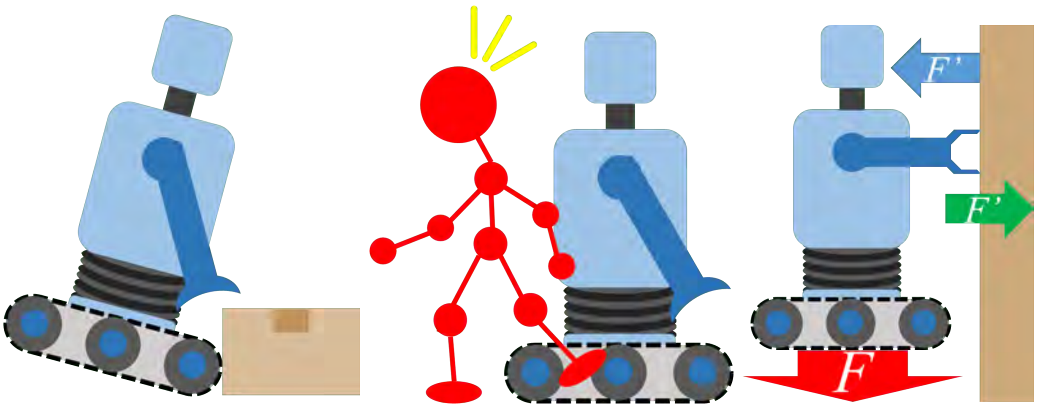


Figure 1. Weight reduction of AGV by adhesion mechanism



(a) Stumble (b) Contact (c) Reaction force

Figure 2. Dangerouse situations

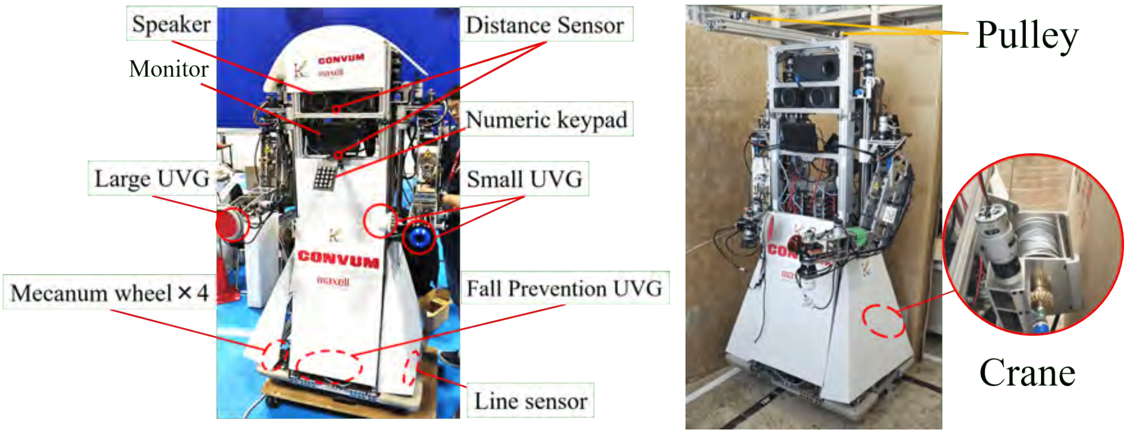


Figure 3. Robot whole image

Table 1. Main specifications for Q-bot

Main dimensions	Height : 1750 mm, Width : 800 mm, Depth : 560 mm
Weight	100 kg
Gripping force	Small-size: 2 kg, Large-size: 40 kg
Vacuum force to the ground	100 kg
DOF	Omni-wheel × 4,vacuum On-Off × 9
Mobility	Mecanum wheel
External input	Numeric keypad, Ubuntu PC, limit switch
External output	Speaker, monitor
Communication	ROS serial, I2C, digital and analog signal
Sensors	Gyrosensor, distance × 6, line × 3, pressure × 2
Arduino	MEGA × 2, UNO × 1
Battery	Lithium-ion battery × 3, DC 24 V5.5 Ah
Vacuum pump	TOPSFLO tzx 512 v12-8015 (-80 kPa) × 9

2.1 *Physical model for Q-bot to hold a heavy object*

We created a dynamic system approximation model for Q-bot's holding a heavy object (Fig. 4). When the robot starts to fall, Eq. (1) holds for the balance around the fulcrum. m is the weight of the package [kg], M is the weight of the main body [kg], D is the distance between the shafts of the tire [m], and f is the suction force of the overturning gripper. Eq. (1) can be modified to obtain a by Eq. (2), and the distance L [m] to start falling can be obtained by Eq. (3):

$$Mg \times \frac{D}{2} + f \times \frac{D}{2} = mg \times a \tag{1}$$

$$a = \frac{MD}{2m} + \frac{fD}{2mg} \tag{2}$$

$$L = \frac{D}{2} + a = (1 + \frac{M}{m} + \frac{f}{mg})\frac{D}{2} \tag{3}$$

In this research, the maximum weight of the object held by Q-bot is set to 35 kg. Assuming that m is 35 kg, D is 0.3 m, and M is 100 kg when UVG is not operated, L is 0.57 m. The details will be described later, but the maximum reach of the arm is 625 mm, which is the

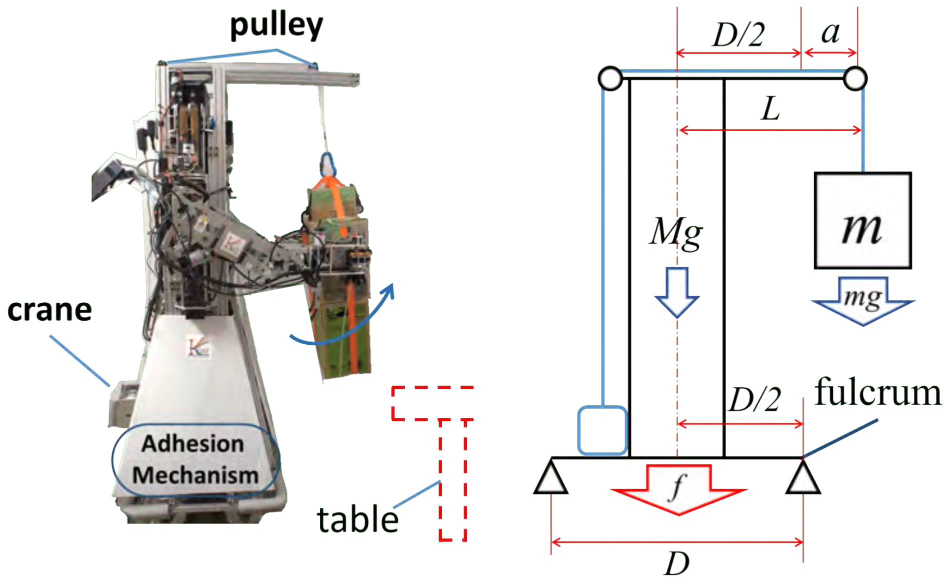


Figure 4. The model of the Q-bot

maximum length at which Q-bot does not fall when the object grasped is pulled toward Q-bot by the outstretched arm. However, this length is also the length at which the Q-bot falls over when the object gripped is pushed away form Q-bot by using the outstretched arm, such as while unloading. Therefore, we calculated the turnover-prevention UVG adhesion force required to prevent Q-bot from tipping over even if the arm is pushed forward. Eq. (3) can be modified to obtain f by Eq. (4).

