How South Korea's DRC-HUBO Robot Won the DARPA Robotics Challenge

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On Saturday, Team KAIST from South Korea emerged as the winner (http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-robotics-challenge-finals-winner) of the DARPA Robotics Challenge (DRC) in Pomona, Calif., after its robot, an adaptable humanoid called DRC-HUBO, beat out 22 other robots from five different countries, winning the US $2 million grand prize. The robot's "transformer" ability to switch back and forth from a walking biped to a wheeled machine proved key to its victory. Many robots lost their balance and collapsed to the ground (http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-robotics-challenge-robots-falling) while trying to perform tasks such as opening a door or operating a drill. Not DRC-HUBO. Its unique design allowed it to perform tasks faster and, perhaps more important, stay on its feet—and wheels.

"Bipedal walking [for robots] is not very stable yet," Jun Ho Oh, a professor of mechanical engineering at the Korea Advanced Institute of Science and Technology who led the KAIST Team, told *IEEE Spectrum*. "One single thing goes wrong, the result is catastrophic." He said a robot with a humanoid form has advantages when operating in a human environment, but he wanted to find a design that could minimize the risk of falls. "I thought about different things, and the simplest was wheels on the knees."

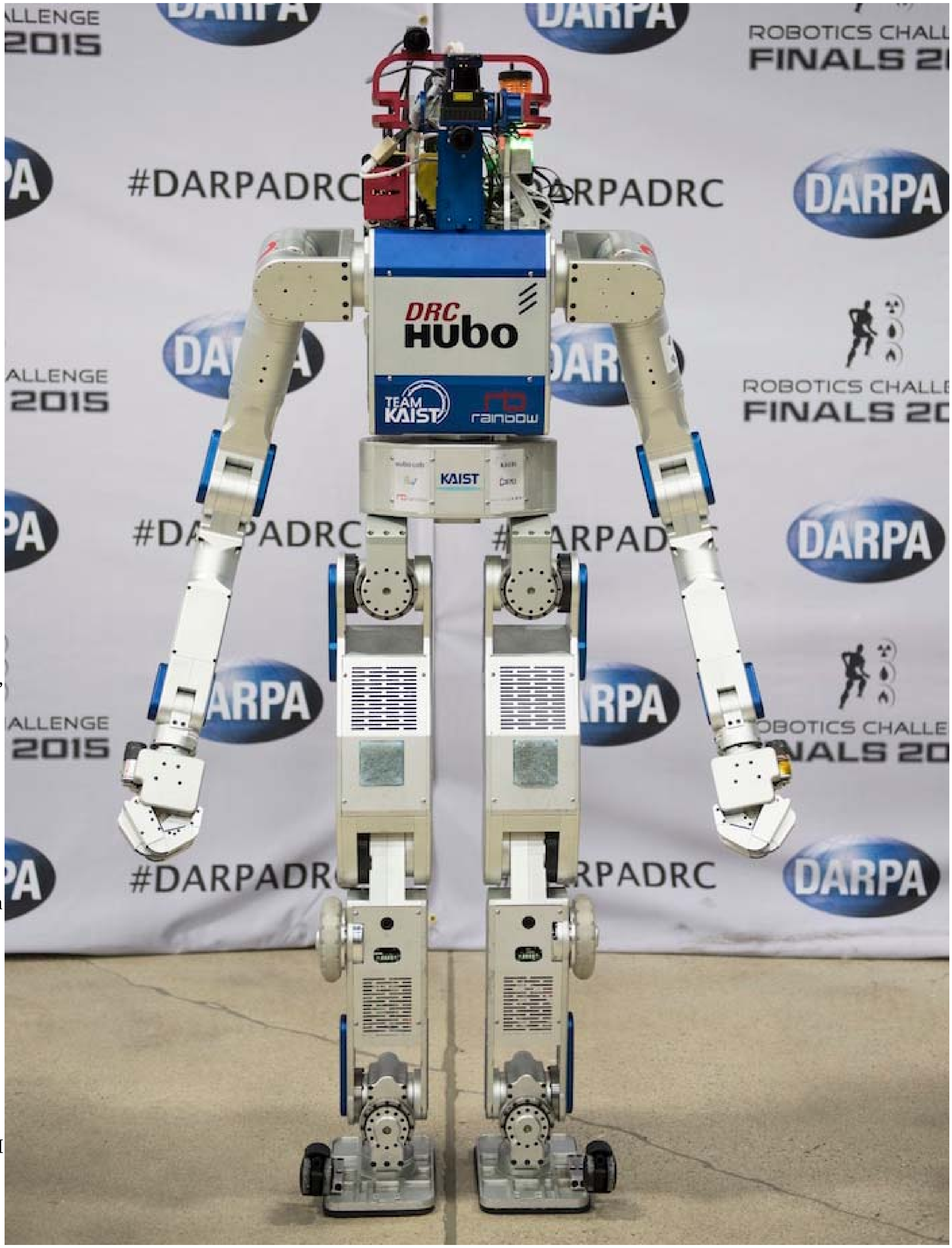
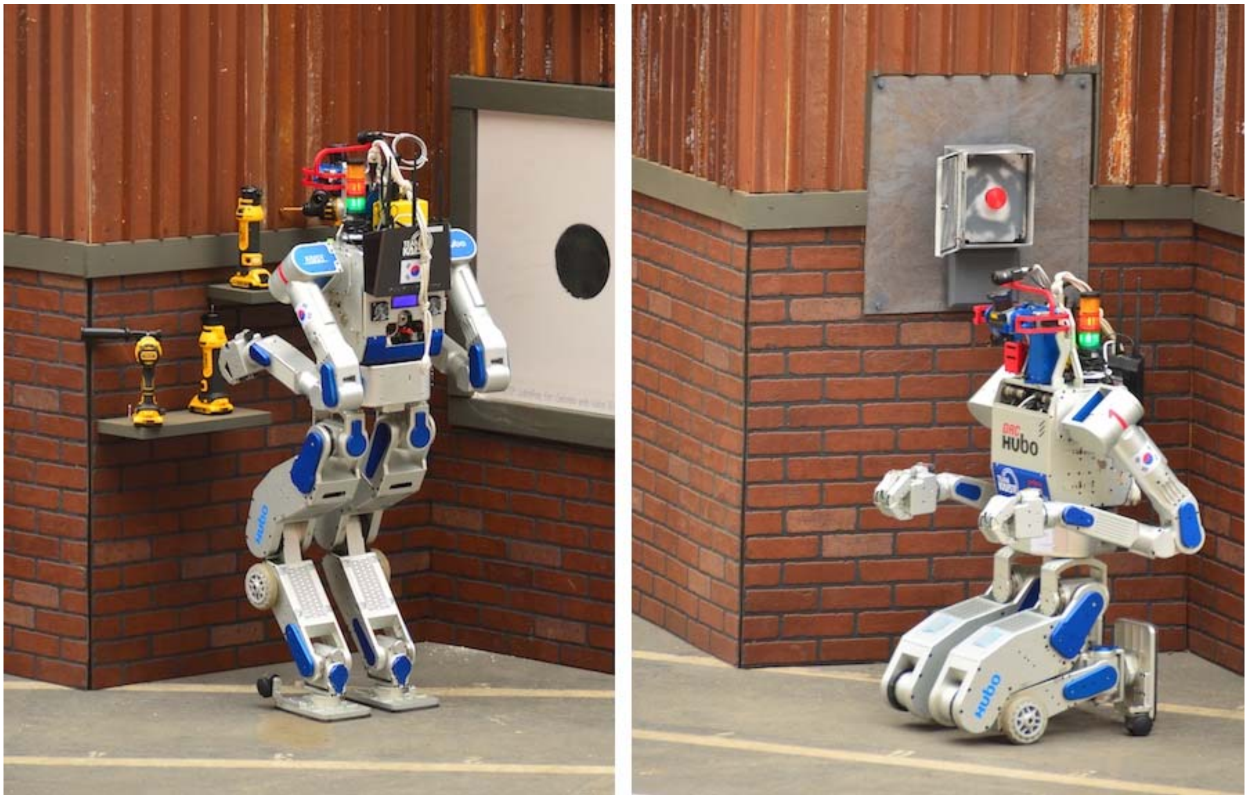


Photo: DARPA

This robot won the DARPA Robotics Challenge 2015.



