Chapter 2

The scientific-technological frame

"Naturally, we are only in the beginning of the beginning of the robotics revolution "

– *Isaac Asimov*

2.1 Introduction

In this chapter the evolution of two types of robots, **the apodal and the modular**, will be studied. Emphasis will be placed on recently created prototypes and it will be seen, from a general perspective, how this thesis contributes to the studies. Many of the ideas and examples have already been presented in the introductory chapter, nevertheless they are included in this chapter as a self contained unit.

In the first place **the problem of locomotion** and some initial ideas will be introduced. This is followed by the evolution of apodal and self-propelled apodal state of the art robots that have been developed in the most prestigious research centres. Then the progress in a new branch of investigation of robotics, what is known as **modular robotics**, will be presented. At present the investigation concentrates not only on the locomotion of these robots, but also on their capabilities to form different structures. Finally **a classification** that includes modular and apodal robots **will be established**.

In the second part **the problem of co-ordination** and the different approaches of how to resolve it will be presented, concentrating on apodal modular robots.

2.2 Locomotion

2.2.1 Levels of locomotion

Locomotion is the capability that living beings belonging to the animal kingdom have, allowing them to decide to move from one place to another. This is one of the characteristics that distinguishes animals from plants. There are two important aspects to have in mind, **control** and **will**. To be accepted as locomotion the individual must want to do it and be able to control it.

The study of locomotion is divided into two levels, that are denominated the inferior level and the superior level. The **inferior level** is in charge of muscle control and co-ordination (or actuators in the case of robots) so that the individual can move. It also includes the different means of moving that can be obtained (turns, movement in a straight line, sideways movement, etc.). The questions to be resolved at this level are: How can I move? How can I co-ordinate all the muscles (actuators) to achieve the desired movement?

The **superior level** is in charge of path planning, navegation and other higher level tasks. It is related to the volition. The questions that define this level are: Where do I want to go? What route must I follow?

This thesis concentrates on the inferior level of locomotion, studying the mechanisms that enable apodal robots to move.

2.2.2 Types of locomotion

In nature the movement of animals has been adapted to the environment in which they live. It is possible to carry out a basic classification according to the environment in which they move. Therefore the locomotion can be: air borne, aquatic or terrestrial. This classification is not definitive. The land mammals are also able to move in water for short distances, for instance to cross a river. In this case they use a different way of walking, or gait, that permits them to swim.

Ground movement can be divided, in turn, into two categories, according to the organs that are employed to achieve movement: **locomotion by means of feet** (mammals, insects) or **by means of body motions** (snakes, caterpillars, worms).

2.2.3 Robot locomotion

One of the research areas in robotics is that of locomotion: giving the robots locomotive capabilities so that they can move from one place to another. These robots receive the generic name of **mobile**

Figure 2.1: Examples of robots with different effectors for terrestrial locomotion

robots. At the same time the study of locomotion is performed at the two levels mentioned above. Investigations of the superior level start with the supposition that robots can move, without taking into account the mechanisms that make it possible (feet, wheels...) and concentrates on the task of the superior level such as path planing, vision, collaboration, etc.

The same happens in animals, in the study of the inferior level of locomotion, robots can be classified according to the effectors employed to move them: **wheels**, **caterpillar tracks**, **feet** or the **body**. This category of **apodal robots** includes those robots, that like their counterparts in nature, achieve locomotion through body motions. These are the four classical categories for the study of locomotion, nevertheless the classification is not definitive. As Mark Yim has noted [155] in his doctoral thesis, new effectors can appear that do not fit in any of these categories. Such is the case of the whegs[110] and his version mini-whegs[97], created by Quinn et al. in the bio-robotics laboratory of the Case Western Reserve University. In them a wheel and a leg are mixed to produce some very interesting results. In the figure 2.1 there are some photos of robots that use different effectors to achieve movement: wheels, caterpillar tracks, whegs, body and four, six or eight feet.

