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# Mobiles Robots – Past Present and Future

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## 1. Introduction

Since their introduction in factories in 1961, robots have evolved to achieve more and more elaborate tasks. The industrial robots now account for a 5 billion dollars market. Positioned along the assembly line, a robotic manipulator can perform tedious and repetitive tasks such as welding, painting, moving or cutting with immense speed and incredible accuracy. As an example, their use in the automotive industry has drastically cut the time it takes to assemble a vehicle.

Since the introduction of the first industrial robot UNIMATE online in a General Motors automobile factory in New Jersey in 1961, robots have gained stronger and stronger foothold in the industry. Several milestones are worth noting since then:

The first artificial robotic arm to be controlled by a computer was designed. The Rancho Arm was designed as a tool for the handicapped and its six joints gave it the flexibility of a human arm.

DENDRAL was the first expert system or program designed to execute the accumulated knowledge of subject experts.

1968 - The octopus-like Tentacle Arm was developed by Marvin Minsky.

1969 - The Stanford Arm was the first electrically powered, computer-controlled robot arm.

1970 - Shakey was introduced as the first mobile robot controlled by artificial intelligence. It was produced by SRI International.

1974 - A robotic arm (the Silver Arm) that performed small-parts assembly using feedback from touch and pressure sensors was designed.

1979 - The Stanford Cart crossed a chair-filled room without human assistance. The cart had a TV camera mounted on a rail which took pictures from multiple angles and relayed them to a computer. The computer analyzed the distance between the cart and the obstacles.

It is no surprising that in face of diverse configurations, functions, applications, and autonomy there is no agreeable universal definition of “Robot”. The well-known definition of Robot from the Robot Institute of America (RIA) is that a robot is

"A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks".

It at best describes industrial robots and applications – not all robotic applications are associated with "move things". "Programmed motions" may have to be augmented for mobile robots that often decide their motion/part based on their situational awareness. A more inspiring and general definition can be found in Webster. According to Webster a robot is:

"An automatic device that performs functions normally ascribed to humans or a machine in the form of a human."

The Webster definition broadly covers robotic tasks and functions beyond moving things as in RIA definition. Being a subset of robots, one may consider that defining mobile robot would be easier and more accurate. Indeed, Wikipedia has this definition:

"A Mobile Robot is an automatic machine that is capable of movement in a given environment."

As opposed to fix based industrial robots, a mobile robot has its movement unlimited by its physical size due to its mobility. As a result, mobile robots can operate in a large workspace and explore unknown environments and therefore are able to perform tasks wherever needed. They have been used to perform a variety functions that are normally performed by humans or a machine in the form of a human, such as surveillance, exploration, patrol, homeland security, domestics helper (e.g. lawn mower), butler, care taker, and entertainer. The recent decade has witnessed an explosion of research activities in mobile robotics. By and large, mobile robots can be categorized into three categories according to their operating environments: i) land (based) robots, ii) aquatic/underwater robots, and iii) aerial (air, flying) robots; each of them possessing sub-categories

Because of the need to operate in unknown and/or uncertain environments, mobile robots demand much higher level intelligence than traditional industrial robots. These requirements have been met by the phenomenal advancement in silicon technology and computing power. The rapid reduction in both size and cost of integrated chips has raised a huge interest for scientists to create intelligent systems.

This chapter provides an overview on mobile robotics. Instead of attempting to cover the wide area of this subject exhaustively, it highlights some key developments. Firstly, a functional model of generalized robots is presented, and serves as a common conduit which helps the analysis and comparison of robotics technology. It then paints a global perspective of mobile robotics market, followed by historical development highlighted by some key milestones. Subsequently, the chapter presents the state-of-the-art in mobile robotics research, and summarizes the works presented in this book. Some critical reflections and challenges ahead are highlighted as far as future development is concerned. Finally conclusions are drawn.

## 2. Functional model of generalized robots

A generalised robot or robotic system possesses a set of functional parts similar to human beings. As shown in Fig. 1, these functional parts include intellectual, statue, motivational, actuation, sensory, communications and energy.

