THE HUMANOID ROBOT CHALLENGE SPONSORED BY THE DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DARPA)

A Summary by Dr. Robert Finkelstein
Based on: http://www.theroboticschallenge.org

To accelerate the otherwise moribund effort to develop humanoid robots in the U.S., DARPA initiated the DARPA Robotics Challenge (DRC) in 2012, which will conclude in 2014. While not strictly a challenge for humanoid robots, humanoid robots are best able to achieve the goals of the program as specified. Also, a humanoid robot was offered by DARPA, as government furnished equipment, to teams developing new control algorithms, where the robot (head, arms, legs, and torso) would serve as a standard platform with which to demonstrate the performance of the new software. Thus those software teams need not have any hardware expertise or humanoid robot in order to compete.

The purpose of the program was to demonstrate the ability of the robots to perform Joint Force humanitarian, disaster relief, and related operations (e.g., natural and man-made disasters such as earthquakes, floods, gas explosions, nuclear power plant failures, terrorist attacks, etc.). These disasters can be military or civil situations. The robots can provide aid to victims in degraded human-engineered environments without endangering first responders and rescue workers. The robots must be able to use standard tools, equipment, and vehicles as a human would do, including adapting to tools and equipment with diverse specifications, and being able to move about in the infrastructure.

To be able to accomplish these goals, improvement is needed in technology for supervised autonomy in perception and decision-making, mounted and dismounted mobility, dexterity, strength, and platform endurance. Autonomy would permit supervision of the robot by non-expert operators, allow one human to supervise multiple robots, and let the robots accomplish difficult tasks with little or no communications (which might not be available).

The DRC involves three events:

(1) The virtual Robotics Challenge occurred in June 2013, focusing on the software-oriented teams, and involved the ability of a simulated robot to perform three tasks in a virtual environment.

(2) The DRC Trials occurred in December 2013 and involved testing the ability of physical robots to perform eight individual physical tasks concerned with mobility, manipulation, dexterity, perception, and operator control.

(3) The DRC final tests will occur in December 2014 and will concern the ability of the physical robots to perform a consecutive sequence of tasks with degraded communications between the robots and their operators. The winning team will receive a prize of $2 million.

DARPA expects a successful competition to accelerate progress in humanoid robot technology and lead to operational humanoids able to assist people in providing rescue and other services in
hazardous environments and disaster zones. To be effective in unpredictable disastrous conditions, DARPA requires that the robots to be adaptable with suitable ability for mobility, manipulation, and dexterity, and be able to demonstrate four key capabilities:

1. Sufficient mobility and dexterity to maneuver in a disaster zone
2. The ability to manipulate and use a variety of human tools
3. The ability to be operated by people with little or no robotics training
4. To be semi-autonomous and make decisions at a task level based on operator commands and sensor inputs

If the competing robots have difficulty satisfying these criteria, DARPA may fund the R&D needed to close the technology gaps. But it may not have to. The previous automotive Grand Challenges started with disappointing performances by the driverless vehicles. But the technology improved rapidly within just a few years, and DARPA did not need to close any technology gaps because companies – in and out of the automotive industry – did it on their own.

DARPA considers the competing humanoid robots to be the metaphoric equivalent of one-year old children, evolving to become the equivalent of two-year old children by the end of the competition. They will then be able to autonomously perform simple commands such as “Clear the debris in front of you” or “Close the valve.” In this initial Challenge, the level of autonomy will be low and human participation high for specifying the tasks which comprise the larger goals. Nevertheless, DARPA considers this humanoid robot competition to be “the beginning of an historic transformation in robotics.” The immediate mission is disaster response and recovery, but the technological achievement of autonomous humanoid robots will impact all sectors of the economy.

The seven teams (Competition Track B/C) which focused on software development and which successfully completed the Virtual Robot Challenge phase were given a modified Atlas humanoid robot, manufactured by Boston Dynamics, with which to implement their software and compete in the final phase of the competition. The Atlas humanoid is based on the earlier Petman humanoid robot.

