Humanoids and the potential role of electroactive materials/mechanisms in advancing their capability

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Keywords: Humanoids, Robotics, Humanlike Robots, EAP, Electroactive Polymer Actuators, Biomimetics, Biologically Inspired Technologies.

Abstract: Humanoids are increasingly becoming capable biologically inspired robots that are appearing and behaving lifelike. Making humanlike robots is the ultimate challenge to biomimetics and, while for many years they were considered a science fiction, such robots are increasingly becoming engineering reality. Progress in producing such robots are allowing them to perform impressive functions and tasks. In 2012, in an effort to promote significant advances in developing humanoids, DARPA posed a Robotic Challenge to produce such robots that operate in disaster scenarios towards making society more resilient. The challenge was focused on the requirements that have been needed after the Fukushima accident in Japan, hoping to advance the field of disaster robotics. This disaster posed significant challenges to emergency responders since radiation prevented people from going into the station and venting the explosive gas. Another significant development in this field is the fact that major US corporations have entered into the race to produce commercial humanoids. As a result, one can expect significant and rapid progress in this field. Developing humanoids is critically dependent of the use of highly efficient, compact, lightweight actuators and electroactive materials are offering great potential. This paper reviews the state-of-the-art of humanlike robots, potential applications and challenges, as well as the actuation materials that are used or could be used.

Introduction

Making humanlike robots is the ultimate challenge to biomimetics and increasingly they are becoming an engineering reality as robots that are behaving lifelike. The progress resulted from the significant capabilities that were developed in the related technology particularly in microelectronics and control software enabling robots to perform impressive functions and tasks. However, there are still many challenges to their development including the required power that limits the operation duration and the fact that their actuation mechanisms are relatively heavy and limited in dexterity.

In an effort to promote significant advances in humanoids technology and making society more resilient, the USA's Defense Advanced Research Projects Agency (DARPA) posed in 2012 a Robotic Challenge to produce such robots that operate in disaster scenarios. The challenge was focused on the requirements that were needed after the Fukushima accident in Japan, where there was limited access to emergency responders as a result of the extremely high radiation around the failed nuclear plant. In response, various humanoids were developed that participated in the DARPA Robotics Challenge (DRC) contests that were held in 2013 and 2015.

In parallel to the DRC, DARPA also posed an endurance challenge for the development of robots. The challenge consisted of giving the robot a fully charged battery and setting it up to walk on a treadmill (tethered for safety but otherwise self-contained) till the battery runs out of charge and determine how far and how long the robot walked. Under funding from DARPA, the robot called DURUS was developed by Sandia National Labs and SRI International that addressed this challenge. The key goal in developing this robot has been to find ways to improve the operation efficiency by determining approaches to reducing losses in actuation of walking robot. The components that are examined for the effect on the efficiency include: motors, mechanical transmissions, motor

controllers, electrical wiring, kinematics, dynamics, walking gait, etc. The biggest improvement that has been made was the enhancement of the walking gait, which instead of using quasi-static robotic gait to keep the robot's center of mass balanced above its feet, it was made to walk dynamically like a human. New software control algorithm has been developed to support the mobility of the DURUS by having it intentionally falling forward and constantly catching itself via taking steps.

Another significant development in the field of humanoids is the fact that major corporations in the USA have entered into the race to produce commercial humanlike robots. As a result, one can expect significant and rapid advances in this field. While improvements are being made in many field that are enabling very sophisticated and capable robots, there is still a critical need for highly efficient, compact, lightweight actuators and electroactive materials are offering great potential. In this paper a review is given about the state-of-the-art of humanlike robots, potential applications and challenges, as well as the actuation materials that are used or could be used.

The need for robots in humanlike form

The development of robots that look like humans is intended to make them as useful as possible by designing them to fit our average body size, shape and capabilities [1, 2]. In a human-like configuration the robot would be able to listen to us at eye level, reach door handles, climb stairs, sit on chairs, drive cars and perform many of our other functions and tasks. These capabilities would make them effective helper in our home, workplace, the tools we use, the car we drive and reach the height at which we keep our possessions. Moreover, it is highly desirable that the robot would speak our language to make the communication simpler. Since we respond intuitively to body language and gestures, it is essential that the robot is able to make facial and body expressions.

