Robotics

Rodney Brooks
MIT

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Robots are programmable physical machines that have sensors and actuators, and are given goals for what they should achieve in the world. Perception algorithms process the sensor inputs, a control program decides how the robot should behave given its goals and current circumstances, and commands are sent to the motors to make the robot act in the world. Some robots are mobile, but others are rooted to a fixed location.

Robots in plays and movies (a 1920 Czech play was where the word "robot" originated) have generally been much more capable that actual contemporary robots. The first deployed robots were in *structured environments* such as automobile assembly lines in the 1950's. At that time, computation and sensors were both very expensive, so the environments for robots were specially constructed so that robots could effectively operate with little sensing or computation. Today's manufacturing robots still follow this approach and so manufacturing robots are only used in industries where the overhead of building the necessary special environments can be absorbed. This restricts them to factories that produce very expensive objects such as automobiles or silicon wafers, or very high volumes of unchanging products over many years, such as disposable medical devices.

Since the 1970's, most research in robotics has been targeted at extending robot capabilities to *unstructured environments* – environments not prepared specially for them. Early attempts concentrated on navigation, both indoors and outdoors, and the 1997 Mars rover Sojourner was the first major deployed success. Ground robots have, since 2002, become common in the US military, tackling the problems of forward scouting and IED remediation in both the Afghanistan and Iraq wars. Great further progress has been made with the 2005 DARPA Grand Challenge where several robot vehicles autonomously drove 200 kilometers across a desert, and in the 2007 DARPA Urban Challenge where a number of vehicles autonomously drove in traffic in a town for six hours. Concurrently, the first service robots have become common, with several million autonomous cleaning robots deployed in ordinary US households.

But there is a lot more that robots are capable of, and many more research challenges beyond navigation that will enable these new capabilities.

Why we need robots

Demographic trends in the US and worldwide demand the increased utilization of robots.

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These trends point not only to the problem of who will fund social security as the ratio of older and largely retired people to younger working people increases, but worse, those social security dollars will be competing for the service labor of relatively fewer people. Other countries will be competing for immigrants to fill labor pools (the tip of the iceberg is the current world-wide competition for emigrating medical professionals from the Philippines). The US will face profound challenges in populating its military, in providing construction labor, in nursing and elder-care, in fire fighting and emergency services, in all aspects of service industries, and in manufacturing. Robots will be a key technology to greatly increase the productivity of individual humans.

The state of the art

The recent conflicts in Afghanistan and Iraq saw the first large-scale deployments of ground robots to combat the IED threat, and the US Army has a large scale robotics component of its new Future Combat System to increase the war-fighting productivity of its ground forces. Unmanned air vehicles have also come into their own in the last decade, but historical insistence on having a "pilot" fly them, even from Nevada, is at odds with the needs of increasing military personnel productivity. The Navy, the Marines, the Army, and the Air Force all will require robots with significantly greater autonomous capability over the next decades if they are to maintain US superiority. The US currently leads the world in military robotics, and with further encouragement, manpower and casualty costs can be held in check and reduced through investment in greater autonomous capabilities for robots.

The US currently leads the world in deployed service robots but is in fierce competition with Japan and Korea to maintain that edge. Both those countries, along with Taiwan, have made domination of the service robotics industry key national goals. The European Union is also investing heavily through its "seventh framework." There is no comparable national program in the US. Robotics research has largely been funded in fits and starts by the Department of Defense and NASA. The former is now more focused on military applications and the latter has little room for extramural research as it struggles to fund a Shuttle replacement. While US floor cleaning robots are relatively well known, there are significant new markets for robotics emerging in healthcare (prostheses, surgery, and hospital operations), fulfillment centers, and agriculture.

Despite the impression from the popular press, US manufacturing remains strong, is the largest manufacturing sector in the world, and has had sustained productivity increases over the last fifty years at a rate even higher than that of the IT industry. At the same time, as a percentage of GDP it has roughly halved, as labor-intensive manufacturing has gone off-shore. Labor-intensive manufacturing would seem to be a high impact target for robotics, but it has not been due to the sorts of successes robotics had early on, casting the die for the direction it would take, effectively restricting manufacturing robots to structured environments. Robotics in high-value areas such as automobile manufacturing has had a fifty-year history in the US, though no domestic manufacturers of such robots have significant US or world market shares any longer (those that were successful were bought up by foreign companies). Today's industrial robots follow the practices set out in the 1950's, though they are cheaper and more accurate. But they have not fully embraced the IT revolution and have very little in the way of flexible computation, perception, or real-time planning. This makes the systems integration overhead of setting up robotic lines, turning factories into structured environments, for "Wal-Mart-class" manufacturing prohibitively expensive, and so such manufacturing has migrated to relatively low labor cost countries such as China. That pool of low-cost labor will not be around indefinitely, and until the recent hiccup in the world economy signs of difficulty were already becoming apparent in China. As we move forward, the US will need to invest in more intelligent industrial robots if it is to retain its manufacturing base, and be able to compete broadly in that arena.

The way forward

The US leads the world in graduate engineering education. Many engineering undergraduate programs have adopted robotics as a teaching tool. And high schools are using robotics as a lure to STEM education, with tens of thousands of high school students from all socio-economic levels taking part in the FIRST robotics competitions. The US has an enviable supply of students trained in and excited by robotics.

To accelerate the field, research in a number of key areas needs to be undertaken. It ranges from fundamental long-term research to practical ready-to-deploy developments, as enumerated in that order below:

Visual object recognition: Our robots today are not very aware of their surroundings, as we do not have general-purpose vision algorithms that can recognize particular objects never seen before as an instance of a known class. (A two-year-old child can instantly recognize most chairs as chairs even if they haven't seen one that looks exactly the same before.)

Manipulation: Our robots today are not very dexterous as we have hardly had any multi-fingered hands to work with. When mobile robot platforms started becoming available to researchers in the 80's and 90's the field of intelligent robot navigation exploded. We need to develop widely deployable robot hands so that hundreds of researchers can experiment with manipulation.

New sensors: Some sensors that robots need have been made incredibly inexpensive by other market pulls, e.g., digital cameras continue to have their price driven down by the cell phone market. But dense touch sensors, 3-D range sensors, and exotic RF and capacitance sensors are still very hard to come by. Direct investment in new sensor modalities for robots will lead to new algorithms that can exploit them and make robots more aware of their surroundings, and hence able to act more intelligently.

Materials science: Materials science is producing radically new materials with sometimes hard-to-believe properties. At the moment, robotics sits on the sidelines and uses these new materials as they might be applicable. A focused program on materials science and robotics would couple researchers in the two fields together to ensure that new materials that specifically benefit robotics are investigated and invented.

Distributed and networked robots: Technology allows us to decompose tasks in ways that humans are incapable. New architectures for robotic components that can self-assemble, whether physically or virtually, will enable new approaches to many application areas.

Awareness of people: Most future applications of robots will require that they work in close proximity to humans (unlike today's manufacturing robots that are so dangerous that people must be kept away). To do so safely, we need both perceptual awareness of people, and actuators and robots that are intrinsically safe for humans to physically contact.

Social interaction: If ordinary people are to work with robots they must be able to interact with them in cognitively easy ways. Our robots can make this possible if they both pick up on social cues from humans (who naturally give such cues to robots, to the surprise of many engineers) and give social signals about their own intentions that a person can easily interpret.

In the 20^{th} century the US led the world in four great waves of technological advancement: electrification, automobiles, airplanes, and computers. The first large technological wave of the 21^{st} century is shaping up to be robotics. There are many competitors but with appropriate research investments the US is well placed to lead once again.

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