The Atlas is the size of a football defensive lineman at 6 feet 2 inches tall and weighing 330 pounds. Its hydraulic power allows it to perform a natural range of movements, including dynamic walking, calisthenics, and the user-programmed behavior needed to perform the disaster response tasks specified in the competition. The algorithms needed for this behavior were developed and tested previously by the teams in the simulation, with a digital humanoid and environment. The software and a human operator will control the robot. At this stage, it is not fully autonomous.

The Atlas has suitable sensors (a Carnegie Robotics sensor head with Lidar and stereo vision) and actuators (28 hydraulically actuated joints) for the tasks to be accomplished, along with: an on-board, real-time control computer; hydraulic pump and thermal management; two arms; two hands (one provided by iRobot and one provided by Sandia National Laboratory); two legs; a torso; and a head.
The six teams (Competition Track A) focused on hardware and software and which passed the initial design review were eligible to compete in the first-round competition trials held during December 2013, along with the Track B/C teams. In addition, a number of unfunded teams (Competition Track D) were also allowed to compete in the December trails. The highest scoring teams will compete in the final round competition in December 2014 for a prize of $2 million (selected teams also received varying amounts of funding, totaling millions of dollars, to prepare for the competition).

The first round competition, in which 16 teams from Tracks A, B, C, and D competed (i.e., focused on software only or hardware and software, funded and unfunded by DARPA), consisted of eight tasks, each of which had two or three (mostly three) subtasks. Each subtask was worth one or two points, so each task was worth three points for successful completion. In addition, a bonus point was awarded for each task performed autonomously (without human intervention), so the maximum total score for the competition was 32 points. The tests involved disaster-related scenarios and examined the robot’s ability for mobility, manipulation, dexterity, perception, and operator control while accomplishing eight tasks: (1) drive a vehicle through a designated course; (2) traverse uneven terrain and piles of rubble; (3) climb a ladder; (4) remove debris and move through a doorway; (5) opening three different types of doors; (6) use tools to cut through and remove drywall; (7) closing three different valves; (8) connecting a hose three different ways. For the final round in 2014, the various tasks will be combined smoothly to replicate a realistic disaster response and mitigation mission.

The eight top-scoring teams were selected to compete in the final round and receive additional funding to prepare for the final round, to be held in December 2014. The team standings for the first round were:

1. 27 Points: Team Schaft (Schaft Inc.)
2. 20 Points: Team IHMC Robotics (Florida Institute for Human & Machine Cognition)
3. 18 Points: Team Tartan Rescue (Carnegie Mellon University and National Robotics Engineering Center)
4. 16 Points: Team MIT (MIT)
5. 14 Points: Team RoboSimian (NASA Jet Propulsion Laboratory)
6. 11 Points: Team TRACLabs (TRACLabs, Inc.)
7. 11 Points: Team WRECS (Worcester Polytechnic Institute)
8. 9 Points: Team Trooper (Lockheed Martin Advanced Technology Labs)

The bottom eight teams did not qualify to receive additional funding for preparation, but can compete in the final round at their own expense:

9. 8 Points: Team THOR (Virginia Tech College of Engineering, Robotics & Mechanisms Laboratory)
10. 8 Points: Team KAIST (Rainbow Co.)
11. 8 Points: Team ViGIR (TORC Robotics)
12. 3 Points: Team HKU (University of Hong Kong)
13. 3 Points: Team DRC-Hubo (Drexel University)
14. 0 Points: Team Chiron (Kairos Autonomi)
The winning company, Schaf f Inc., a start-up robotics company from Japan, was acquired by Google during 2013 in its rapid acquisition of robotics companies and robotics technology (including robotic cars, humanoids, and other robots). The Schaf f team scored 27 points out of a possible 32, seven points more than IHMC Robotics, which used the Atlas humanoid. The Schaf f robot lost points because, during one task, it could not hold onto a door because of a wind gust, and during another task it had trouble climbing out of the vehicle it drove successfully through the obstacle course.

On the whole, the performance of the higher-scoring robots exceeded DARPA’s expectations, despite the slowness of the robots compared with humans. They needed to pause between subtasks to perform the necessary calculations controlling their behavior. Some of robots had poor bipedal balance and were saved from falling only by harnesses. They also used onboard sources of energy (e.g., batteries) that need improvement, and some of the robots were not completely humanoid.