The themes for investigation at the lower level of locomotion are the properties of the various effectors, how to achieve the co-ordination of the actuators, the different gaits, algorithms of control, etc. In the remainder of the chapter, when speaking of locomotion, it always refers to the inferior level.

2.2.4 Design of Mobile Robots

As in the animal kingdom, where locomotion of individuals is specifically adapted to the environment in which the animal normally functions, to design a mobile robot it is essential to know the terrain in which it is going to move. **The environment** is the key in deciding which effectors will be chosen and what gaits will be implemented. Therefore, for example, if the robot is going to move on flat surfaces where there is no need to overcome obstacles, wheels, or even caterpillar tracks, are sufficient.

The design process can be resumed in the following steps:

1. The study of the environment in which the robot is going to operate
2. The selection of effectors.
3. The implementation of the gaits.

These steps are very important. A wrong choice at this level will imply having to reconstruct the robot. For this reason investigations at this level are important: the better the properties of the effectors are known, the possible gaits, their efficiency, etc. greater will be the information available that enable the right design decisions to be made. Leger [78], in his doctoral thesis, addressed the problem of the automatic design of robots, using an evolutionary approach. His central idea is that the search for solutions to locomotion is so wide ranging that it is necessary to create new software tools to explore the greatest possible number of solutions before taking a decision about which design to implement. At this level an error in the configuration of the robot is critical. For this reason he proposed using evolutionary algorithms to help the designers at this stage.

Nevertheless, applications exist where it is difficult to know a priori and in detail the ground, which leads to a lot of uncertainty in the initial stage of design. Such is the case when designing robots for **search and rescue operations** or **planetary exploration**. Due to this, the robot has to have the **maximum versatility** possible. Investigations concentrate on studying the most versatile effectors and all the different gaits possible.

2.2.5 The problem of locomotion

One of the biggest challenges in developing a robot is to make it able to move in all types of terrain, even the roughest and most broken. That is to say, a robot that is extremely versatile. This is of special importance in applications where the environment is insufficiently known or changeable, as in the exploration of the surfaces of other planets, hostile environments or search and rescue operations. What is it best to use, feet, wheels, caterpillar tracks...? How many feet? What type of movement? And if it has feet, how to configure them?.

The NASA has particular interest in this problem, financing projects destined to the building and evaluating of alternatives, so that the robots can move in rugged environments. Two of these projects in the initial stage (end of the 80's) were the CMU Ambler[72] and the Dante II[3]. They are examples that illustrate the design model described above: designs of specific structures based on the environmental specifications.

The Ambler is an autonomous robot for planetary exploration taking into account movement on the surface of Mars. Based on the specifications the robot was designed with 6 feet, 3.5 meters high and a weight of 2,500 kilos. The type of movement selected was by feet, in theory the most efficient mode[3]. Nevertheless this robot was never sent to Mars. The dimensions and weight of the robot were excessively large for the requirements and power consumption was very high.

The robot Dante II was also designed to explore broken ground and was tested in 1994 for the exploration of the mountain volcano Spurr, in Alaska. In this case the robot had 8 feet with a locomotion system called 'framewalker'. Despite knowing the specifications of the terrain, and that it had a cable maintaining it fixed to the summit and by which it descended, on the fifth day it tipped over and could not be recovered.

For exploring Mars, the NASA opted for using wheels[80] that up to now have given very good results. Nevertheless, wheels are very limited. They only allow the robot to move in controlled surroundings. This is one of the reasons why it is necessary to plan carefully and in advance the places to which the robot will be sent, not only taking into account the importance of atmospheric conditions, the collection of scientific data, etc, but also permits the robot to move easily in its surroundings[36]. This is a big handicap.

Inspired by the marvellous locomotive abilities of animals with feet, Dirk Spenneberg et al. of the University of Bremen developed the robot Scorpio[26], with 8 feet, able to move on sandy and rocky terrain, in places impossible for wheels. This project was financed by the DARPA and the robot was proposed as an alternative for the exploration of Mars. Motivated by the results, the development of the ARAMIES[131] was begun. This robot is a quadruped that can move on extremely adverse terrain and can, besides, carry on board scientific experiments. One of the aims is to explore the locomotive capabilities of quadruped robots in this type of surroundings.