$$f = \frac{2Lmg}{D} - mg - Mg \tag{4}$$

Considering safety, we set the length L to 1.0 m. When Eq. (4) is solved, f is 964 N, and the corresponding adhesion force is 1000 N.

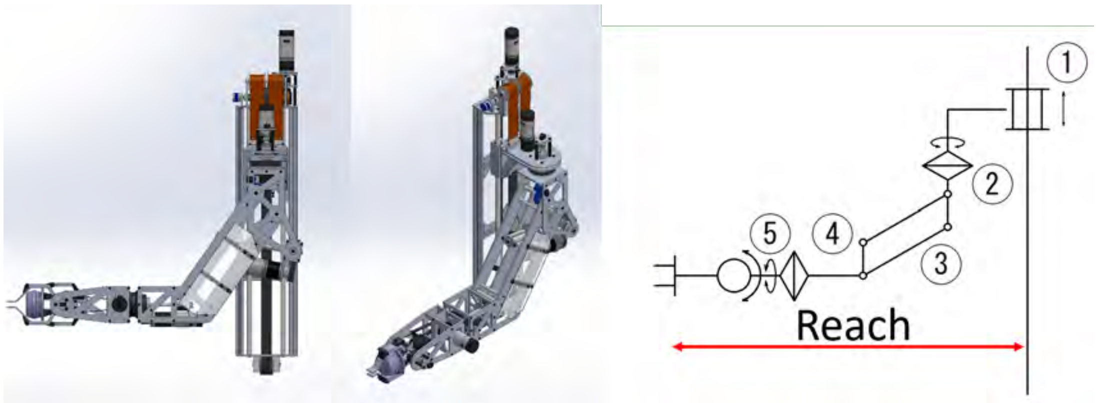
2.2 *Q-bot hardware*

2.2.1 Q-bot dual arm

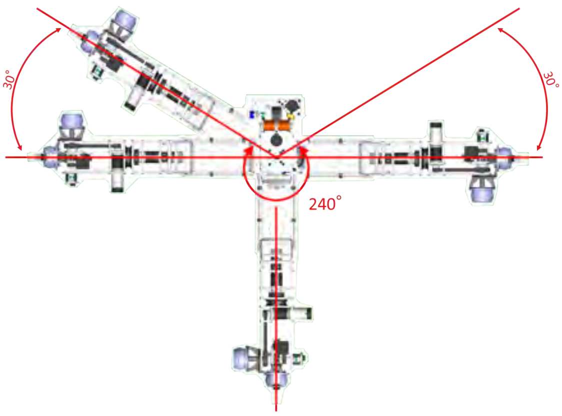
The robot has two arms with five degrees of freedom (DOF1 through DOF5) and a UVG attached to the tip of each arm. (Fig. 5(a)). The arms' range of movability is shown in Fig. 5(b), and the arm mechanism and operating angles are shown in Fig. 5(c). DOF1 is used as a constant-force spring (to compensate for gravity) and as a self-locking worm-gear mechanism (to prevent an arm's dropping when loading more than load-resistant hangs over the tip of the arm). DOF2 keeps the motor straight (to protect wiring); beside, the operation range of the arm is 240 degrees, and turning an arm even if the main body of the robot does not move, can cause problems. DOF3 maintains a parallel linkwork; as a result, the object grasped can be kept horizontal, parallel to the ground. (Thus, even if the object held is liquid, it can be stably transported without spillage.) DOF4 can rotate 360 degrees, so it can change the direction of the object. DOF5 can be rotated 180 degrees in the vertical plane. The maximum reach of each arm is 625 mm.

2.2.2 Q-bot bogie and body

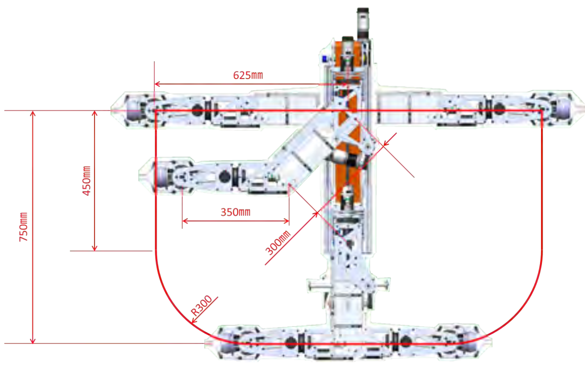
Q-bot is equipped with mecanum wheels, which are movable in all directions. The design of the bogie and body is based on an aluminum frame. Fig. 6 shows the dimensions of the bogie. Fig. 7 shows the structure of the bogie and body, including the cylinder and the UVG for turnover prevention (mounted at the center of the bogie). The robot has a battery, a personal computer, and a board. For this reason, the robot's body adopts a box to optimize the space.