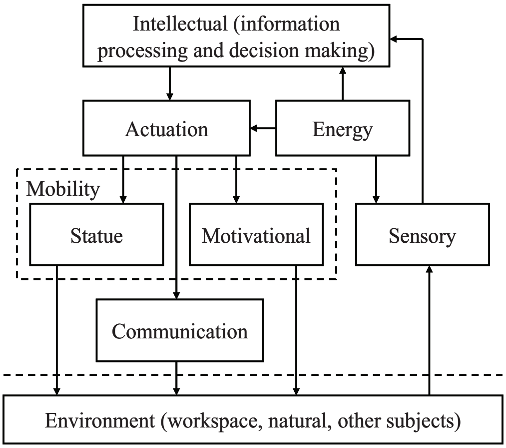

Fig. 1. Functional model of generalised robots

The functional model in Fig. 1 clearly illustrates the energy forward path and information feedback path. The intellectual part commands the actuation part, which in turn drives the mobility system - statue and motivational parts. Mobility is achieved through statue and motivational parts driven by actuators. Statue refers to body frame (skeleton) in case of a human being, and mechanical frame for a robot. In industrial robots, the mechanical frame is the mechanical links linked through joints. In mobile robots, the mechanical frame is the airframe for aerial robots, hull structure for underwater vehicle, and chassis for land vehicle, mechanical structure for humanoid robot.

Motivational parts are accessory mechanical parts to robots and limbs to human beings. They either enlarge or refine the robot mobility to execute specific tasks. Wheels, tracks, propellers increase the range of robot movement well beyond its statue. Grippers and end-effectors enhance the dexterity of the workspace and manipulation. Like a human, a robot accomplishes a delicate task like assembly, welding, and polishing by being equipped with motivational parts.

In accomplishing a defined mission, a robot, through its statue and motivational blocks, physically interacts with its operating environment. Robot operating environments can be classified into the following three categories:

Pre-defined and structured environment. The robot has all the knowledge about the environment and objects to deal with. It typically exists in factory automation

Semi structured environment. The robot has some pre-knowledge (e.g. GPS maps) about the environment, but it may change spatially and temporally. An example would be surveillance robot which tours its familiar territory, but the environment and objects inside it may change spatially and temporally.

Unstructured environment. The robot has no priori knowledge about it, with underwater being an example. The robot has to rely on its powerful sensory and navigation system to operate autonomously. A practical approach would be semi-autonomous system which accepts remote intervention from time to time.

In the energy forward path, a robot exerts energy onto the environment. In this process, the primary energy source (typically electrical) is converted to other types of energy such as kinetic, mechanical, wave, etc while a task is performed by the robot. In this process, the robot communicates with the environment through data, image, video or sound. It receives situational information through its Sensory functional block, which closes the control loop.

Although both robots and human beings possess the same set of functional blocks, hence have correspondence in each block. A parallel drawn between robots and human being in terms of realisation of these functions is shown in Table 1. It is apparent that for a robot to perform similar tasks like a human being, it indeed needs to possess the seven essential functional parts. Nevertheless, for simple applications in a more deterministic operating environment some of the functions such as sensory function are reduced to minimal.

| Functional Blocks | Human Beings | Robots |
|---|---|---|
| Intellectual | Brain | Microprocessor (computer hardware and software) |
| Statue | Skeleton | Mechanical frame (airframe, chassis, hull). |
| Motivational | Limbs | Wheels, legs, tracks, propellers, grippers, etc. |
| Actuation | Muscles | Hydraulic, electric, pneumatic. piezoelectric, electrostatic actuators; artificial muscles. |
| Sensory (perception) | Eyes, ears, skin | Cameras, optic sensors, sonar, sound, infra-red light, magnetic fields, radiation, etc. |
| Communication | Speech, gesture | Data, image/video, sound |
| Energy | Food / energy storage | Power source / energy storage. |

Table 1. Robots versus human beings: functional blocks

As a result, a mobile robot is a complex assembly of fundamental building blocks, each of which has to be carefully chosen based on specifications such as terrain, mission duration, goal and atmospheric conditions. The “optimal” design aims for the robot to accomplish a specific mission most cost effectively and efficiently. In contrast, a human being always uses the same set of “functional bocks” to accomplish any type of missions - marathon, sprinting, assembly, inspection and entertainment.

The mobility system accomplishes certain tasks by interacting with its operating environment, known or unknown. It is therefore important to take the various functions into consideration when design a mobile robot.

Mobility: Mobility in mobile robots requires mechanical frame and motivational parts. Another consideration is to give the mobile robot locomotion capabilities based on its deployment environment and missions. If the robot will only encounter smooth ground, wheels or tracks would be reasonable. Rougher terrain would require bigger wheels. In search and rescue mission in debris, leg locomotion is desired.

Sensors: A large collection of sensors are available to detect information about the environment. They can be used for monitoring purposes (chemical sensors, thermometers) or to help the robot to maintain its operations (accelerometers, GPS, etc…).

Actuators: They allow the robots to perform extra tasks besides mobility.

On-board Computation: Depending on its purpose a mobile robot will require more or less advanced on-board computation. Simple robots will just need steering computation capabilities whereas robots interacting with humans will require advanced electronics to successfully communicate.