2.3 Apodal robots

In contrast to terrestrial movement by means of feet, are the living beings that use corporal movements. The robots that use this kind of movement are known as **apodal robots**. The word apodal means “lacking feet”.

These robots possess characteristics that make them unique, the same as their counterparts: snakes, worms and maggots. On one hand is the ability to change their form. Compared with the rigid structures of the rest of the robots, the apodals can bend and adapt to the form of the terrain on which they move. On the other hand their section is very small compared to their size, which permits them to enter small tubes or orifices and get to places inaccessible to other robots.

This section analyses the apodal robots created in the most important research centres and their evolution up to now.

2.3.1 Tokyo Institute of technology: acm family

Hirose, of the Tokyo Institute of Technology pioneered studies of snake’s bio-mechanics for its application to robotics. It was implemented in 1976 the first snake robot called ACM-III (*Active Cord Mechanism*). In 1987 in the reference book "*Biologically Inspired Robots*"[47], the results of his investigation were collected and published.

One of Professor Hirose’s most important contributions to science was the discovery and formulation of the **serpenoid curve**[143], which is the form adopted by the snakes when moving. He proposed a model of vertebrae that moves by means of the action of two opposing muscles controlled by two springs that provoke a sinuous movement. Then he calculated the spinal column curve’s equation and finally compared it to the experimental results obtained from real snakes.

Figure 2.2: Evolution of the snake robots of the ACM family: (Active Cord Mechanism). Hirose-Fukushima Robotics Lab

In figure 2.2 the different prototypes developed up to the present are shown. The first one is the **ACM-III**[1] that measures 2 metres long and is made up of 20 articulations that move parallel to the ground (*yaw*), capable of moving at a speed of *40cm/s*. Each module has some passive wheels that allow the robot to crawl along the ground. These wheels have the effect that the friction coefficient in a tangential direction is very low compared with the normal drag. It is this principal that allows the propulsion of the robot when the articulations are oscillated correctly. This mechanism has been baptised '*glide propulsion*' and is not only similar to that of snakes, but also to the movement of skaters.

The ACM-III prototype was about 20 years ahead of its time. This line of investigation was forgotten until, owing to the advent of modular robotics, prototypes of snake robots reappeared. Hirose and his collaborators renewed their interest in this system and they redesigned it with new technologies. In this way the **ACM-R1**[48] was born. It was a revised and modernised ACM-III. It included wireless communication with the robot to eliminate the need of cables. This prototype has 16 modules and can move at a speed of something like *50cm/s*. The modules are smaller and better finished. Among the new experiments carried out the highlight is the trial of propulsion sliding on ice, using the same kind of blades that are used on ice skates [29].

The following prototype, **ACM-R2**, has greater freedom in each module allowing pitch as well as yaw[142] which permits the robot to adopt three dimensional forms. This prototype served principally

[1] More information is obtainable on the web: http://www-robot.mes.titech.ac.jp/robot/snake_e.html

to study the viability of the robots with axes of pitch and yaw, and later evolved to the **ACM-R3**[95]. The functionality of the ACM-R3 is the same as the ACM-R2, nevertheless the design is completely new. Now each module has one degree of freedom. It is designed in such a way that when they are connected in chain the movements of pitch and yaw are alternated. The structure is more compact and lighter than its predecessor. One of the design novelties was to integrate some large sized wheels on either side of the module. This novel design permits the wheels to be always in contact with the surface, independently of the robots orientation, allowing it to be propelled in inclined positions. The prototype was used to investigate new ways of locomotion such as rolling, sinus-lifting or inclined movements[96].

