Autonomous Robotics: Action, Perception and Cognition

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What comes to your mind when you hear the word “robot”

Google search “robot” (21 apr 2020)
=> Humanoids (or anthropomorphomic) robots
compliant arms

Robot companions are... cnet.com

The artificial skin that allows robots... cnn.com

Robot at the helm: A space humanoid, an... zdnet.com

Why are we reluctant to trust robots... theguardian.com

Why Can We Bond With Robots... technologynetworks.com

Biped Robot Timelines – How Long Until... emnej.com

DJI makes push into educational robots... asiatimes.com

Two-legged robots and self-driving cars... techcrunch.com

5 Industries Majorly Impacted by... analyticsinsight.net

4 Robots You Can Use In Real Estate... corelogic.com.au

DJI makes push into educational robots... asiatimes.com

A Technology Trend Every Business Must... forbes.com

Role of Robots in Recruitment... careerenlightenment.com
in reality, industrial robots are much more common today than humanoids or autonomous vehicles

fundamentally, all factory automatization is a form of robotics: “programmable” machines…
Survey of kinds of robots

other than humanoid or industrial
Industrial, Personal, and Service Robots

Robots are able to provide logistics support in office and industrial environments by transporting materials (packages, medicines, or supplies) or by leading visitors through hallways. Remotely controlled and monitored robots are also able to enter hazardous or unpleasant environments. Examples include underwater remotely operated vehicles, pipe cleaning and inspection robots, and bomb disposal robots. Some examples are shown in Fig. 5.5.

The challenges in service and personal robotics include all the challenges for industrial robotics. Dexterous manipulation and integration of force and vision sensing in support of manipulation is critical to the growth of this industry. In addition, mobility is a key challenge for service robotics. The current generation of robots is only able to operate on two-dimensional, even, indoor environments. Because service robots must be mobile, there are challenges for designing robots that are capable of carrying their own power source. Further, operation in domestic environments imposes constraints on packaging. Finally, service robots, especially personal robots, will operate close to human users. Safety is extremely important. And because interaction with human users is very important in service robotics, it is clear the industry needs to overcome significant challenges in human-robot interfaces.

INTERNATIONAL ASSESSMENT

U.S.

Most of the industrial robotics industry is based in Japan and Europe. This is despite the fact that the first industrial robots were manufactured in the U.S. At one time, General Motors, Cincinnati Milacron, Westinghouse and General Electric made robots. Now, only Adept, a San Jose-based company, makes industrial robots in the U.S.

However, there are a number of small companies developing service robots in the U.S. iRobot and Mobile Robotics, companies in New England, are pioneering new technologies.

Europe

The two big manufacturers of industrial robots in Europe are ABB and Kuka. Over 50% of ABB is focused on automation products and industrial robots are a big part of their manufacturing automation with annual revenue of $1.5B. ABB spends 5% of their revenues on R&D, with research centers all over the world. As in

Figure 5.5. Examples of service robots.

[photo credits: WTEC final report 2006]
some of our own (older) autonomous vehicles
outdoor vehicles

Figure 2.1. NASA Mars Rover (NASA Jet Propulsion Laboratory (JPL)).

Another example of a hostile and hazardous environment where robotic vehicles are essential tools of work and exploration is the undersea world. Human divers may dive to a hundred meters or more, but pressure, light, currents and other factors limit such human exploration of the vast volume of the earth's oceans. Oceanographers have developed a wide variety of sophisticated technologies for sensing, mapping, and monitoring the oceans at many scales, from small biological organisms to major ocean circulation currents. Robotic vehicles, both autonomous and ROV types, are an increasingly important part of this repertoire, and provide information that is unavailable in other ways. Figure 2.2 shows an autonomous underwater vehicle (AUV) called ASTER under development at Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), the French National Institute for Marine Science and Technology. ASTER will be used for coastal surveys of up to 3,000 meters in depth and is capable of carrying a wide variety of instrumentation for physical, chemical, and biological sensing and monitoring. In United States research, the evolution of remotely operated vehicles for deep ocean exploration enabled the discovery of the sunken Titanic and the ability to explore that notable shipwreck.

Figure 2.2. IFREMER ASTER autonomous underwater vehicle.