Software: The software includes all the processes required by the robot to operate. They range from low level mobility processes up to behavioural processes.

Energy: Mobile robots usually operate in remote environments where energy is not readily available. Carrying the necessary energy to finish the assigned task is a necessary condition when creating a mobile robot.

Communication: In many applications, communication is essential to a mobile robot. It can be used to monitor the robot, to communicate with other robots or to communicate information.

## 3. Global perspective of mobile robotics market

They are several identified markets for mobile robots: service and military robots.

### 3.1 Service

Service robots are usually divided into 2 sub-categories: Professional and Domestic robots. The first one includes robots designed to serve either humans or equipment. As an example, medical robots can be used to assist for surgeries as well as help for the training of surgeons. Robotically-assisted surgery systems markets are supposed to have rapid growth. The market that was at $626.5 million in 2007 is anticipated to reach $1 billion in 2008 and is forecast to reach $14 billion by 2014. Mobile robots are also developed to work as tour guides (Toyota's "Robina" or Fujitsu's "Enon").

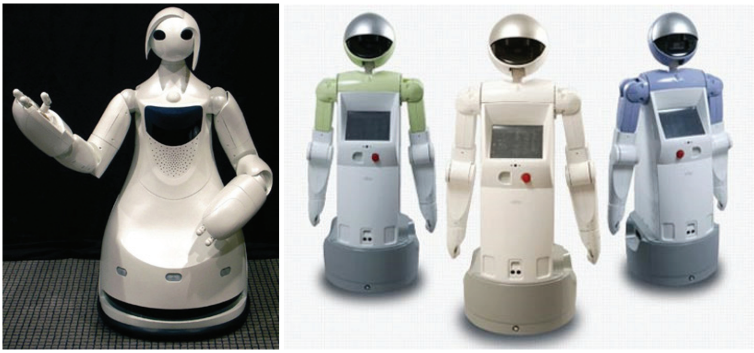

Fig. 2. Robina, Toyota's tour guide (left) and Fujitsu's Enon (right)

Service robots are also developing for equipment service such as pipe and window cleaning. They are designed to perform tasks such as inspection, maintenance and repairs.

The latter category of service robots is known as personal robots. It includes educational robots, home care, entertainment and home assistance. Educational robots are usually very versatile platforms that help students get a global experience with mobile robots. MobileRobots platforms represent a reliable base and powerful software that helps make students' robotics experiences a success. The market for educational robotic kits at $27.5 million in 2007 is forecasted to reach $1.69 billion by 2014. Home care robots introduced so far are rather simple (vacuum robots such as Roomba® or lawn mowing robots such as the Robomawer®), but general purpose home-care robots are on the way. Consumer robot markets for house cleaning; lawn mowing, pool cleaning, and general home services reached $227 million in 2007 and are expected to attain $1.7 billion by 2014.

Fig. 3. The Roomba® robot and the latest Care-O-bot®

Entertainment robots such as robot toys represent a growing part of consumer electronics and toy robots are usually “Must-have” for many children during the Christmas season. A good example of the success of toy robots is Robosapiens from Wow Wee that sold over 4 million units.

### 3.2 Homeland Security and Military

Robots play a major part in the quest to automate military ground systems. They provide vital protection of soldiers and people in the field and will potentially reduce the number of fatalities in combat.

The use of remote-control robots in Iraq started as simple robots to investigate possible roadside bombs. Since then, a lot of robots have been developed to dispose of bombs in a combat or urban environment. Smaller and cheaper MARCBOTs and BomBots models are being engineered to provide even more help.

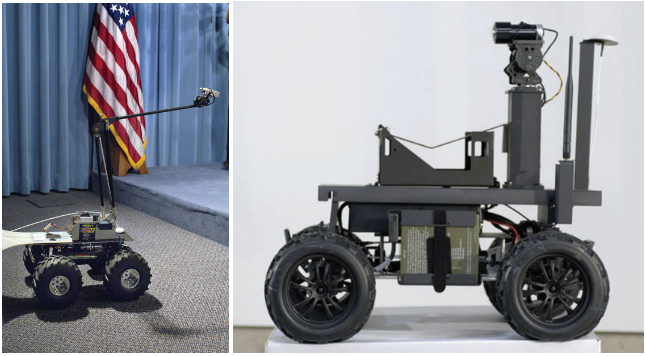

Fig. 4. Multi-Function Advanced Remote Control Robot (MARCBot - left) and BomBot (right)

The U.S. Department of Defense (DoD) released a report in 2007 that investigates at the future of military's unmanned systems for the next 25 years. This report puts into perspective the most urgent needs that are supported both technologically and operationally by various unmanned systems. These needs are listed below and should be considered by researchers as they will probably represent a large amount of funding from the DoD.