Generally, it is argued that a human-like form is the most efficient for having humans teach robots (for example, motion capture or using a demonstration that the robot then imitates), which may play a fundamental role in making robots more intelligent [3]. It is interesting to note that children today are spending more time with smart phones, tablets and computers than with peers of their own age or with others. These makes them have less developed social skills and with poor understanding of the body language cues that were taken for granted by prior human generations. This concern may be addressed by incorporating human-like robots into education, therapy, or games while providing realistic simulation. Also, robots that are humanlike are already being used for treating children with autism and the reported results show great promise [4].

Making a human-like robot

Several key technologies and mechanisms are essential for constructing a lifelike humanoid including the materials, actuators, sensors, smart controls, hands and legs for mobility and manipulation, hearing and verbal communication, seeing and image interpretation, as well as collision and risk avoidance capabilities [1]. The robot needs to have effective control and artificial intelligence algorithms to operate humanlike and interact with its environment and with humans. Also, it needs to have parts and functions that are as similar as possible to those of a real human including:

Head, face, skin and brain: Besides appearance similarity, the head is used as the housing of the sensors that help the robot operate safely in its interaction with humans and the surrounding. Video cameras are used to provide vision and communication cues from facial expressions for acting socially appropriate. Microphones are used to produce sound and speech content, while acoustic receivers acquire information about the type and the direction of the sound sources. The verbal communication is interpreted by speech recognition and the sophistication of the related software has been advanced already to the level of "understanding" hundreds of words [1]. To communicate with humans, voice is synchronized and synchronized with lip movements and body gestures to generate lifelike speech. The head can also include an artificial nose and tongue to provide the robot with information about the smell of odors and the taste of objects.

The robot's head has a face that provides the identity as well as the facial expressions that convey verbal and the nonverbal communication. It is interesting to note that robots are already making realistic facial expressions that make them significantly more lifelike [1]. Humans are visual creatures and our ability to recognize faces and facial expressions is hardcoded within our nervous system. For this reason, mimicking our face's appearance, shape and movements is essential for creating lifelike expressions.

Progress in materials science have led to covering of robots that is increasingly being humanlike. The artificial skins are made to look and feel like a living person enabling to be highly elastic and create facial expressions without residual deformation. One of the notable developed artificial skins is Frubber [5] and an example of a robot head with such a skin is shown in **Figure 1**. This rubbery material was demonstrated to require minimal force and power and produce naturally looking large deformations. The robot head that is shown in **Figure 1** serves as a platform for engineers worldwide who are developing artificial muscles and need to test their developed actuator [6].

A microprocessor is used to control the operation of the robot and it acts as the equivalent of the human brain. Software is used to control the operation and functions of robots, including the mobility, image processing, verbal communication, body language and facial expressions, as well as many other tasks and functions that the robot needs to perform.

Figure 1: Using Frubber, a human-like head that makes facial expressions was produced as a platform for testing artificial muscles. This head that was created by David Hanson, Hanson Robotics, has been photographed by the author at JPL. This head is located at the author's NDEAA lab, Jet Propulsion Laboratory (JPL)/Caltech, Pasadena, CA, USA.

The appendages: Like humans, humanoid's appendages include arms, hands and legs, and they have the same functions [1]. However, even though these are easy functions for humans, in robots they are quite difficult to control. The progress in dynamic balance control and bipedal operation led to making them more stable when walking [7]. Sensors are mounted on the legs, arms and hands to support the control of the operation of the appendages in walking, carrying object and manipulating them as well as avoiding obstacles. These includes sensors that are used to determine the grip pressure, and to interpret tactile impressions. Spinoff the success in making humanlike robotic hands, arms and legs for robots has benefited disabled humans with the development of highly effective and lifelike prosthetics (**Figure 2**).

Figure 2: A prosthetic arm that was developed under a DARPA program. The photo was taken by the author at the DARPATech that was held in Anaheim, CA, 7-9 August, 2007.