Photos: Evan Ackerman/IEEE Spectrum

DRC-HUBO can modify its posture, standing on two legs to walk and reach higher objects or kneeling down to move around on wheels in a stable position.

DARPA decided to organize the DRC after the Fukushima accident (http://staging.spectrum.ieee.org/robotics/humanoids/darpas-rescuerobot-showdown) in Japan, hoping to advance the field of disaster robotics. The DRC Finals called for teams of semi-autonomous robots and human operators to work together in a simulated disaster environment. The robots created by universities and companies for the competition varied widely in size and shape and include legged robots, wheeled robots, and hybrids (http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-robotics-challenge-drc-finals-know-your-robots) as well.

DRC-HUBO prevailed over other robots because it completed all eight tasks (http://spectrum.ieee.org/automaton/robotics/humanoids/drc-finals-course) flawlessly in the shortest amount of time (44 minutes and 28 seconds). Other teams also performed well in the competition, but setbacks made their robots lose time. These included Tartan Rescue's CHIMP, a robot with legs and tank-like tracks that was the only robot to get back up after a fall (http://spectrum.ieee.org/automaton/robotics/humanoids/drc-finals-cmu-chimp-gets-up-after-fall-shows-how-awesome-robots-can-be); the University of Bonn's Momaro, an elegantly simple wheeled machine with a spinning head and two arms; NASA Jet Propulsion Laboratory's RoboSimian, a four-legged robot that seemed to perform yoga moves (https://www.youtube.com/watch?v=OesfwU1rsyg); IHMC's ATLAS, a large hydraulic-electric humanoid made by Boston Dynamics (http://spectrum.ieee.org/automaton/robotics/military-robots/atlas-drc-robot-is-75-percent-new-completely-unplugged) (and used by other DRC teams).

"Flexibility may be the most important thing," DARPA program manager and DRC organizer Gill Pratt (http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-robotics-challenge-qa-with-gill-pratt) said at a media briefing, commenting on the different robot designs. A robot that could change its configuration from using legs to using wheels, he explained, might be heavier and more complex, but would "give you that flexibility."

Professor Oh is an

Photo: DARPA

DRC-HUBO performs the valve task. Note its upper body turned 180 degrees.

internationally recognized expert in humanoid robots. He and his students at KAIST in Daejeon, South Korea, have been improving their HUBO platform over several generations. Below is a video from a few years ago, when Professor Oh gave us a tour of his lab and a demonstration of HUBO 2 (http://spectrum.ieee.org/automaton/robotics/humanoids/033010-hubo-ii-humanoid-robot-is-lighter-and-faster).

For the DRC Finals, Professor Oh decided to make significant modifications to specifically address the tasks the robots would face. At a workshop after the competition, he said DRC-HUBO is “nothing very special, just a humanoid robot.” But in fact, his team at KAIST custom designed and built almost every part of the robot. He estimated the cost of each humanoid at between $500,000 and $1 million. Here are some of the key features that helped the robot win the competition:

- **Wheels on knees:** DRC-HUBO has motorized wheels on both knees as well as casters on its feet [right]. The wheels let the robot move around in a fast and stable manner. When rolling on the ground, it uses optical sensors on the shins for optical flow odometry.