1. Reconnaissance and Surveillance.

Unmanned systems will play an important role in the field of reconnaissance, both electronic and visual. It has become essential for troops to be able to survey areas of interest while being under cover. Efforts should be made to increase the standardization and interoperability of unmanned systems as the number and diversity of users is going to increase significantly.

2. Target Identification and Designation.

Identification and localization of military targets are still to be improved as they are critical. A mistake usually results in the non-destruction of a target or worse, the death of innocent civilians. It is therefore important to reduce the latency and increase the precision of GPS guided weapons. The capability of unmanned systems to operate in high threat environments is not only safer for troops but potentially more effective than the use of current manned systems.

3. Counter-Mine Warfare.

The military authorities have pointed that sea mines have caused more damage to the fleet than all other weapons systems combined, and that Improvised Explosive Devices (IEDs) are the number one cause of casualties in Iraq. A lot of work has already been done to improve the military’s ability to find, tag, and destroy both land and sea mines, and unmanned systems naturally seems to be the solution to fulfil these missions.

4. Chemical, Biological, Radiological, Nuclear, Explosive (CBRNE) Reconnaissance.

Efforts should be made in developing unmanned systems able to identify and locate chemical and biologic agents and to survey the extent of affected areas.

The military robots markets were $145 million in 2007 and are anticipated to reach $6.9 billion by 2014.

## 4. Historical development of mobile robots

### 4.1 Evolution from fixed base robotics to mobile robotics

Interest in mobile robotics mainly comes from the need to explore areas that humans cannot explore. The reason may be that the environment is hazardous (radioactive, at deep sea level) or too far in distance and time (space exploration). Under such conditions, fixed-based robots are not sufficient.

### 4.2 Milestones of autonomous ground vehicle

Grey Walter's tortoises (1948-9, Bristol)

Grey Walter tortoise was an attempt to demonstrate that rich interconnection between a small amount of brain cells has the potential to create to complex behaviors. His first two robots, which were called "Machina Speculatrix", were developed between 1948 and 1949 and were named tortoises because of their shape and speed. These very early three-wheeled robots were indeed capable of photo taxis (they could find their way to a recharging station when they were low on power).

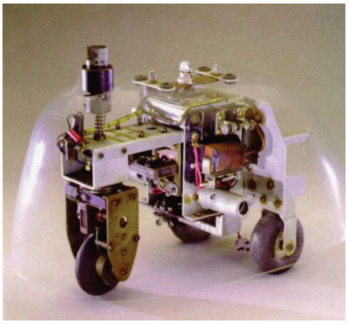

Fig. 5. Reconstitution of Grey Walter's tortoise

Shakey (1968, SRI)

Shakey was the world's first mobile robot capable of "reason" by taking actions based on its surroundings. Shakey was equipped with a TV camera, a triangulating range finder, and bump sensors, and was connected to DEC PDP-10 and PDP-15 computers via radio and video links. The robot was using programs for perception, world-modeling, and acting. Low-level action routines took care of simple moving, turning, and route planning. Intermediate level actions strung the low level ones together in ways that robustly accomplished more complex tasks. The highest level programs could make and execute plans to achieve goals given by a user. The plans could be stored for possible future use.

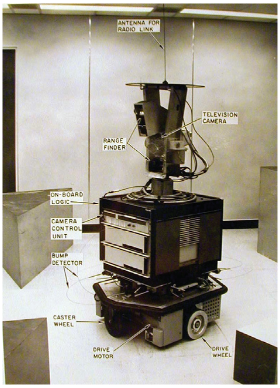

Fig. 6. Picture of Shakey

### Stanford cart (1979)

In 1979, the Stanford Cart was able to cross a room full of chairs without human assistance. The cart was equipped with a TV camera mounted on a rail which took pictures from multiple angles and relayed them to a computer. The computer would then analyze the distance between the cart and the obstacles and steer accordingly.

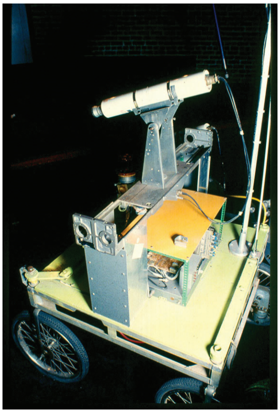

Fig. 7. Stanford Cart

### Genghis (1988, MIT)

The Mobile Robots Group at MIT developed a six-legged walking robot named Genghis Khan, which was able to teach itself how to scramble over boards and other obstacles.