Actuators and artificial muscles: Actuators are functioning in robots as the equivalent of biological muscles to mobilize them and allow for manipulating their arms and legs. Electric, pneumatic, hydraulic, piezoelectric, shape-memory alloys and ultrasonic actuators are generally used to drive mechanical functions of robots. To produce the movements of humanlike robots, electric motors are widely used. However, the mechanism that drives electric motors is quite different than our natural muscles. Addressing the key control requirements for making a robot operates lifelike requires the use of actuators that emulate more closely the operation of our muscles. Specifically, natural muscles are both compliant and linear in behavior [8]. The actuators that are the closest to do so are the electroactive polymers (EAP) and, for this reason, they are referred to as "artificial muscles" [1, 6]. Many of the EAP materials that are known today have been discovered and emerged in the 1990s. However, they are still weak with regards to their capability to make actuators perform significant mechanical tasks including lifting heavy objects. In recognition of the need for international cooperation, the author initiated and organized in March 1999 the first annual international EAP Actuators and Devices (EAPAD) Conference [9]. Also, the author posed at the opening of this Conference a challenge to scientists and engineers worldwide to develop a robotic arm that is actuated by artificial muscles to win an arm-wrestling match against a human opponent (see the icon of the match in (**Figure 3**).

Figure 3: The icon of the challenge for artificial muscles to win arm-wrestling match against a human opponent.

On 7 March 2005, the first contest was held where a 17-year old high school female student represented humans in an arm-wrestling match. Three EAP actuated robotic arms participated and the girl won against all of them. In the second arm-wrestling contest, which was held on 27 February 2006, rather than wrestling with a human opponent, a custom-made measuring fixture was used. The fixture allowed for testing the EAP-actuated arms for speed and pulling force and for

performance comparison baseline, the capability of the student from the 2005 contest was measured first. It is interesting to note that the 2006 results showed that the capability (force and speed) of the EAP actuated arms has been two orders of magnitude lower than that of the student. No other contests were held since the second one in 2006, however, the weakness of EAP as actuators of mechanisms is still a challenge. Once sufficient advances are made in EAP capability to make them faster and stronger that EAP-actuated robotic arms, a professional wrestler will be invited for a human/machine wrestling match.

The DARPA Robotics Challenge (DRC)

To advance humanoids capabilities, the DARPA Robotics Challenge (DRC) was posed in 2012. Generally, DARPA is an agency that is focused on stimulating innovation by focusing on short term efforts through posing challenges that are not impossible and have high risk with tremendous potential payoffs. They take specific technology that is almost ready and, by defining a challenge, important advances and breakthroughs are being made. As a related example, in addressing the 2004 challenge to develop driverless vehicle, the first race had many cars crashed immediately, and the most successful one traveled a distance of only 7 miles out of the 150-mile goal before it got stuck on a rock with its wheels caught on fire. However, in the following year, five teams finished the course. The success has led to the point that this year, Google, Tesla, Uber, and possibly Apple are all involved with the development of autonomously driven cars.

In 2012, under the lead of Pratt Gill, DARPA sought to advance the state of the art of humanoids by challenging roboticist to develop them to operate in disaster scenarios that would make society more resilient. Specifically, the DRC was focused on the requirements that were needed after the Fukushima nuclear plant accident in Japan. The strong radiation from the accident prevented the emergency responders from entering the station and venting the explosive gas. Unfortunately, the capability of the available robots in those days couldn't operate the required machinery and tools even if they could pass though the physical obstacles that stood in their way. To better assist in such disasters, the DRC was launched as a competition for humanoids to navigate in terrain conditions that are designed for humans. Specifically, the challenge was intended to lead to the humanoids that can assist humans in responding to natural and man-made disasters while operating in extremely difficult conditions.

The prized DRC sought to have semi-autonomous robots and remote human operators work together in a simulated disaster environment. Humanoids were created that varied widely in size and shape, including legged, wheeled, and hybrids of the two. The participating teams represented some of the most accomplished robotics R&D organizations in the world and they collaborated on a very short timeline to develop the required hardware, software, sensors, and human-machine control interfaces. This development enabled their robots to complete a series of challenging tasks selected by DARPA for relevance to disaster response. The DRC contests that were held are as follows:

1. June 2013 - The Virtual Robotics Challenge (VRC) tested software teams' ability to effectively guide a simulated robot through three sample tasks in a virtual environment.
2. December 20-21, 2013 - The DRC Trials took place in Florida, where teams guided their robots through eight individual, physical tasks that tested their mobility, manipulation, dexterity, perception, and operator control mechanisms.
3. June 5-6, 2015 - The DRC Finals took place in California. This event required robots to attempt a series of consecutive physical tasks, with degraded communications between the robots and their operators.