- **Powerful motors:** Like SCHAFT, the robot that won a preliminary DARPA robot challenge and was acquired by Google (http://spectrum.ieee.org/automaton/robotics/humanoids/schaft-robot-company-bought-by-google-darpa-robotics-challenge-winner), DRC-HUBO draws a lot of power from its motors (there are 33 in the robot, which has 31 degrees of freedom). With customized motor drivers and an air cooling system (fans and fins), the robot is able to drive 3x to 4x more current than what is listed in the motor specs, with peaks of 30 amperes in some cases.
- **Compliance:** The team wanted to make their robot compliant, but didn't want to use force-torque sensors and a conventional feedback controller (which they feared would introduce instabilities). So instead the implemented compliance on their custom motor driver, using a special amplifier.
- **Rotating torso:** DRC-HUBO can turn its upper body up to 180 degrees. That means that the robot can have its knees pointing one way and its eyes looking at the opposite direction (*you* try that!). This capability works both in standing mode and kneeling mode, and the robot relied on it during several tasks, including driving the vehicle, cutting the wall [right], pushing away rubble, and climbing stairs.

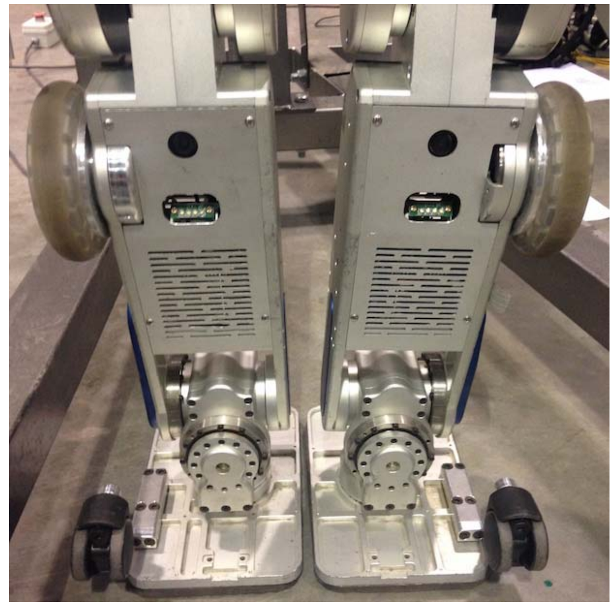


Photo: Erico Guizzo/IEEE Spectrum

The lower leg has wheels on the knees and casters on the feet. The oval holes on the shins are optical flow sensors for odometry. The ankles have 6-axis force-torque sensors and accelerometers.

Photo: Team KAIST

The air cooling system on the robot's upper leg and lower leg allows it to overdrive the motors.

- **Long arms:** The KAIST Team realized that the arms of HUBO 2 were too short for some tasks, so they designed longer 7-degrees-of-freedom arms for DRC-HUBO, and they also tucked all cables inside, to prevent them from getting caught on things. Each arm can hold up to 15 kilograms, and has an "adaptive gripper" capable of grasping hard or soft objects.
- **Simplified sensing:** Instead of a sensor-packed head with stereo cameras and a lidar that is

continuously scanning the environment (used in the ATLAS robots (http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-unveils-atlas-drc-robot), for example), DRC-HUBO uses a simplified vision system; operators rely on a regular camera most of the time, and a lidar, attached to a servo, scans the environment only when needed. In fact, the robot appears to have no head, "only eyes," one KAIST student told us.

- **Robust power:** When motors draw lots of current, the main power system may fail to provide enough power to critical components. To avoid that, the team used a supercapacitor system that keeps computers, communications, and some sensors like gyros running even if the main power system goes down.
- **Custom software:** The team uses the Xenomai real-time operating system for Linux and a customized motion control framework called PODO developed at KAIST. They also use the Gazebo simulation environment (http://spectrum.ieee.org/automaton/robotics/robotics-software/open-source-robotics-foundation-prepares-for-drc-finals-and-beyond). The team designed their software with a focus on the low bandwidth and unstable nature of communications between operators and robot.

Photo: DARPA

The robot's upper body can rotate up to 180 degrees, a helpful capability.

Photo: Team KAIST

The torso is stuffed with a computer for motion and another for vision, IMU, gyroscopes, and batteries.