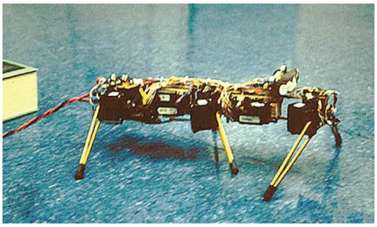

Fig. 8. MIT's Genghis Walking Robot

Khepera (1994, EPFL)
The Khepera is a small (5.5 cm) differential wheeled mobile robot that was developed at the LAMI laboratory of Prof. Jean-Daniel Nicoud at EPFL (Lausanne, Switzerland) in the mid '90s.

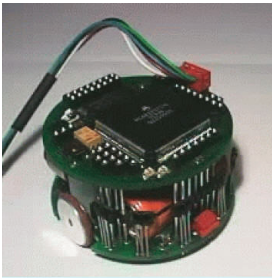

Fig. 9. The Khepera Robot

Stanley (2005, Stanford)
Stanley is an autonomous car, winner of the 2005 DARPA Grand Challenge (>200km in desert paths in ~7h). The vehicle incorporates measurements from GPS, a 6DOF inertial measurement unit, and wheel speed for pose estimation. The environment is perceived through four laser range finders, and a monocular vision system. Map and pose information are incorporated at 10 Hz, enabling Stanley to avoid collisions with obstacles in real-time.

Fig. 10. Stanford Autonomous Car "Stanley"

### 4.3 Milestones of unmanned aerial vehicles

1916: aerial torpedo - Hewitt-Sperry Automatic Airplane
The Hewitt-Sperry Automatic Airplane project was started during World War I. Its purpose was to develop an aerial torpedo, carrying onboard components capable of sustained flight over a long period of time without the need of human manipulation. The "brain" of this

unmanned vehicle consisted of gyroscopes, mechanically coupled to the aircraft control surfaces so as to maintain its stability.

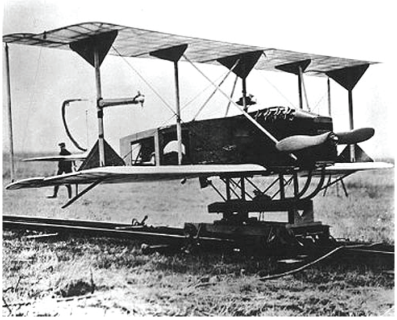

Fig. 11. The original Sperry Aerial Torpedo, 1918

1923: Pilotless Airplane
In 1923, the Army Air Service announced that a pilotless airplane, equipped with an automatic control device had been developed to a point where it has made successful flights of more than ninety miles. At the time, it was said to be more accurate and dependable than any human pilot.
1935: Drones and Radio Controlled Aerial Target
In 1935, a large number of RC targets were produced, the "DH.82B Queen Bee", derived from the de Havilland Tiger Moth biplane trainer. The prototype was first flown on January 5, 1935. The name of "Queen Bee" is said to have led to the use of the term "drone" for remote-controlled aircraft. These were used as targets for military anti-aircraft gunnery practice.

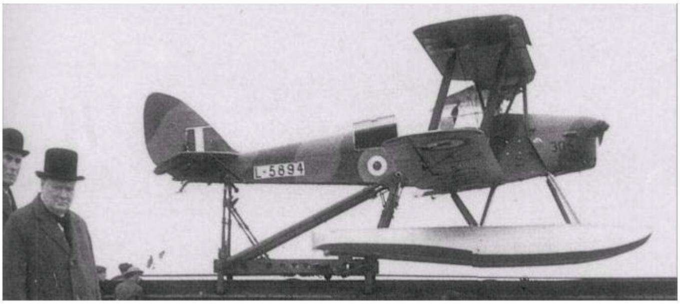

Fig. 12. The De Havilland DH.82B Queen Bee

1956 : Surveillance Drones
Drones used as target were successful and this led to it being used for other purposes. The Ryan Firebee was a good platform for test experiments, and tests to use it for reconnaissance missions were successful. A series of reconnaissance drones derived from the Firebee, known generally as "Lightning Bugs", were used by the US to spy on Vietnam, China, and North Korea in the 1960s and early 1970s.

Fig. 13. Firebee Lightning Bugs

1964: Unmanned Combat Air Vehicle
In 1964, "Project CeeBee" was created to experiment using a Firebee, fitted with underwing pylons, to carry two 115 kilogram (250 pound) bombs. The Firebee was launched from a ground station, using a booster for initial propulsion. However, the CeeBee experiments were not successful enough; the cause being that shooting at a target proved much more complex than flying over an area and taking pictures. The very first launch of a missile, a Maverick, from a UAV occurred on 14 December 1971, thanks to more advanced guided munitions.
1992: Miniature UAVs (MAVs)
During the early 1990s, the idea that small UAVs could be of interest was introduced. DARPA started a 35 million dollar project to develop and test a UAV. The specifications were that the MAV needed to carry a night / day imaging device, and operate for at least 2 hours. This study came to an end in 2001, and DARPA then investigated commercial vendors capable of producing MAVs to the initial design specification.
The majority of modern MAVs are designed to be smaller than conventional UAVs, but not as small as originally envisioned. Most UAVs used by the military and government organizations are hand launched units, able to be transported, deployed and operated by a single user. Smaller MAVs are still under investigation, but currently the majority of used MAVs are on the larger side.