In addition to space and oceans, there are many applications where human presence is hazardous. Nuclear and biological contamination sites must often be explored and mapped to determine the types and extent of contamination, and provide the basis for remediation. Military operations incorporate many different autonomous and remotely operated technologies for air, sea, and ground vehicles. Increasingly, security and defense systems may use networks of advanced mobile sensors that observe and detect potential events that may pose threats to populations.

In a second class of applications, robotic vehicles are used in routine tasks that occur over spaces and environments where machine mobility can effectively replace direct human presence. For example, large-scale agriculture requires machines to cultivate, seed, irrigate, and harvest very large areas of terrain. The ability to track an autonomous vehicle using global positioning systems (GPS), sensing the soil and plant conditions in the field, encourages the implementation of robotic vehicles for agricultural or field applications. Figure 2.3a shows an example of an agricultural robotic vehicle under development in the United States. Figure 2.3b shows a large autonomous mining haul truck developed in Australia.

Figure 2.3. Agricultural robotic vehicle (Int Harv, U.S.) (a). Mining haul truck (ACFR, Australia) (b).

Similar challenges occur in areas of environmental monitoring, where mobile vehicles may move through air, water, or ground to observe the presence of contaminants and track the patterns and sources of such pollutants. In large manufacturing facilities, mobility is essential to transport components and subassemblies during the manufacturing process and a variety of robotic guided vehicles are utilized in these domains.

Figure 2.4. IBOT advanced wheel chair (DEKA, U.S.).

A third class of applications of robotic vehicles occurs in the support of personal assistance, rehabilitation, and entertainment for humans. A robotic wheelchair may provide mobility for a human who would otherwise not be able to move about. The integration of sensors, computational intelligence, and improved power systems have made such personal robotic aides increasingly capable and practical for everyday use. An example of a wheelchair that utilizes emerging robotic technologies for guidance and balance is shown in Figure 2.4. More details on medical robotics and robotic aids to the handicapped will be described in Chapter 6.

Other examples of such personal aides include vehicles that support elderly care through feeding, household tasks, and emergency notification. Many daily household tasks may benefit from enhanced mobile robotics, and there are rapid commercial developments of vacuum cleaners and lawn mowers that utilize advanced sensor and navigation systems. Also, advanced entertainment systems will incorporate robotic vehicles including locomotion of humanoids and biomimetic pets that entertain and provide interactive companions. The Japanese development of humanoids and robotic pets with sophisticated locomotion systems, as shown in Figure 2.5, is a major topic of this international comparative study. More detailed examples of personal and entertainment robotic vehicles will be described in Chapter 5, and of humanoid robots in Chapter 4.
cars: autonomous driving

It's like watching a hybrid of a NASCAR reality show and a high-tech road trip. Grant Imahara of Mythbusters, along with helicopter pilot Jamie Hyneman, is televising the event on three huge screens in a vast tent. Jamie Hyneman and Grant Imahara have hired a host of robots to compete in the Urban Challenge, a contest for autonomous cars that DARP A (Defense Advanced Research Projects Agency) has organized. Each car is controlled by a team of robotics experts and engineers, and they must navigate a course that simulates a real-world driving scenario.

Junior, Stanford's Volkswagen Passat, and has 99,257 miles (159,705 km) on it, with just one wire falling off, something essential is lost. There's only one curve from which to takeoff. Myرة, the robot from Team CarOLO, the other German squad, collides with MIT's Talos and loses sensors. TerraMax, the hulking Anheuer Outback that belonged to Harper's wife, takes third and $500,000. There's a glitch. Interference from a jumbo TV screen knocks out the GPS.
Up to now 10 six-legged walking machines have been built and distributed: three to museums and seven to universities or research groups in Germany and Europe.

Several projects involve cooperation with medical personnel on visual identification of target areas for surgery on the skull, estimation of spine and neck muscle properties to determine the extent of whiplash injuries, and automatic calibration of medical instruments with imagery for image-guided surgery.

Figure C.58. The walking machines built by Dillmann’s group.
biologically inspired robotics
snakes, crawlers, climbers

Figure C.56. Mobile robot platforms in Dillman’s laboratory. Two SwissLog products are shown on the extreme right.