(a) The whole image of the arm



(b) Arm's movable angle



(c) Arm mechanism

Figure 5. Arm dimesion

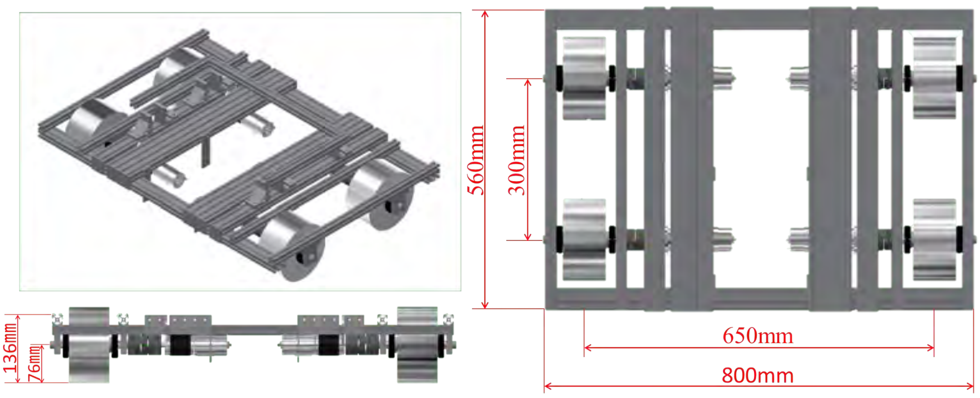


Figure 6. Bogie dimensions

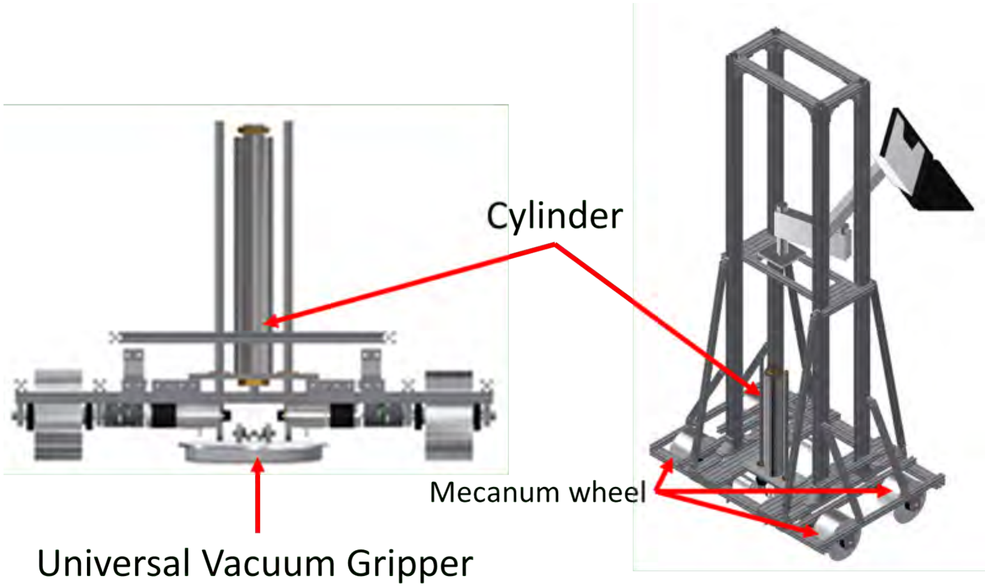


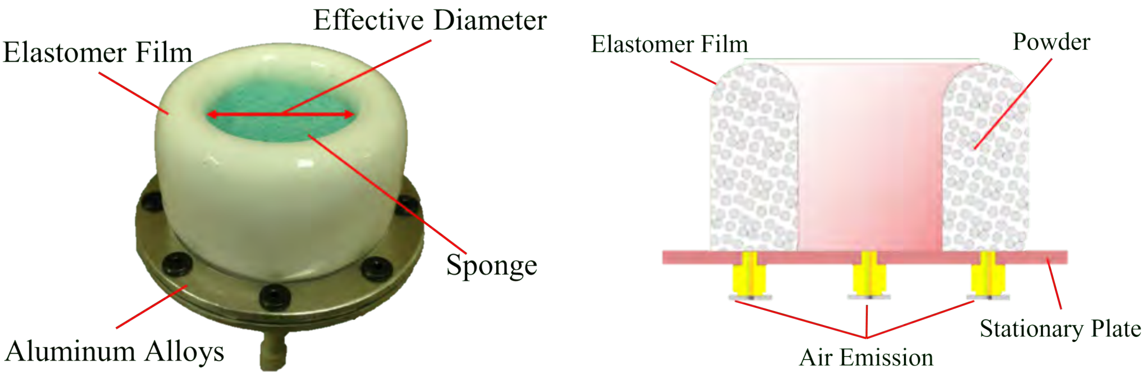
Figure 7. Bogie and body structure

2.3 *Universal Vacuum Gripper(UVG)*

2.3.1 Adhesion principle

The UVG(Fig. 8) uses vacuum suction with a universal gripper[11–13] for the lip of the suction cup. The universal gripper packages granular material in a balloon made of an elastomeric membrane. In this state, the powder and particles cause a jamming-transition phenomenon by evacuating the inside of the balloon when pressed against an object, and deforming to a shape encompassing the contour of the object, thereby gripping the object. The jamming transition is a phenomenon in which the powder changes from a liquid to a solid phase when compressed and reaches a specific minimum density. This enables it to hold various light objects regardless of shape, with some exceptions; for instance, it is difficult for it to grasp a flat plate without an object or protrusion larger than the diameter of the univeral gripper. Although a general vacuum suction cup can hold a flat, heavy object, if the object has an uneven or curved surface, a gap between the lip and the suction surface causes an air leak and vacuum loss, making it difficult to grip the object. To solve this problem, we combined a universal gripper and a vacuum-suction cup.

Because the applications deffer for the small UVG , the large UVG, the large UVG,and the turnover-prevention UVG, they required different film thicknesses and different powders or other granular material (Fig.. 9) enclosed by the film inside the elastomer balloon. Because the purpose of the small UVG is to grip small items such as pens, the film thickness should be 0.5 mm, and the granular material should be alumina balls with a diameter of 1 mm to improve compliance. Because the large UVG is intended to hold heavy objects such as suitcases, the film thickness is 0.5 mm, and powder used is polyethylene PE#40. Because the turnover-prevention UVG needs to support the robot body, the film thickness is 1 mm, and the granular material consists of rubber chips, which favor strength and elasticity over fluid flow.