The winning Schaf f Robot, called the S-One, weighed 209 lbs with a height of 4 feet 11 inches tall, considerable smaller and lighter than the Atlas. It was based on the ancestral HRP-2 humanoid, from a decade earlier, and which was able to walk on uneven surfaces. The second place Team IHMC, which was focused on software development, used the Boston Dynamics Atlas robot provided by DARPA (6 feet 2 inches tall and weighing 330 pounds) to demonstrate its humanoid control system. The third place Team Tartan Rescue designed a humanoid robot called CHIMP (CMU Highly Intelligent Mobile Platform). It weighed 400 pounds and was 5 feet 2 inches tall. It vaguely resembled a human, but moved on rubberized tracks, not legs, which provided stability on uneven surfaces. It had multiple sensors, including two rotating lidars on its head to provide a three dimensional map of its environment. Thirty-nine motors activated its servomechanisms. The fourth place TEAM MIT used the DARPA-supplied Atlas robot, which was controlled by their software, while the fifth place Team RoboSimian developed a monkey-like robot weighing 238 pounds with a height of 5 feet 5 inches.

As previously mentioned, in the DARPA humanoid robot Challenge there were eight tasks, each consisting of subtasks. While oriented toward disaster rescue and recovery, the robots’ actions, such as driving a standard vehicle driven manually by humans, could be generalized and applied for many other civil and military missions and applications. Also, the underlying technological foundation achieved in this program could be transferred to other kinds of behaviors and robots, such as those for elder care. The summarized and paraphrased tasks and subtasks, as provided by DARPA, follow.

**Task 1: Vehicle**

A course configuration, with pylons, barrels, and boundaries, was designed for the vehicle task. There were two subtasks: (1) The robot was to drive the vehicle through the course (worth 1 point); and (2) then exit the vehicle and leave the course end zone on foot (or wheels, as the case may be) (worth 2 points). No human intervention was allowed for this task.
The first sub-task started with the robot in the driver’s seat of the vehicle, the key in the ignition, the vehicle turned on and running and in high gear. The robot had the option to operate the shift lever to change gear, but this was not required. To drive the vehicle, the robot had to depress the accelerator and rotate the steering wheel. The first sub-task was completed when the robot drove through the course and crossed the finish line, with both rear wheels of the vehicle crossing the finish line. To exit the vehicle, the robot was not required to move the shift lever from “drive” to “park,” although it was considered prudent to prevent the vehicle from moving while the robot was getting out. The second subtask was completed when the robot exited the vehicle and made its way, e.g., on foot, out of the end zone of the course. A score of zero was awarded if any barrier was struck by either the vehicle or the robot on foot and moved more than 3.5 inches. Also, a score of zero was awarded if all four wheels of the vehicle crossed the outer boundaries of the course.

**Task 2: Terrain**

A course was designed for the terrain task with three segments, each of which had a surface comprised of blocks arranged into different kinds of challenging surfaces: a slope to descend and then a hurdle; an ascending and descending irregular step-like surface; and an irregular rubble-like surface. The terrain task consists of three sub-tasks, worth one point each. Each subtask involved traversing one of the three course terrain segments: initial, middle, and final. Visible color-coded lines marked the boundary between terrain segments and the end zone.

For the first subtask the robots began behind a green start line and then crossed a sloping surface to a hurdle one block (6 inches) high which it had to climb over. The first subtask was completed when the robot no longer had contact with the first terrain segment, crossing successfully to the middle terrain segment. For the second, middle terrain segment sub-task the robot crossed blocks arranged as ascending, and then descending, flat top steps. This sub-task was completed when the robot no longer had contact with the second terrain segment. For the third sub-task in the final terrain segment, the robot crossed a surface where the blocks were arranged to ascend irregularly, like broken terrain with rubble, and then level off with the surface still irregular. This sub-task was completed when there was no longer contact between the robot and terrain in the final terrain segment. i.e., the robot was in the end zone. If a human intervention took place during the first sub-task, the robot had to be reset at the start of the course. If an intervention took place during the second sub-task, the robot had to be reset at a place chosen by the team with ground contacts entirely in the initial terrain segment. If an intervention took place during the third sub-task, the robot had to be reset at a place chosen by the team with ground contacts entirely in the middle terrain segment. A physical tether to the robot was required for emergency stops that was independent of the availability of power or communications to the robot.