## 5. The state of the art in mobile robots

### 5.1 Design methodology

The development of any type of mobile robot is challenging and takes a lot of time and considerations. It would be possible to improve the productivity of the development work by optimizing the design methods and tools.
The design process of a mobile robot can be divided into three logical parts based on its architecture: software, hardware and mechanical.
The software is usually divided hierarchically into two parts:

High level software that allows the mobile robot to function autonomously and fulfil its designated mission.

Low level software includes the basic motor functions such as the steering algorithm as well as reflex functions like communication routines or collision avoidance programs.

To create the software architecture, the most common approach is to replace the sequential programs into a collection of simple, distributed, and decentralized processes with capability for each to access information from sensors as well as to send commands to the actuators of the robot. This approach was first introduced under the name "subsumption architecture" and was proposed by Rodney Brooks at MIT. Local behavioural routines run constantly in parallel using only local available information. The emergent overall behaviour turns out to be flexible and robust. All these emergent approaches are based on biological systems. They try to mimic mechanisms from biological systems, especially adaptive behaviours. Adaptation, combined with a decentralized bottom-up approach, is often seen as a solution to the problem of generating and maintaining stable behaviours in partially unknown and dynamic environments.

The hardware part is twofold. Electronics parts, such as digital, analog and power electronics components, are used to convert software requests into actuator control signals and to scale and digitize sensor signals. Actuators provides mobility to the robot by transforming its input signal, likely electrical, into motion. The types of actuators used for mobility have to careful chosen depending on the environment where the mobile robot will ambulate (air, land, sea). Sensors are used to measure a physical quantity from the environment and convert it into a signal used either for locomotion or monitoring a variable of interest.

The mechanical part can be divided in two. Mechanisms can be used to transform the movement of the actuators; for example change the rotational movement of a motor into a translational one. The body is designed to protect the main parts of the robot from the environment; it gives the robot its integrity.

### 5.2 Perception and situational awareness

The terms such as perception and awareness have been replaced by the more general term "cognition". In robotics, cognition includes the creation of high level information from the combination of low level pieces of information and memory. Such high level information can be a "mental" map of the surroundings as well as a prediction of the future evolution of that environment. Cognition also requires different types of behaviour such as planning, sensing, recognition, learning, coordination and other "human-like" tasks.

There exist several possible states of cognition. To illustrate these different states, we introduce a cognition model found in (Patnaik, 2007). This model includes seven different mental states (sensing & acquisition, reasoning, attention, recognition, learning, planning, action & coordination) as well as two separate types of memory (short-term and long-term). The cognition is this model is realized by three cycles. These three cycles are the "acquisition cycle", the "perception cycle" and the "learning and coordination cycle".

The purpose of the acquisition cycle is to memorize the information from the sensors into a short-term memory. The data are then compared to what is known (i.e. stored in the long term memory) for validation. The perception cycle uses information stored in the long term memory to interpret data gathered during the acquisition cycle. Finally, the learning and coordination cycle plans the future actions of the robot based on stored information of the surroundings.

In robotics, cognitive behaviours are achieved with the help of computing techniques. The most common pattern is that sensor readings are used by a micro-controller to steer the robots actuators so as to achieve a specific task.

Two of the most researched areas in perception are vision and recognition. To operate a mobile robot in an unknown environment, it is necessary to be able to analyze that environment to maintain the safety and integrity of the robot.

Whereas vision mostly depends on hardware, recognition is mostly based on computational techniques. Here is a list of recognition techniques:

Template matching: this technique is based on image processing where the image is scrutinized to find a match of a template image.

Feature-based model: instead of looking for templates, the image is analyzed to find some features or patterns. Such features are usually geometric shapes or specific colours.

### 5.3 Control of mobile robots

#### 5.3.1 Formation Control

A large number of different strategies for formation control of a group of mobile robots can be found in the literature. Several frameworks stand out by the number of strategies that have been developed including the leader- follower schemes, behaviour-based methods, and virtual structure techniques. Between these three techniques, the leader- follower approach is the most acknowledged: one or more mobile robots are designated as leaders and are in charge of leading the formation, the other robots have no information about their headings and simply follow the leader(s): they are called followers. The followers usually try to maintain a set distance between them and the formation leader.