(a) UVG appearance (b) Sectional view of UVG

Figure 8. UVG

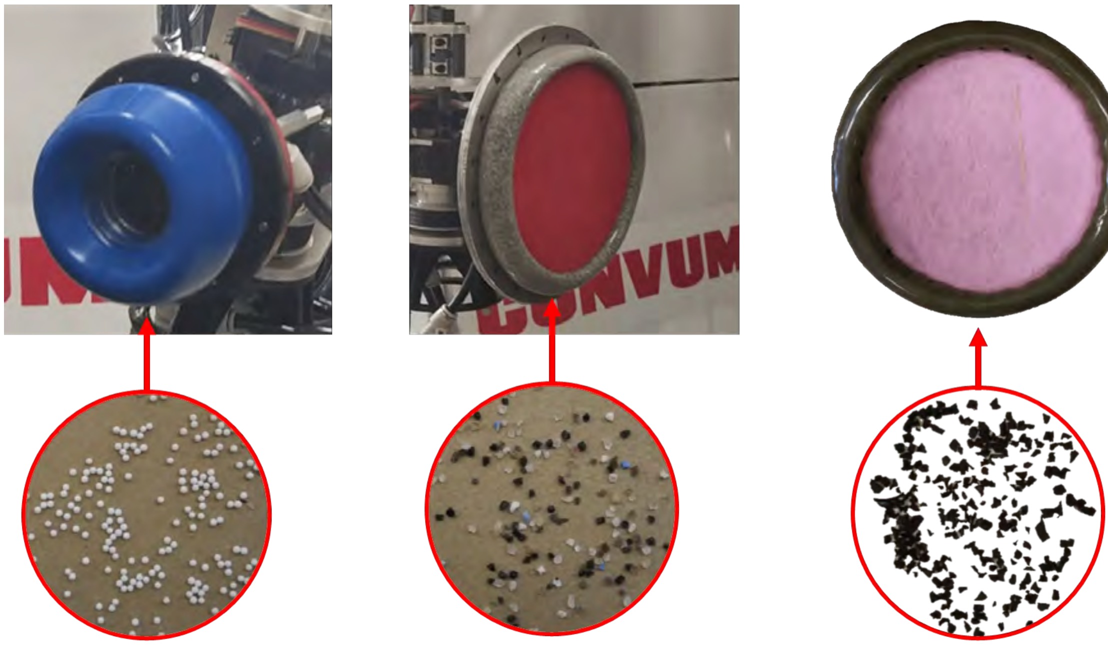


Figure 9. Alumina ball for small-size UVG (left), PE # 40 for large-size UVG (center), rubber chip for turnover-prevention UVG (right)

2.3.2 Universal Vacuum Gripper adhesion force

In this research, the design of the UVGs was based on the suction cups' selection criteria. The weight of the object is the theoretical lift force, for which the formula was back-calculated (using Eq. (5)) to determine effective diameter,or the inside diameter of the suction cup (Fig. 8):

$$f = P \times \frac{\pi D^2}{4} \times \frac{1}{t} \tag{5}$$

Eq. (5) can be modified to obtain D by Eq. (6).

$$D = \sqrt{\frac{4ft}{P\pi}} \tag{6}$$

where f is theoretical lift force [N], P is vacuum pressure [MPa], D is effective diameter t is a safety factor [-]. For the large UVG (Fig. 10), we set the adhesion force f to 400 N because it needs to support a 35 kg load; when P is 0.09 MPa and t is 4, D is 150 mm. It is difficult for the large UVG to grasp an object having a diameter of 150 mm or less, because the object to be grasped needs to block the surface of the sponge (Fig. 9). The small UVG is intended to grasp an object that can't be grasped by the large UVG. For the small UVG (Fig. 11), we set the adhesion force f to 30 N; when. P is 0.09 MPa and t is 4, D is 40 mm. From Eq. (4), the adhesion force f for the turnover-prevention UVG is 1,000 N; when P is 0.09 MPa, and t is 3, D is 210mm.

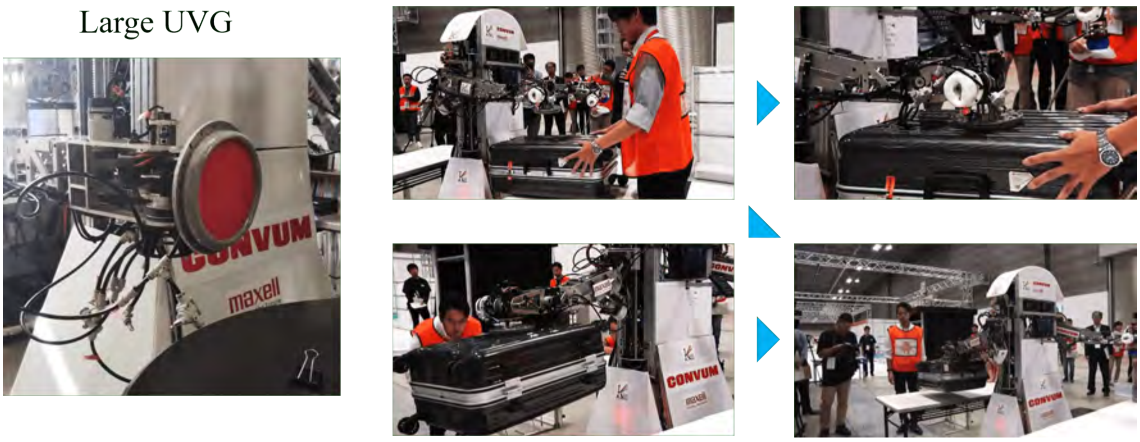


Figure 10. Large UVG

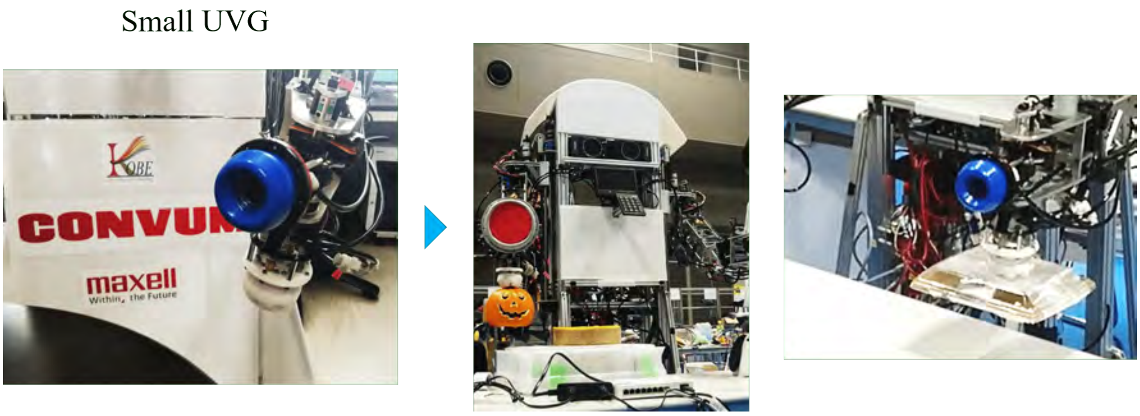


Figure 11. Small UVG

2.4 *System onfiguration*

The outline of the system configuration for this robot is shown in Fig. 12.