The DRC goals and accomplishments

The 2013 DRC Trials provided DARPA with a baseline on the state-of-the art of relevant robots as well as ranked the competing teams for selecting the best ones to continue receiving funding for advancing their potential. DARPA understood that the progress will be slow and the process will be similar to baby steps of learning how to walk and interact with the world while stumbling and falling in the process. In the 2015 Finals, three teams had the perfect scores and the tie was broken by

comparing their total performance time. The first place went to the South Korean team, KAIST, and their DRC-Hubo robot (**Figure 4**), the second place went to IHMC for their ATLAS Running Man, and third went to the Tartan Rescue robot of CMU NREC. Overall, the robots performed better than in the DRC Trials. However, there were variety of failures and they highlighted the difficulties that have remained, including the Running Man robot that fell over while waving to the crowd after successfully completing all eight tasks.

The teams made impressive progress beyond the point of joint-by-joint teleoperation, however the robots only had basic operation autonomy levels. Even though the robots were shaped like humans, they were operated by people with some of the teams had eight or nine operators having each member focusing on a separate task of the robot's sensory system. The human assistance was intended to address the difficulty of robots with perception and object recognition in unstructured terrains. The viewers of the competition could not avoid reaching the conclusion that the technology is still limited since most of the thinking and perception is done by humans behind the scenes. The DRC pushed the teams to greater robotic autonomy by adding a further challenge: once they entered the interior portion of the course, the communication between the robots and their human operators deteriorated. For many tasks, especially climbing stairs, it was important that the robot had the capability to see its own feet since they lacked any other kind of sensors for determining feet position and contact to the stairs. It is interesting to note that big robots had hard time bending their body and maintaining balance.

Figure 4: The DRC-Hubo robot of the South Korean team, KAIST, won the first prize in the 2015 DRC Finals. The robot's upper body can rotate up to 180 degrees, which is quite helpful capability. Also, there are wheels on its knees and casters on its feet allowing greater stability. Photo: DARPA

The JPL's RoboSimian performance

RoboSimian is an ape-like robot that was developed at JPL in collaboration with University of California, Santa Barbara, and Caltech (**Figure 5**). It participated in the DRC Trails and Finals and was ranked 5th out of the 16 and among 23 participants, respectively [10]. The RoboSimian was designed to operate under supervised autonomy in quasi-static mode rather than dynamic as in the biology world but this approach made it quite stable. It is equipped with long limbs allowing to have a great reaching capability. The wrists and ankles were designed as the equivalence of 4 fingers with a self-locking mechanism that is very robust and can be used as a clipper. The RoboSimian was designed to traverse complicated terrains and perform dexterous tasks using seven sets of stereo cameras for seeing and with its four limbs for maneuvering and manipulation. The drawback of the drive trains that contain the actuators is that they are relatively heavy, weighing 1.82 kg each. Using identical actuators on its 28 articulated joints allowed for many advantages particularly with regards

to servicing and the control algorithm. Like the other robots that participated in the DRC, its LIDAR device is used for mapping its environment in 3-D. The RoboSimian uses 2 KW/hr battery and it can be controlled by a small crew that consist of 2-3 people.

Figure 5: The JPL's RoboSimian is coming out of the vehicle during the DRC Finals. Courtesy: NASA/JPL, Pasadena, CA, USA.

Conclusions of the DARPA Robotics Challenge

Significant advances in the humanoids technology have been showcased in the DRC competitions and they served as a reality check about the state-of-the-art of these robots. Despite the significant increase in acquisitions, investments and recruiting in the last few years, robotics is still far from maturity. Even the most capable robot in the DRC had taken a long preparation time to execute such tasks as the turning a handle, and pushing a door. In contrast, after the last DARPA's Urban Challenge in 2007 driverless cars were recognized as ready to the next step of being commercialized. Cars had been driven through a mock city with no one behind the wheel or controlled remotely, and only a couple had crashed. Today, autonomous cars are already at a functionality level that is better than humans, and they are being tested over many complex roads and terrains. Unfortunately, the results after the completion of the 2015 DRC Finals highlighted the weaknesses of the humanoid technology and seems to suggest that there is still a "long" road ahead.