**Task 3: Ladder**

A course was designed for the ladder climbing task, where ladder was 8 feet high and attached at the top to an ISO (International Standards Organization) container of the kind in which freight is shipped (20 feet long, 8 feet 6 inches wide, and 8 feet high). The teams could specify the angle
(with respect to the ground) at which the ladder leaned against the ISO container, from 60 to 75 degrees. The teams could also specify whether the ladder had one, two, or no handrails. The robots had to be connected to a fall limiting system. At the conclusion of the climbing task, the robots were not required to descend the ladder; they were lowered to the ground. If there was human intervention during the tasks, the robot would have to start at the beginning, at the bottom of the ladder to perform the first subtask.

The three subtasks were worth one point each and consisted of: (1) contact with steps on or above the first step; (2) contact with steps on or above the fourth step; and (3) no contact below the landing.

**Task 4: Debris**

A course was designed for the debris task, in which debris was simulated by lightweight wood, such as Balsa, lying in front of a doorway and blocking access to it. Five of the debris pieces had dimensions 2 x 4 x 36 inches, and five had dimensions 4 x 4 x 24 inches. At least one end of all the debris pieces was initially set, for each competitor, at a height of at least 16 inches. At the beginning of the run, the debris pieces were supported in part by a truss so that none of the pieces were lying on the ground. The robot began the task behind the start line with the debris lying directly between the starting point and the doorway. The debris task consisted of three sub-tasks, each worth one point: (1) remove five pieces of debris; (2) remove an additional five pieces of debris; and (3) move through the open doorway. For the first and second subtasks, the robot removed debris by moving it from its initial position to a position outside the path the robot needed to access the doorway. No part of the cleared debris was allowed to touch the floor inside a rectangle formed by the doorway and start line. The first and second subtasks were complete when five pieces of debris were removed for each subtask and placed outside of the lane between the concrete block walls. The robot could lean cleared debris against the wall or place it on top of the wall. The robot could also place cleared debris on either side of the wall, or behind itself, as long as the debris was placed away from the doorway. The robot could also remove the truss (the metal structure holding the debris), but it was not required. For the third sub-task, the robot had to move through the open doorway, which had no threshold. This third subtask was complete when the robot crossed a line marked on the ground on the other side of the doorway.

Any human intervention during subtasks 1 or 2 required that the five debris pieces for the subtask had to be reset and the robot start over again for that subtask. A human intervention during subtask 3 required the robot start again to move through the doorway without debris pieces blocking the entrance.

**Task 5: Door**

The course designed for the door task consisted of a structure with three differently functioning doors, each within a 36-inch wide door frame (albeit, with door jamb and the side of the door, the width was 33.5 inches). The doors did not have thresholds, and the floors were flat. Each door had a specified lever-style handle that rotated upward or downward. The height of a door
handle was about 40 inches above the ground (but no less than 32 inches above the ground and no more than 48 inches above the ground). A force of several pounds was required to open the pull door with the weighted closer.

For each subtask, worth one point each, the robot started at specified line and had to open a door and move through the doorway and cross a line on the far side. For the first subtask the robot had to open a push door; for the second it opened a pull door; and for the third it opened a pull door with a weighted closer. The subtasks had to be completed in the order specified. Each subtask was completed when all parts of the robot moved through the doorway it opened and crossed the line on the other side.

If a human intervention were to occur during a subtask, the robot would have to return to the starting line for that subtask before relevant door, which would be closed.