The Q-bot loads multiple Ubuntu14.04 PCs and Arduino dispensers. There are a numeric keypad, speakers and a monitor on the front of the robot. Communication is by Robot Operating System (ROS)[14]. Communication between Ubuntu14.04 PC and each Arduino takes place via Ros serial. In this system, Ubuntu14.04 PC receives external instructions through the numeric keypad. Based on the received information, the Ubuntu14.04 PC transmits values such as the joint angle and the ON / OFF command for the vacuum pump, (set in advance) to each Arduino. At the same time, voice synthesis software is used to display a message from the speaker about

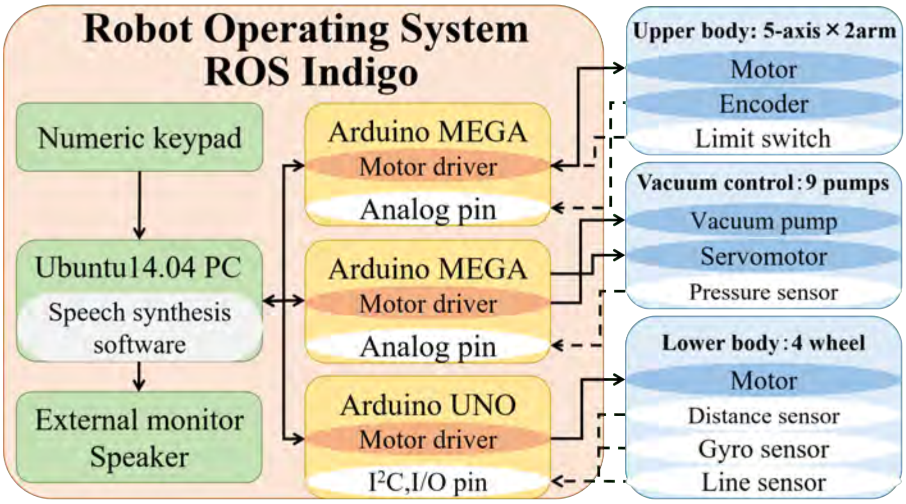


Figure 12. System summary

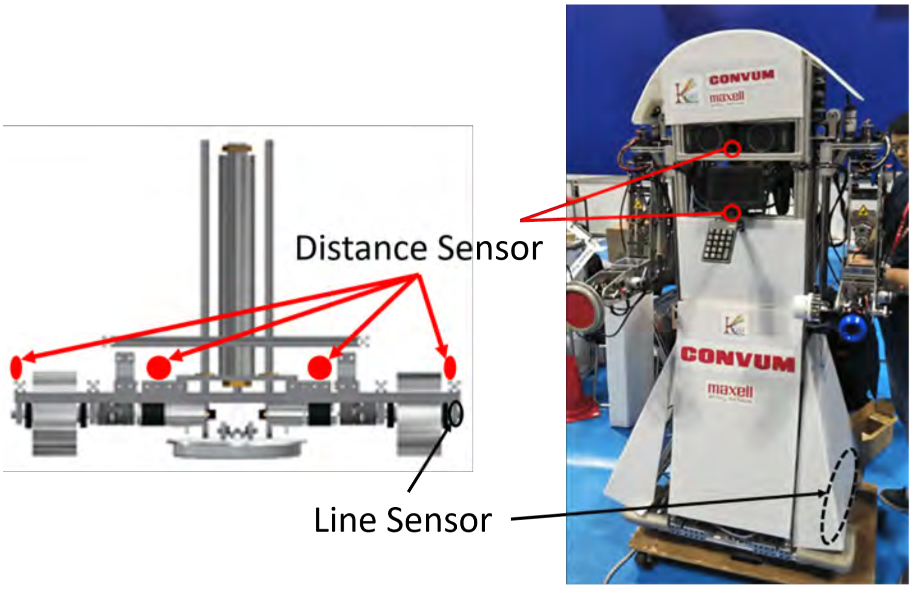


Figure 13. Position of ranging sensor and line sensor

the operation to be performed and a note on the external monitor. For example, after giving an audio signal "I will carry," the monitor will show the note to being carried. The Arduinos compare the value sent from the Ubuntu14.04 PC for each sensor in the robot body and drives the motor driver. By carrying out this series of operations, the Q-bot grasps and transports the object. Two distance measurement sensors (Fig. 13), at the center of the robot's torso, are used to and detect object and walls. An object to be held when it is in front of the robot is detected by monitoring changes in distance values. Also, the gyro sensor is corrected on the basis of distance measurements (two places in front, one on the left, and one on the right) from the robot to a wall by a sensor attached to the bogie. Also, line sensors are mounted low on the side of the robot (Fig. 13).

3. Experiment

3.1 *Experimental method*

We verified fall overturning prevention and self-weight compensation by the turnover-prevention UVG. As shown in Fig. 4, the pulley attached to Q-bot supports the load by a crane and wire. The robot uses the arms to prepare the load. In Experiment 1, the robot uses the arms to prepare to grasp the object. We verified that linear movement and rotational transfer could be performed in that state. In Experiment 2, the robot uses the arms to move an object to be grasped on the table. At this point, we checked whether the robot falls over by using the UVG ON / OFF switch.

3.2 *Experimental results*

In Experiment 1(Fig. 14). Q-bot was advanced from the start position and then turned a corner. There was no fall during the series of movements. From this result, we concluded that the robot can perform transportation with the arms stored. In Experiment 2 (Fig. 15), the turnover-prevention UVG was alternately not activated and We found that when Q-bot used the arms to push forward the object to be grasped , the turnover-prevention UVG was not operated but did not fall when it was operated. Thus it is possible to prevent falls by using the turnover-prevention UVG. Besides, given that it was not possible to grasp and unload the load without operating the turnover-prevention UVG, we concluded that the turnover-prevention UVG was acting on its weight compensation.