In the behaviour-based methods, the robots maintain formation thanks to two complementary processes: the first one , called detect-formation-position, computes the robot's ideal location within the formation based on sensor readings; the second one, called maintain-formation, generates the control commands to steer the robot toward the position determined by the first process. The virtual structure method uses the idea that points in space maintaining a fixed geometric relationship can be observed as behaving in the same way as points on a rigid body moving through space. When robots behave in this way, they are moving inside a virtual structure.

#### 5.3.2 Control of non-holonomic mobile ground robots

Nonholonomic robots dynamics are characterized by equations involving the time derivatives of the system’s variables and constrains. These dynamic equations are non integrable. Nonholonomy is usually encountered when the system has less control inputs than controlled variables. As an example consider a wheeled mobile robot that has two controls (linear and angular velocities) while the domain it evolves in is 3-dimensional. Therefore, every feasible control signal does not necessarily correspond to a feasible path for the system. This is the reason why the geometry-based techniques developed in motion planning for holonomic systems cannot be directly applied to nonholonomic ones.

The purpose of motion planning is to obtain open-loop controls to steer a nonholonomic mobile robot from an initial state to a desired final state along a feasible trajectory that is possibly optimal. The principal motion planning techniques can be classified as differential geometric, geometric phase, and optimal control. Differential geometric techniques are based on an extended set of equations for the system in conjunction with the original one. A first control sequence is computed from the extended system and is used to create the final control input used on the real system. Geometric phase techniques use the concept of holonomy and path integral along an m-polygon to transform the differential constraints of the system to algebraic geometric phase equations. The optimal control path planning problem is usually formulated as a two point boundary value problem with various problem constraints. The optimization criterion being minimized is a control performance index which can include energy saving, formation, collision avoidance or bang-bang conditions. This technique can easily be extended to robots moving in a three dimensional environment.

Obstacle avoidance can also be considered and increases the motion planning's difficulty. The methodology then needs to take into account both the constraints due to the obstacles and the nonholonomic constrains. It appears necessary to combine geometric techniques addressing the obstacle avoidance together with control theory techniques addressing the special structure of the nonholonomic motions.

Readers can refer to (Li and Canny, 1993) for a more complete review of motion planning techniques for nonholonomic systems.

### 5.3.3 Control of unmanned air vehicles

Unmanned air vehicles are usually controlled by an autopilot, i.e. a system allowing the UAV to fly autonomously. Nowadays, autopilot systems are automatically implemented in modern aircrafts. The purpose of the UAV autopilot system is to steer the UAV so as to follow either a predefined path or fly between waypoints. Advanced UAV autopilot systems are able to fly the UAV during all flight phases such as take-off, ascent, descent, trajectory following, and landing.

To our best knowledge, all commercially available autopilots are simple PID controllers. It is the best solution for most users as they are simple and require little knowledge to tune on a small UAV. However, PID controllers are also well known in control system theory to lack in optimality and robustness. Researchers have developed several advanced control techniques that can be used in autopilot systems for improved flight performances. We can cite fuzzy logic, neural networks, LQG and $H\infty$ as successful examples of such techniques. Fuzzy logic and neural network techniques are not model-based (knowledge-based for fuzzy logic and data-driven for neural networks) and don't require advanced control knowledge from the user. They represent a good alternative to PID controllers as they usually perform better for multivariable flight control. However, in terms of guaranteed stability and performance, optimal and robust control techniques such as LQG and $H\infty$ sounds more suitable. A combination of Linear Quadratic Gaussian controller and Kalman filter can be used to achieve better altitude control performance. $H\infty$ loop shaping techniques can also be used on small fixed wing UAVs for improvements in noisy or even payload changing circumstances.

## 5.4 Biomimetic robots

Mobile robotics researchers have been inspired by the trans-disciplinary development in bionics, also known as biomimetics, or biomimicry. Bionics applies biological methods and systems found in nature to the study and design of engineering systems and modern technology. The exceptional natural abilities in many animals and insects have drawn much attention from biorobotists. A common approach is to build animal-like features into robots, and such robots are called biomimentic robots or simply biorobots.

It is debateable whether biologically inspired robotics should be simply emulation of some general feature like legs or wings of an animal, or a more considered approach in which specific structural or functional elements of particular animals is emulated in hardware or software (Delcomyn, 2007). It is difficult to draw a line between the two, although the latter may rely on biological aspect more.