Pipe Inspection Robots

Prof. Dillmann’s lab has developed several articulated, snake-type robots for pipeline inspection. Some are now commercially available and used to inspect water pipes and oil pipelines (including the Alaska pipeline).

Figure C.57. Inspection robot.

Current work is concentrated on enabling the system to work in an unstructured environment. A multi-articulated system with six links will be used for inspection tasks in sewer pipelines.

Legged Locomotion

There are labs dedicated to the development of control systems for four- and six-legged robots, as well as bipeds. The emphasis appears to be in the application of artificial muscles (McKibben-type muscles with a rubber shield), reduction of size and weight, and joint design. Historically, they have fabricated several of the Lauron-type six-legged machines usually associated with Friedrich Pfeiffer at the Technical University of Munich (TUM). Apparently there has been a long-term cooperative effort between the two labs.

7. Networked Robots

Networked robots also result in improved efficiency. Tasks like searching or mapping, in principle, are performed faster with an increase in the number of robots. A speed-up in manufacturing operations can be achieved by deploying multiple robots performing operations in parallel, but in a coordinated fashion.

Perhaps the biggest advantage to using the network to connect robots is the ability to connect and harness physically-removed assets. Mobile robots can react to information sensed by other mobile robots in the next room. Industrial robots can adapt their end-effectors to new parts being manufactured upstream in the assembly line. Human users can use machines that are remotely located via the network. (See Fig. 7.3.)

The ability to network robots also enables fault-tolerance in design. If robots can in fact dynamically reconfigure themselves using the network, they are more tolerant to robot failures. This is seen in the Internet where multiple gateways, routers, and computers provide for a fault-tolerant system (although the Internet is not robust in other ways). Similarly, robots that can plug and play can be swapped in and out, automatically, to provide for a robust operating environment.

Finally, networked robots have the potential to provide great synergy by bringing together components with complementary benefits and making the whole greater than the sum of the parts.

Applications for networked robots abound. The U.S. military routinely deploys unmanned vehicles that are reprogrammed remotely based on intelligence gathered by other unmanned vehicles, sometimes automatically. The deployment of satellites in space, often by astronauts in a shuttle with the shuttle robot arm, requires the coordination of complex instrumentation onboard the space shuttle, human operators on a ground station, the shuttle arm, and a human user on the shuttle. Home appliances now contain sensors and...
underwater vehicles, ships

Figure 2.1. NASA Mars Rover (NASA Jet Propulsion Laboratory (JPL)).

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Robotic vehicles developed for both military and space applications are intended for use in rough terrain, that is, without roads or cleared areas. In this context, the experience of off-road robotic vehicles in the U.S. has also provided a basis for research in field robotics, the application of robotic vehicles to other unstructured domains, such as agriculture, mining, construction, and hazardous environments. In addition, U.S. industrial companies active in these areas have invested in prototype developments for these applications. Figure 2.3 is an example of these prototype vehicles.

Undersea Robotics

The United States has supported research in several different types of applications of underwater vehicles. These include:

a. Military and Defense Applications

As described in Military and Defense Systems, U.S. defense technologies have included many fundamental prototypes and products that provide both ROV and AUV technology for the military. Figure 2.9 shows several of these vehicles.

b. Coastal Security and Environmental Monitoring Systems

AUV systems may be used as surveillance and observance of systems with both defense and environmental implications. Figure 2.10 shows an overview of the Autonomous Oceanographic Sensor Network (AOSN) systems, deployed as an experiment at the Monterey Bay Aquarium Research Institute (MBARI) in California, which integrate many different robotic and sensor resources.

Figure 2.10. Advanced Oceanographic Sensor Network (MBARI, U.S.).