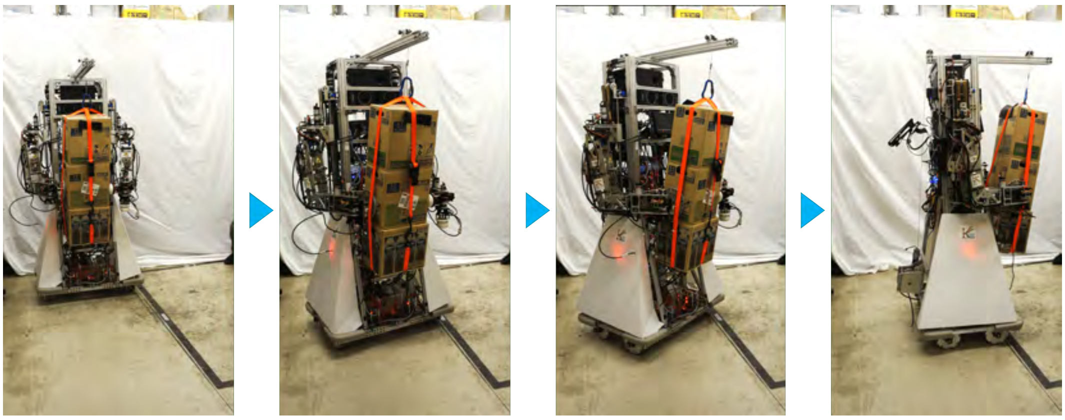


Figure 14. Transportation

(a) UVG OFF

(b) UVG ON

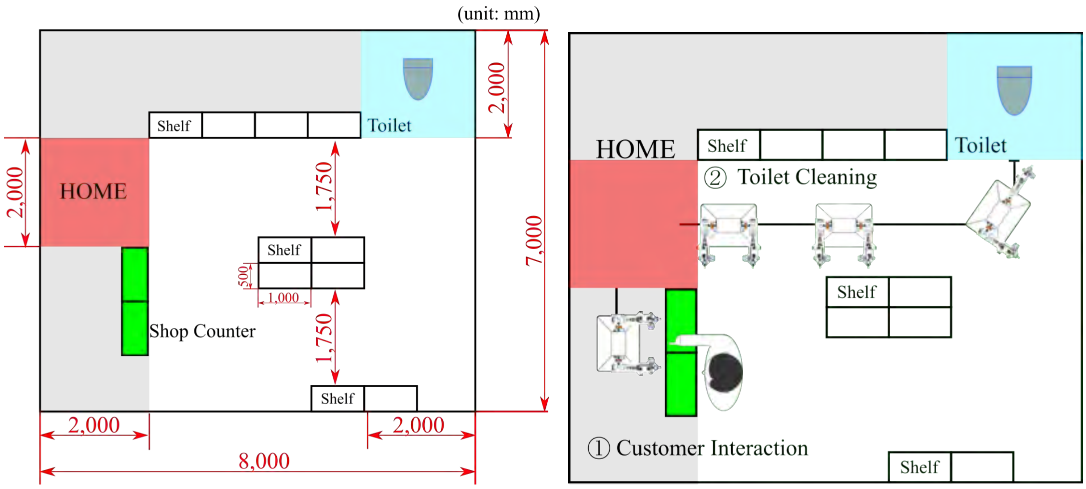
Figure 15. Experimental result of turnover Prevention UVG

4. Result of World Robot Summit 2018 Future Convenience-Store Challenge

4.1 *Rule for customer-interaction task in Future Convenience-Store Challenge*

According to the WRS-FCSC rulebook[15] concerning customer-interaction tasks, each team participating in this competition task was to develop a robot that autonomously moves and interacts with customers, as well as develop infrastructure to install inside a simulated convenience store. In this challenge, participants were to use the robots and infrastructure that they develop to compete in terms of the innovation, viability, and feasibility of their systems when performing a customer-interaction demonstration in a simulated convenience-store space. The time limit for this task (total for all phases) would be 20 minutes. The task was to proceed in three sequential phases: (1) renovation time, (2) setting time, and (3) cleaning demonstration. Participants could distribute the time to each phase as they prefer.

Fig. 16(a) is a sketch of the inside of a simulated convenience store.The demonstration we set up is as follows. The Q-bot was initially located at home, and moved to the front of shop counter to act as the cashier by following line 1 in Fig. 16(b). (The line for line tracing is installed at the setting time.) Next, when the customer came to the shop counter, looked at the command table on the front of the robot, and pressed the numeric keypad. The robot then performs the gripping and transport operations.



(a) Store sketch (b) Competition

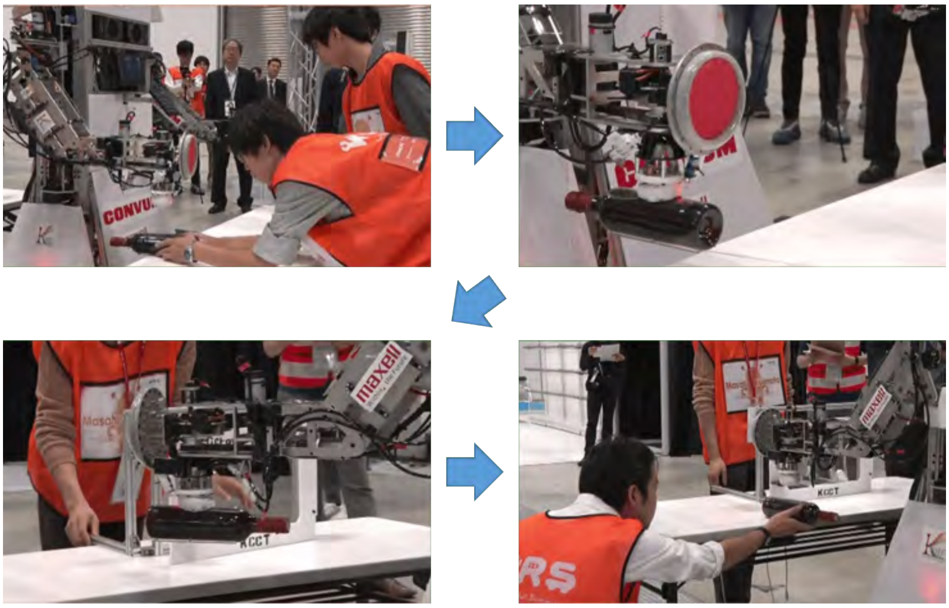
Figure 16. Refreshment booth

4.2 *Results of the customer-interaction task*

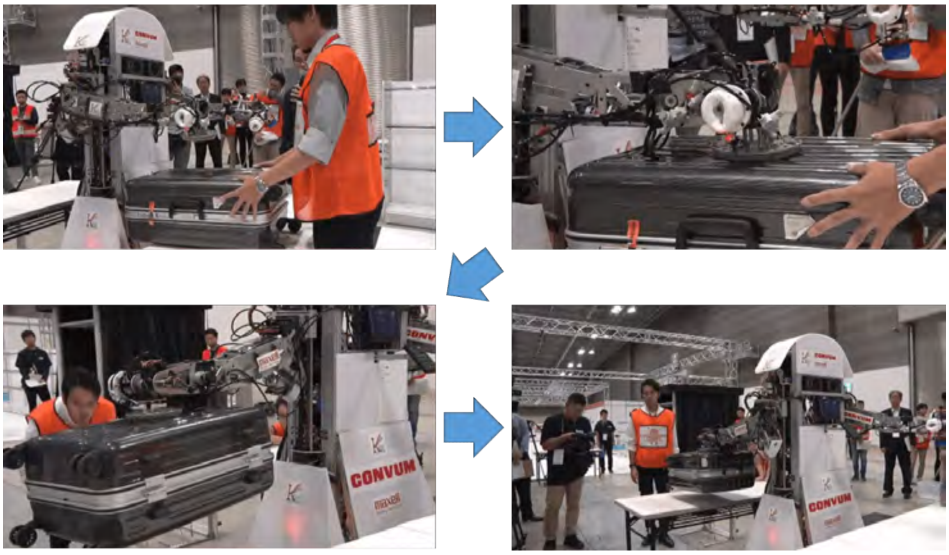
The heavy-load crane was removed from the Q-bot in order to use the crane in the WRS-FCSC. Table 2 shows the objects to be held and the results. Fig. 18 shows how Q-bot succeeded in gripping wine (720 ml), and a suitcase (4 kg). However, because the plastic bottle lid did not fit inside the UVG lip, the connection could not be sealed, air leaked from the gap, vacuum pressure was not reached, and gripping failed.