Now let's take a closer look at DRC-HUBO going through all eight tasks in the run that gave Team KAIST its victory (if you want to watch the full run back-to-back, we uploaded it here (https://www.youtube.com/watch?v=UjASpfHwAyg); the full run at 20x is here (https://www.youtube.com/watch?v=v6-heLIg85o)):

1. Drive Task: Teams were allowed to make certain modifications to the Polaris vehicle so their robots

could drive it and get out of it more easily. Team KAIST placed a metal contraption with two levers on the floor of the vehicle; when DRC-HUBO pressed one of the levers, a cable system made the second lever press the accelerator. The robot holds on to the vehicle with its left hand and steers with its right one. It completes this task very, very fast (in a little over a minute) and, unlike other teams, it doesn't stop while going around the barriers.

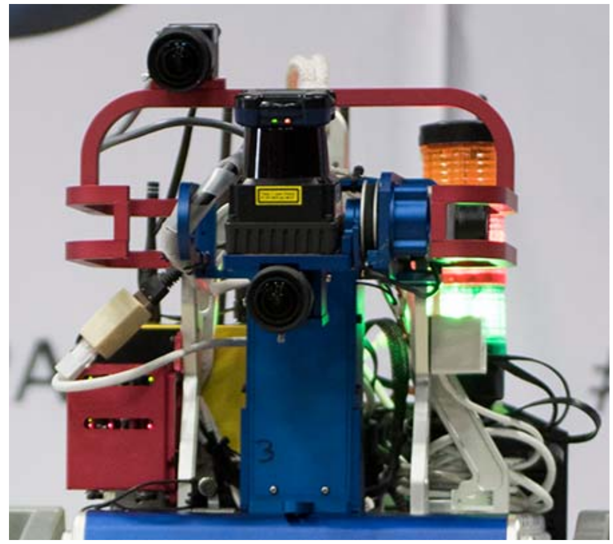


Photo: DARPA

The sensing head has a lidar and camera mounted on a gimbal that turns only when the operators want a new scan (there's also a fixed camera at the top).

2. Egress Task: This was one of the most difficult tasks in the competition. When planning for it, Professor Oh said he got in and out of the vehicle himself several times, to see what kind of motions and parts of his body he needed to use. He concluded that a "dynamic approach" was needed. His team programmed DRC-HUBO to put its arms up and hold on to the frame of the vehicle. Then the robot applies 100 newtons of pulling force to each arm. As the arms pull the robot's body up, it pretty much falls out of the vehicle, albeit in a controlled manner (hence the "dynamic approach"). Pay attention starting at 1:00. It's a beautiful egress maneuver! Professor Oh said the team burned several motors perfecting this motion, but solved the problem using their high power custom motor drivers. In the actual run, the robot is able to get out in less than 4 minutes, and once it's off the vehicle, it gets on its knees and zips away.

3. Door Task: Unlike several other robots that had to stand (and balance on two legs) to perform this task, DRC-HUBO could stay on its knees to manipulate the door knob. It elegantly uses its other arm to hold the door open while it releases the knob. In less than 2 minutes, it's going through the doorway on its knee-wheels.

4. Valve Task: Note at the beginning of the video how the lidar moves up and down to give the operators a scan of the scene ahead. Then, as DRC-HUBO approaches the valve, it performs a 180-degree upper body rotation. Pay attention at 0:20 or you'll miss it (the camera angle doesn't show the lower part of the robot, unfortunately). In this configuration, while still kneeling, the robot can raise its body just enough so that it can better manipulate the valve (why stand if you don't have to?). The robot performs some more lidar scans, adjusts its position, and in about 3 minutes it's done with the task. Note that only one full turn was required but DRC-HUBO performs two complete turns! At 2:01 you can see the robot "undoing" the torso rotation.