Autonomous operation is the opposite of tele-operation, where the robot operates independently rather than being given step-by-step commands of motion and maneuver. The DRC contest required "supervised autonomy" tasks in which operators were allowed/required to complete tasks despite low fidelity (low bandwidth, high latency, intermittent) communications. Robots still have significant limitations when they need to operate in unpredictability and unstructured environments. These environments require effective maneuver in terrains or conditions that have not been encountered before, using human tools without the need for extensive reprogramming and being able to continue operating autonomously with no human intervention. Addressing these challenges semi-autonomously requires that the robots is given a command and the robot would be able to execute the task without further instructions. This means that the robot will be able to take into account the sensing and motions that are involved, for example, with identifying the door handle, applying the right force, and properly maneuver to perform the function.

The Valkyrie Robots and the NASA's Space Robotics Challenge (SRC)

For many years, NASA has been engaged with the development of humanoids as a robotic helper to human astronauts. It includes the Robonaut-1 that was first generation and was tele-operated humanoid that has the upper body mechanism. The development was followed with Robonaut-2 that is semi-autonomous operation and the latest is the robot Valkyrie (**Figure 7**).

Figure 6: The semi-autonomous model of the Robonaut-2 shaking the hand of the author.

Figure 7: Valkyrie robot. Source: NASA/JSC

Generally, there is a lot of similarities between developing a humanoid that can function in disasters and ones that can function in such extreme environments as on other bodies in the solar system as on Mars. Developing humanoids, such as *Valkyrie*, can help testing the landing of humans before sending humans to Mars. Thus, the focus can be on confirming the habitability of Mars and avoiding the need for life support systems and other risks to human operators. Later, it can be used to work alongside the human astronauts, taking care of maintenance and other tasks that we wouldn't want to waste the astronauts' time on. Right now, up on the International Space Station there is a Robonaut-2 robot with the objective of testing maintenance tasks so that it can eventually take such tasks from the astronauts and potentially do them better. As a follow on to the DRC, NASA Johnson Space Center (JSC) posed a Space Robotics Challenge (SRC) that is focused on space operations in general. Funding from NASA and the National Science Foundation (NSF) have been put together to enable a couple of U.S. university teams that participated in the DRC to host a Valkyrie robot (designated as R5) to keep humanoid robotics research advancing post-DRC.

Conclusions

In recent year, humanoid technologies have been progressed significantly but they are still far from replicating the full capabilities of real people. Current robots can perform only a limited number of functions and primarily execute specific tasks. Also, they are limited when performing simultaneous tasks, i.e., walking is not performed while other physical tasks are being executed. Using AI, humanlike robots are capable of interpreting facial expressions and have personalized behavior that varies between duplicates of the same particular robots. Some robots can walk or dance similarly to humans; however, there are many basic human tasks that remain beyond current robots' capabilities. The process of overcoming these challenges robots is expected to be evolutionary.

The DRC has been a forum that led to advances in making such robots becoming faster, more autonomous, and more adaptable but they still have significant shortcomings. These include the need for more powerful batteries, stronger actuators, and better perception and object recognition. The robots showed mostly poor stability and it was relatively easy for the humanoids to lose balance. Other shortcoming has been the lack of tactile and robust sensors including, at a minimum, ones on the bottom of the feet and on the hands. The DRC gave a snapshot of state-of-the art as well as a preview of what our future relationships with them might look like.

Robotic hardware will need to be made significantly lighter and equipped with many miniature actuators and sensors with distributed processing capability. Specifically, effective actuators are required with high power density, as well as high operational and reaction speeds. Furthermore, there is a need for advances in miniature motors to control nuanced facial expressions or the movement of fingers, miniature drive electronics, and high sensitivity sensors. Electroactive polymers can potentially operate as lifelike actuators that drive humanoids to function humanlike. However, there are still many challenges ahead and the arm-wrestling contests will continue to provide a gauge of the technology advances towards making them drive such devices as prosthetics and others that will greatly benefit humans.

Acknowledgement

Some of the research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). The author would like to express his appreciation to Leon Alkalai, JPL/Caltech, for his support provided through the JPL's Blue Sky Program.

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