Table 2. Objects and gripping results

Pen	✓
PET bottle	×
Wine	✓
Lunchbox	✓
Suitcase	✓



(a) wine(720ml)



(b) Suitcase(4kg)

Figure 17. Holding object

4.3 *Rules for the toilet-cleaning task in Future Convenience-Store Challenge*

According to the WRS-FCSC rulebook[16] concerning toilet-cleaning tasks, this challenge aims to develop technology to automate restroom cleaning, which is a daily task for employees at a convenience store. Participants in this competition task were to develop a robot that operates autonomously and performs cleaning operations as well as develop infrastructure to perform cleaning operations that can be installed inside the restroom area of the convenience store.

In this challenge, participants were to use the robots and infrastructure that they develop to compete by demonstrating cleaning the toilet and the floor of a simulated restroom space. The time limit for this task (total for all phases) would be 20 minutes. The task was to proceed in three sequential phases: (1) renovation time, (2) setting time, (3) cleaning demonstration. Participants could distribute the time to each phase as they prefer. The restroom area consists of a toilet, the floor, and an area to install infrastructure in the layout (Fig. 18.) The demonstration was to consist of the following two subtasks: Cleaning simulated urine on the toilet, the rim (top of toilet bowl), the toilet seat (when up),and the floor around the toilet. (The inside of the toilet bowl would not need to be cleaned.) The second subtask was to be clean up garbage scattered on the floor (toilet roll and scraps of toilet paper). A comprehensive explanation about the cleaning will be described in the following sections.

The task is to have a total of 100 points in total: Cleaning the Simulated Urine (50 points) and Cleaning the Garbage (50 points). Judges of Cleaning the Simulated Urine were to disperse simulated urine (300 ml) around the restroom by using a sprayer aimed around the toilet bowl with the toilet seat open (as by a standing boy). The simulated urine is a fluorescent paint(UV ink) diluted with water. Images were to be taken to record the state of the restroom before spraying the simulated urine as well as before and after cleaning, and the removal rate of the simulated urine is to be measured. The full 50 points would be given to participants with an 80% or higher removal rate.

Judges of Cleaning the Garbage were to randomly scatter a total of five pieces of garbage composed of four scraps of toilet paper (maximum length about 5 cm) and one toilet paper roll. Furthermore, the garbage was to be scattered after the simulated urine is sprayed and thus may become slightly wet due to prior spraying. The restroom will be deemed to be clean by either throwing the garbage in the garbage can or storing the garbage inside the robot itself. Participants are allowed to decide the shape of the garbage can and its placement in the area for the mobile robot's use as well as in the infrastructure installation area during the renovation time or setting time. 10 points will be awarded for each piece of garbage that is cleaned up, for a maximum of 50 points.

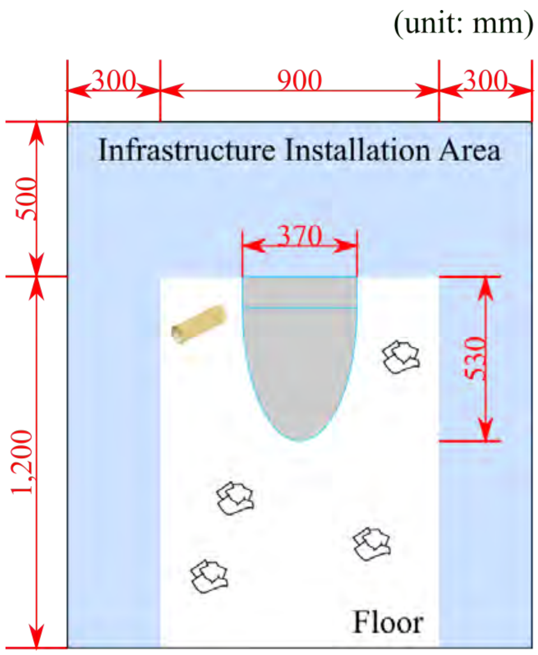


Figure 18. Toilet

4.4 *Results of the toilet-cleaning task*

At the setting time, Q-bot was moved to the home position, and a trash can was made available for placement in the infrastructure installation area. Q-bot was provided a mop during setup (Fig. 19). Then it was directed to follow line 2 (Fig. 16(b)) and go to the front of the toilet, then lower the mop to the floor and go forward while moving the mop left and right. At the end of the timed task, Q-bot dropped the mop. The sequence is shown in Fig. 20, and the results are shown in Table 3. The removal of simulated urine was not scored as we made two attempts during the competition. Also, the core and waste paper that could not be collected were both behind the toilet bowl where the mop did not reach.