5. Wall

Task: This
was a tricky task for most teams because it required a precise grasp of a drill, and the robots had to press a trigger or on/off button to use the tool. DRC-HUBO relied on a force-torque sensor on each hand to help with grasping. You can see the robot moving itself and even repositioning the drill on the shelf (even knocking down another drill out of the way) to find a good way to grab it. Once the robot has the tool, operators indicate where to cut and the robot does the rest autonomously. It keeps 20 newtons of force against the wall, and you can see how it uses its whole body to move the drill in a perfect circle. Completing this task takes about 11 minutes.

6. Surprise

Task: The
surprise task consisted of pulling out a plug and putting it back into another socket. Note how DRC-HUBO scans the floor and notices that the drill it had knocked down earlier is on its path. The robot turns around and pushes the tool away with its knees. It then tries to turn around but looks like it hits the wall. The operators apparently notice the problem and drive forward a bit and then are able to turn. Finally they approach the wall with the plug, which is positioned higher than the valve and door knob. It's time to get up on its feet, and you can watch that happening starting at 3:05. DRC-HUBO takes some steps forward and after a while it initiates the grasping process. It grabs the plug by its cable; we believe that was intentional, to allow the operators to better see the plug and prevent the robot's hand from obstructing their view, which would make the task nearly impossible. Inserting the plug proves tricky, and at 7:47 you can see how the robot tries to push it in and misses the socket. After some corrective motions, success! The task takes 13 minutes and 30 seconds, the slowest in the run.

7. Rubble

Task: While
kneeling, DRC-HUBO can drive with its knees pointing forward, or it can turn its upper body 180 degrees and drive with its feet pointing forward and acting as a bulldozer's blade. And that's what it does for this task. You can see the torso rotation starting at 0:28. It's so cool. The robot then puts its arms up, probably for stability and preventing them from getting caught in the debris. It then starts plowing through the rubble. It stops momentarily when it appears that a piece of wood might get stuck on the cinder blocks, so it turns left a bit to get that out of the way. It then moves the plastic tube to the right. At 4:14 it rotates its torso once again and positions itself in front of the stairs. The task took less than 5 minutes.

8. Stairs Task: Professor Oh said that, for many tasks, especially climbing stairs, it's important that the robot is able to see its own feet. Big robots like ATLAS have a hard time doing that, having to bend their bodies and making balancing more difficult. DRC-HUBO solves this problem in a very clever way. It climbs the stairs backwards! By doing that, its knees don't block the robot's cameras from seeing its feet and the ground, and another advantage is that its shins won't ever hit the steps when it bends its legs. But how does it see its own feet if it's climbing the stairs backwards? By rotating its upper body, of course! You can see the process starting at 0:26. The robot is kneeling in front of the stairs when it suddenly turns its back to it. It then stands up and at 0:55 you can see it turning the torso 180 degrees. Now it can scan the stairs and start the climb. But note that, before doing that, it takes two steps sideways, to the left (1:45)! After a couple of minutes—which felt like an eternity for those watching—the robot finally starts going up, climbing the final three steps in a continuous maneuver. Neat! After less than 7 minutes, DRC-HUBO is atop the platform. The video has no audio, but at this point the team and audience had exploded in cheers (https://www.youtube.com/watch?v=fQ6b5Wm5Glw).

KAIST built
four
DRC-HUBOs and had been practicing without safety cables for over a month prior to the event. They did their runs outdoors, on a parking lot with rough ground and under a variety of conditions, including heavy sunlight and strong winds. "If we don't remove safety, operators are too fearful," Professor Oh said at the post-competition workshop.

He added that, during practice, they completed all tasks with the robot both in walking and kneeling modes (their average time was about 30 minutes). The team was particularly good at clearing debris with DRC-HUBO's arms, something they didn't get a chance to demonstrate at the DRC Finals, and they could also comfortably perform the tasks on much more difficult terrain than the one at the competition.

"Pity that we could not present that kind of beautiful walking at the challenge. . . . It was too easy!" Professor Oh said, walking off stage to applause.

Photo: Evan Ackerman/IEEE Spectrum

Professor Jun Ho Oh and his team celebrate their win at the DRC Finals on Saturday.