Figure 2.11. HROV (Hybrid ROV) project (Johns Hopkins University (JHU) and Woods Hole (WHOL), U.S.).

c. Scientific Mission and Deep Ocean Science

AUV and ROV technologies are the only means to actively explore large portions of the ocean volume. The study of ocean currents, ocean volcanoes, tsunami detection, deepsea biological phenomena, and migration and changes in major ecosystems are all examples of topics that are studied with these systems. Several of the major scientific laboratories in the world are located in the U.S. and are leaders in these fields. A new project, HROV, is funded by the National Science Foundation (NSF) to develop a new hybrid remotely operated vehicle for underwater exploration in extreme environments, capable of operation to 11,000 meters depth as shown in Figure 2.11.
Historically, there have been examples of technologies that could be controlled through remote mechanical linkages (e.g. mechanically coupled manipulators for handling dangerous chemicals), and other technologies that provided pre-programmed motions (e.g. missiles and torpedoes). However, only with the development of microelectronics and embedded computation has it been possible to design systems that combine both mobility and autonomy. Four major research challenges have dominated these developments, and they continue to represent the key themes observed in this international study:

**Mechanisms and Mobility**
As described above, both engineering and biomimetic approaches have been taken to design mobile robotics vehicles, and current research efforts continue to follow both of these strategies. Key research themes include:

**Principles of Motion**
Basic studies of kinematics and dynamics of motion in all domains (ground, air, and water) continue to examine fundamental issues of devices that contact and interact with the forces around them. A primary example of this work is the study of bipedal locomotion and the distinction between quasi-static walking and dynamic walking. Algorithms used in recent full humanoids exhibit very sophisticated motion and balance, but still do not achieve all of the characteristics of human dynamic balance. New theories and experiments continue to impact this research. Similarly, such studies have a direct effect on different walking patterns, such as trotting and running gaits, and how these may be executed on two-legged and multi-legged robotic vehicles.

**Materials Properties and Design**
Materials considerations are also of primary interest for new mechanisms, and uses of light and strong materials, with controllable compliance, are current research topics.

**INTERNATIONAL SURVEY**
Robotic vehicles have been a principal theme of robotics research in many of the laboratories that were visited in this international survey. In many cases, the emphasis of types of vehicles, approaches to design, and the applications of interest have varied among these different international communities. This section summarizes these observations.

**Research on Robotic Vehicles – United States**
In the United States, research on robotic vehicles has emphasized work in the following five areas:

**Military and Defense Systems**
U.S. investment in robotic vehicle research has strongly emphasized the development of ground, air, and underwater vehicles with military applications. As shown in Figure 2.9, there have been significant accomplishments in these areas in which large development programs have resulted in capable and reliable vehicle systems. Many of these systems are deployed in a remotely-operated mode, that is, a human controller works interactively to move the vehicle and position based on visual feedback from video or other types of sensors. In addition, there is a strong emphasis on integration of autonomous probes and observers with other parts of the military tactical system. The integration of sophisticated computer and communications architectures is an essential feature of these systems, and the use of algorithms such as SLAM to interpret complex scenes is an important contribution to these systems. The U.S. is generally acknowledged as the world leader in military applications of robotic vehicle technologies.

**Space Robotic Vehicles**
The field of space robotics was identified as a topic for separate focus in this study and the major results of that effort will be presented in Chapter 3. In the context of vehicle technologies, the recent Mars rover programs have uniquely demonstrated perhaps the most successful deployment of robotics vehicle technologies to date in any domain of applications. The rovers have landed and explored the surface of Mars and have carried out important scientific experiments and observations that have dramatically enhanced human understanding of that planet and its natural history. This U.S. NASA effort has been the only successful demonstration of interplanetary vehicle space technology and is clearly recognized as the world leader in this domain.
robotic manipulators, hands

Figure 4.10. Dexterous arms at DLR, NASA and UMASS.
some of our own robotic manipulators
mobile robot manipulators

Figure C.28. Dexterous arm on mobile base, opening door (left), robot passing through doorway (right).
our own mobile robot manipulator

autonomous robotics

- *auto-nomos*: giving laws to oneself
- minimally: autonomous robots generate behavior based on sensory information obtained from their own on-board sensors
- in contrast to industrial robots that are programmed in a fixed and detailed way
autonomous robotics

- but: even an industrial robot uses autonomous control to reach its programmed goals...

- => autonomy is expected to go beyond control, include decisions=qualitative change of behavior

  - e.g. avoid obstacle to the left vs. to the right
  - e.g., reach for one object rather than another
but: we do not expect autonomous robots to just do whatever “they want”… we expect to give them “orders”
autonomy as a “programming interface”:

give instructions to a robot at a high level, in regular human language and gesture in a shared environment…

… and let the autonomous robot deal with the “details” of how to achieve goals
why autonomous robots?
why autonomous robots?