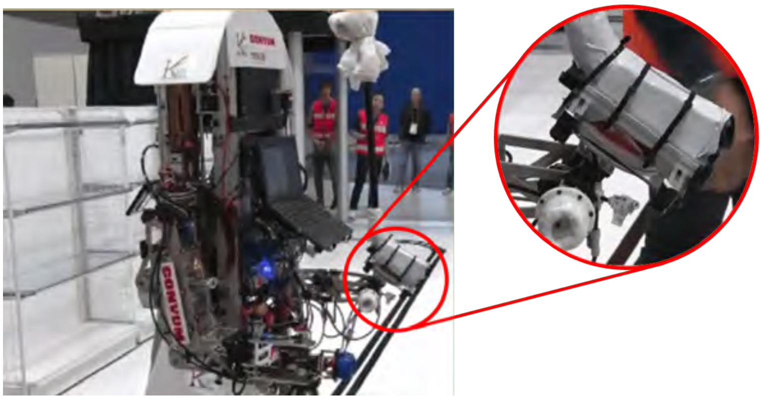


Figure 19. Mop in hand

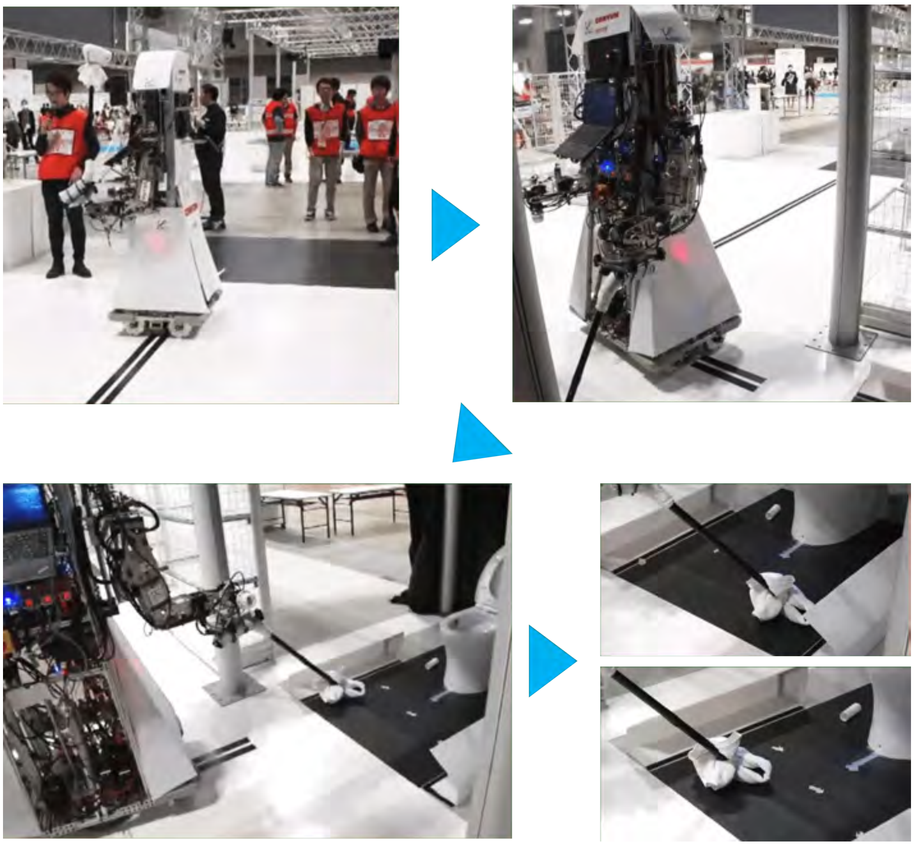


Figure 20. Toilet Cleaning

Table 3. Result of the toilet-cleaning task

	Cleaning	Points
Garbage	3	30
Simulated urine	22.52%	0
Total		30

5. Conclusion and future work

In this study, we developed a humanoid robot called Q-bot that can perform part of the work at a convenience store. One of its features is UVG technology designed for turnover or fall prevention and supported by self-weigh compensation, which were found to be an element necessary for transportation in our experiment. We verified movement (range and navigation) as well as objects transportation and unloading. We found that Q-bot was able to move while holding a 35 kg object. In addition, the unloading, of even heavy objects that originally caused Q-bot to fall over could be completed without overturning by activating the turnover-prevention UVG . In the WRS-FCSC, the Q-bot gripped wine and a lunchbox with the small UVG while using the large UVG to hold the suitcase and the mop. When gripping objects of different shapes and weights, a robot must be equipped with appropriate end effectors. Q-bot grasped them using just two UVGs.

In this study, we did not consider the time required to adhere to the object. Therefore, the experiment was conducted on the premise that the risk of falling was known in advance. However, in reality, it is rare that one can predict the risk of falling, if at all. In our future investigations, we will address such unforeseen events.

Acknowledgement

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About the Authors

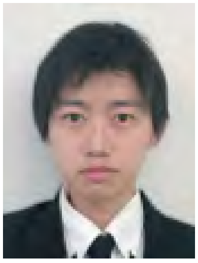
Isamu Matsuo received his Associate Degree from the Kobe City College of Technology, Japan in 2018. He is currently a Undergraduate students at the SHIMIZU's Laboratory in Mechanical Systems Engineering Dep, Kobe City College of Technology Major course. His current research interest is Wall Climbing Assisting suit based on Universal Vacuum Gripper. He is a student member of the Japan Society of Mechanical Engineers.

Toshihiko Shimizu is an associate professor at the Department of Mechanical Engineering, Kobe City College of Technology. He received his B.Eng., M.Eng. and Ph.D. in Osaka university, Osaka, Japan, in 2007, 2009, and 2012. He joined the Italian Institute of Technology (IIT), Genova, Italy as the researcher, in 2010, and moved to the current College of Technology, in 2012. His research interests include biologically inspired robots, machine learning, universal jamming gripper and universal adhesive robots.

Yusuke Nakai received his Associate Degree from the Kobe City College of Technology, Japan in 2018. He is currently a Undergraduate students at the SHIMIZU's Laboratory in Mechanical Systems Engineering Dep, Kobe City College of Technology Major course. His current research interest is Universal Vacuum Gripper with built-in soft fingers. He is a student member of the Japan Society of Mechanical Engineers.

Masahiro Kakimoto received his B. Eng. from the Kobe City College of Technology, Japan in 2019. He works at Kawada Robotics Corp. He is a member of the Japan Society of Mechanical Engineers.

Yuki Sawasaki received his B. Eng. from the Kobe City College of Technology, Japan in 2019. He works at FANUC Ltd. He is a member of the Japan Society of Mechanical Engineers.



Yoshiki Mori received his B. Eng. from the Kobe City College of Technology, Japan in 2019. He is currently a Master ' s student at the Graduate School of Advanced Science and Technology, JAIST. His current research interest is development of soft-robotic gripper based on jamming transition.

Takamasa Sugano received his Associate Degree from the Kobe City College of Technology, Japan in 2018. He is currently a Undergraduate students at the Toyohashi University of Technology.

Shuhei Ikemoto received his Ph.D. degree in engineering from Osaka University in March 2010. He had been a JSPS Research Fellow from April 2009 to March 2010, an assistant professor in the Department of Multimedia Engineering, Graduate School of Information Science and Technology, Osaka University from April 2010 to June 2014, and a specially appointed assistant professor of The Institute for Academic Initiatives, Osaka University since July 2014 to March 2015. He was an assistant professor in the Department of System Innovation, Graduate School of Engineering Science, Osaka University since April 2015 to March 2019. He is now an associate professor in Graduate School ofLife Science and Systems Engineering ,Kyushu Institute of Technology. His research interests include biologically inspired robots and algorithms, machine learning, and physical human-robot interaction.

Takeshi Miyamoto is a Professor at the Department of Mechanical Engineering, Kobe City College of Technology. He received his B.Eng., M.Eng. in Osaka university, Osaka, Japan, in 1989, 1991. He joined the Department of Mechanical Engineering of Osaka University as the assistant professor in 1991, and moved to the current College of Technology, in 2006. His research interests include methodology of cutting the difficult-to-cut materials and composite materials, grinding with Multi-layered belts, development of CBN grinding wheels.