The intensive research effort in searching for hardware and software solutions to emulate specific features of a real animal would expose their efficiency and deficiency, and improve our understanding of those animal features and engineering capabilities and limitations. Whether a design solution comes from engineering or a biological perspective, it is generally agreed that certain degree of fusion and integration between engineering and biology takes place. Despite minute differences in interpretation and emphasis, bionics, biorobotics, biomimetics, or biologically inspired robotics is emerging as a discipline in its own right. It has witnessed an explosion of research interests and efforts in the past few decades worldwide. Researchers working in this field rightfully claim their own identity – biorobotists, or bionicists. It is fitting to recognise that engineers apply biological principles to construct robots, and biorobotics in turn can advance biologists' knowledge and understanding of those same biological principles

Rapidly growing interests in biorobotics were confirmed by the statistics shown in (Delcomyn, 2007). There are more than 1.5 million hits one obtained by conducting a Google search on the phrase "walking robot". In terms of research literature included in the ISI Web of Knowledge database, the number of papers on mobile robotic machines with biological inspiration or variants as a key phrase has increased from an average of 9.2 papers per year between 2000 and 2004, to 16 in 2005 (an increase of over 70%), and 30 in 2006 (another increment of more than 85%). Though not large, this is nevertheless a field that is attracting much attention.

Biorobotics research has covered many types of animals to be emulated - fish and eel underwater; dog, cockroach, gecko on land; and black flies, wasps, bumblebees and other flying insects in air. These robots are built to swim, walk, climb a wall or a cable, or fly. Wall climbing robots have been considered to replace human beings to perform dangerous operations on vertical surfaces like cleaning high-rise buildings, inspecting bridges and structures, or carrying out welding on a tank. The locomotion of a wall climbing robot has become a key research, which is achieved through some kind of attachment mechanism.

Generally speaking, three main types of attachment mechanisms are used: suction, magnetic and dry adhesion mechanisms. The suction method creates vacuum inside cups through vacuum a pump, the cups are pressed against the wall or ceiling so that adhesion force is generated between the cups and the surface. This effect is dependent on a smooth impermeable surface to create enough force to hold the robot.

A wall-climbing robot with a single suction cup has been studied in (Zhao et al., 2004). It consists of three parts: a vacuum pump, a sealing mechanism with an air spring and regulating springs, and a driving mechanism. Two application examples were considered: i) ultrasonic inspection of cylindrical stainless steel nuclear storage tanks, and ii) cleaning high-rise buildings.

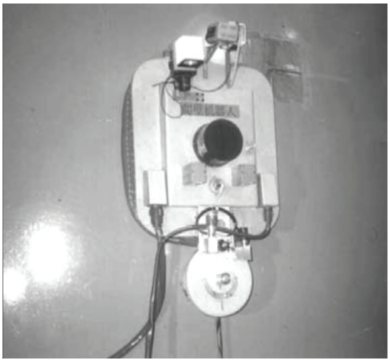

Fig. 14. A wall-climbing robot with a single suction cup

Magnetic adhesion has been implemented in wall climbing robots for specific applications such as nuclear facilities or oil and gas tanks inspection (Shen, 2005). In specific cases where the surface allows, magnetic attachment can be highly desirable for its inherent reliability.

Recently, researchers have developed and applied synthetic fibrillar adhesives to emulate bio-inspired dry adhesion found in Gecko’s foot. An example is Waalbot using synthetic dry adhesives developed by Carnegie Mellon University, shown in Fig. 15. Fibres with spatulae were attached to the feet of the robot, and dry adhesion is achieved between the robot feet and the surface.

Also based on the dry adhesion principles is a bioinspired robot “Stickybot” (Kim et al., 2008). It is claimed that the robot climbs smooth vertical surfaces such as glass (shown in Fig. 16), plastic, and ceramic tile at 4 cm/s. The undersides of Stickybot's toes are covered with arrays of small, angled polymer stalks. In emulating the directional adhesive structures used by geckos, they readily adhere when pulled tangentially from the tips of the toes toward the ankles; when pulled in the opposite direction, they release.

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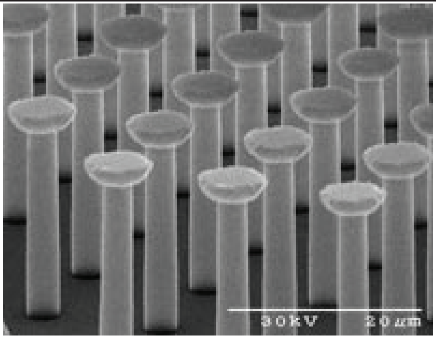
| |  |
| (a) CAD model | (b) Fibres with spatulae to achieve dry adhesion |

Fig. 15. Tri-leg Waalbot (http://nanolab.me.cmu.edu/projects/geckohair/)