Task 6: Wall

The course designed for the wall task was, basically, a wall made of wallboards consisting of one-half inch thick drywall. The robot had to use a conventional cordless drill to cut through wall boards to remove a prescribed right triangular shape (there were with no obstructions or supports directly behind the place the pattern was to be cut. The three vertices of the right triangle were six-inch diameter circles colored green. Two of the vertices had a height of 36 inches, and the other vertex had a height of 48 inches. The edges connecting the vertices were six inches wide and colored blue. The vertical edge was 12 inches long, and the horizontal edge 24 inches long. The task required the cutting to be exclusively within the area colored green or blue to remove the red area, while not cutting any gray area outside the constraints. Once all green areas were connected with cut lines, the robot was allowed to push the drywall to try to remove the red area. If the drywall were removed that way, all breaks in the drywall had to be within the perimeter constraints. If the cracks extended into the gray area, the final task was not considered complete. There was no requirement specifying the order or number of cuts necessary to remove the inner triangle.

The robots could choose between two different drills and two different drill bits. If there was an accident or problem with one drill during the task, the robot could switch to the other drill. If both tools ceased to function, the team could have a human intervention where the robot was returned to the start and two new tools were placed on the shelf for the task to begin again. The wall task was scored with (1) one point for cutting one edge between two green vertices; (2) one point for cutting a second edge; and (3) one point for cutting a third edge and removing a triangular piece from the wall.

Task 7: Valve

The course designed for the valve task consisted of a wall in front of which were three vertical air-flow pipes, each of which had a valve, where each was different. One valve had a 90-degree ball valve, with a 13-inch handle that required a rotation of 90 degrees to close. The valve handle could be moved with five pounds of force or less applied to the tip of the handle. A second valve was a mid-size rotary valve with a 9-inch diameter wheel handle that required one
complete clockwise rotation to close. The valve handle could be moved with five pounds of force or less applied to the edge of the handle. A third valve was a large rotary valve with an 18-inch diameter wheel handle that require one complete clockwise rotation to close. The valve handle could be moved with a force of five pounds of force or less applied to the edge of the handle. The height of each valve center was about 40 inches above the ground, between 32 to 48 inches above the ground, with the center-to-center distances between the valves about two feet.

The valves controlled air flow in the pipes, with indicators that visually showed the air flow. For each of the three sub-tasks, completion required turning the valve until the air flow stopped.

The task was initialized by first closing the rotary valves (no air flow) and then opening them one revolution (air flowed). The task was for the robot to close each valve, so no air flowed, in succession. The three valves could be closed by the robot in any order, with each successful closing worth one point. The task began with the robot closing the first valve it selected, flowed by the second and third. If a human had to intervene during any of the subtasks (i.e., while any of the valves were being closed), the robot was returned to the start to begin the entire task again.

**Task 8: Hose**

The course designed for the hose task consisted of a three-walled enclosure in which there were a fire hose on a reel mounted on a wall and a wye connector (i.e., a “Y” shaped hose connector) mounted on another wall in the enclosure. The specifications for the wye were given, e.g., it had a 1.5-inch inlet and outlet and was about 40 inches above the ground (no less than 32 inches and no more than 48 inches). The specifications for the hose and reel were also provided, e.g., a 1.5-inch diameter, 25-foot long hose, with the center of the hose reel about 40 inches above the ground and perpendicular to the wall.

The hose task consists of three subtasks, worth one point each. For the first subtask, the robot moved from behind the starting line to the hose reel. The robot grasped the hose nozzle, unreeled the hose, and moved the hose nozzle past a designated line. The second subtask required the robot to move the hose nozzle to the wye connector, and it was completed when the hose end physically contacted (just touched) the wye. The third subtask required the robot to attach the hose nozzle to the wye. There was no required procedure for doing this, but usually such an attachment would require that one hand hold the hose in place while the other hand rotated the hose collar to mate with the wye. If only the hose body were rotated, the nozzle threads would engage with the connector. Also, there was requirement for the number of turns of the collar or on the number of nozzle threads engaged in the connection. The third subtask was completed when the hose end remained in contact with the wye, unsupported by the robot.

If a human intervention took place during the first subtask, the robot was re-positioned behind the start line and the hose replaced on the reel before the robot began again. A human intervention during the second subtasks required that the robot be re-positioned behind the line for the second subtask, but the unreeled hose was placed on a hose-holding fixture on the wall, so the robot could grasp the nozzle without having to pick it up from the ground.

A human intervention during the third subtask followed the same procedure as an intervention during the second subtask.