- ideas I hear from lay-people
  - to clean up, to serve drinks..
  - just generally cool..
  - robot soldiers..
toy/entertainment/animation

including therapy (autism)
assistance robotics

- at home, in the work place
- collaborate with human users
autonomous vehicles

... well, for autonomous transport...

[Amazon robotized warehouse]
military, fire fighting, rescue

the “ideal” application because desire to remove human agent from the scene is consensual ... 
much research
(robot ethics...interesting topic)

- May a military robot decide autonomously to shoot
  - ...nay ships do that already...

- May a autonomous car decide between avoiding a pedestrian and preventing danger for car occupants?
  - Fundamental problem: off-loading decisions from user to designer ...
autonomous robotics as a “playground” of research
autonomous robotics as a “playground” of research

modern engineering models systems, treating the remainder stochastically…. autonomous robotics act in natural environments that are difficult to model
autonomous robotics as a “playground” of research

modern engineering uses modular design that limits the range over which modules interact/interfere…autonomous robotics: requires system integration
autonomous robotics as a “playground” of research

- highly interdisciplinary field
  - sensing
  - perception
  - mechanics
  - control
  - AI/planning
  - embedded computing
  - communication / data security
  - user interfaces
state of the art: current explosion

- fast computation makes approach real-time that used to be not viable
- laser range finder… probabilistic approaches
- modern software engineering facilitates programming
- … through maturation of technology
4 core problems/challenges

- perception
- interacting with humans
- movement generation
- background knowledge
(1) perception

- no autonomy without perception
- perception is NOT estimating the stimulus
- it is learning about the environment and extracting meaning—that what enables action
(1) perception

4 core problems of perception

- attention
- recognition/classification
- segmentation
- estimation

=> WS lecture course
(I) perception

- much progress in SLAM and variants
  - exploiting multiple/low level sensors
- much progress in computer vision
  - driven in part by Deep NN
- but not as successful in robotic settings: where we have much experience with few objects rather than little experience with many objects
(2) interaction with humans

- in part a problem of perception as well...
- perceptually grounding language
- intention perception
- gesture recognition
- joint attention
- dialogue management
- emotion recognition

=> WS lecture course
(3) background knowledge

- implicit knowledge how the world works
  - how to open a door
  - that milk is in the fridge
  - how to grasp a glass vs. a cup vs. a spoon
  - how to grasp an object to achieve a particular goal
  - to clear space before moving something to a new place...
“background” is a core problem of classical artificial intelligence

- knowledge bases
- reasoning
- action planning
- architectures
implicit knowledge in behavior based robotics…
the background is in the individual skills and how they are connected

world

- obstacle avoidance
- roaming
- target acquisition
- create a map
(4) movement generation

- classical approach
  - motion planning based on precise world models
  - using optimal control to address control problems…

- but:
  - high demands on perception and on modeling of plant/ objects
  - unclear if it works for soft actuation for safe interaction with humans
  - need for flexible, human like movement and movement sequences
this is what we’ll cover a lot

- exploit analogies with human movement coordination, movement primitives

- exploit analogy with muscle: soft visco-elastic actuators
Particular perspective of the course

We look at autonomous robotics as a research field that interacts with the **theory of cognitive systems**

1) robots as examples of such systems… learn about principle problems here
   => integrative framework of dynamical systems

2) robots as tool to test neural models of cognition and behavior…
   => proof of process account and source of ideas/discovery of problems
Particular perspective of the course

- dynamical systems
  - “behavioral dynamics” ...
  - neural dynamics => WS course on Neural Dynamics
  - but we will touch on some aspects of neural dynamics in the “rate code” picture ...
  - (while the WS is focussed mainly on the space code/population picture)
Particular perspective of the course

This course is NOT a standard introduction into autonomous robotics from a technical point of view

although it provides some elements of that
Syllabus

dynamical systems tutorial

vehicles: path planning
  attractor dynamics approach
  other approaches

robot arms
  kinematics
  dynamics
  inverse kinematics
Syllabus

- timing
  - coordination
  - movement primitives
  - a neural architecture of movement

- motor control
  - principles of control
  - human motor control
  - muscles and reflexes