With the idea of improving the model so as to be able to function in real situations, where there is dust, water, areas with difficult access, etc., the **ACM-R4**[152] was developed. It can be considered as an industrial version to be employed for inspection or search tasks in tubes or steep ground. Snake type propulsion requires many modules. With the idea of reducing the size, the wheels, that before were passive, are now active and can be moved by a motor. The ACM-R4 has only 9 modules. This characteristic has led to the appearance of new locomotive capabilities. It can be seen in one of the experiments how the robot advances along the ground, lifts up its body, supports itself on a chair, climbs onto it and finally gets off , showing how it can move in quite complicated terrain.

A characteristic of the snakes is that they can move as easily on the ground as in water. From ACM-R4 and an amphibious prototype, **Helix**[139] the version **ACM-R5**[151] was born. The robot can move along the ground using glide-propulsion, by means of some small passive wheels. Also each module has four fixed fins that in normal movement through water produce high resistance and low resistance for tangential movements.

2.3.2 Shenyang Institute of Automation

Hirose's work has served as inspiration for other investigators. One of them is Shugen Ma who repeated and enlarged Hisore's work in glide-propulsion and developed a simplified version of ACM-R1 with 12 less mechanically complicated modules and an improved system of control[82]. He also developed a software to simulate the real movement of the robot on different surfaces. The theory is that the robot moves along the serpenoid curve and that no normal slipping exists. Nevertheless, in practice this side slipping does appear, and produces loss of propulsive power. By means of the simulator it is possible to determine the values of the losses and find the optimum angle of the serpentine movement for each surface[83]. Lastly the locomotion of the robot on inclined terrain was studied[85]. Parallel to this, Professor Shugen Ma's group also started to study apodal robots with pitch and yaw connections[84]. A module that possessed a certain degree of freedom and activated by a servo was developed and with it configurations of robots were created to study different movements and their adaptations to the environment. Concretely a rolling movement to overcome obstacles was suggested[11], and in [10] the problem was studied in a more general way, suggesting other gaits depending on the environment.

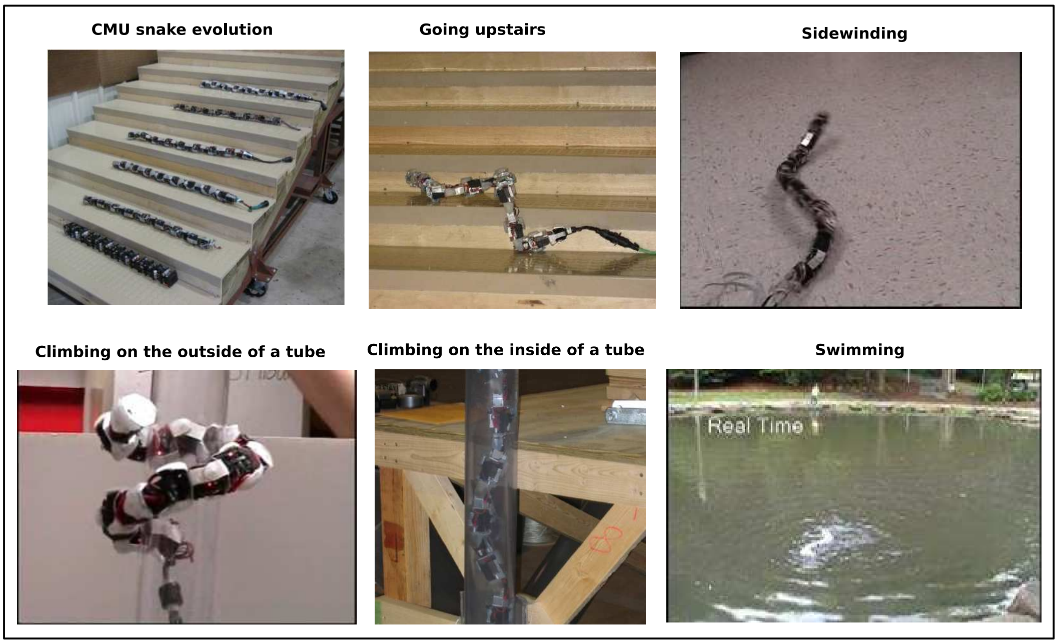

Figure 2.3: CMU's snake robot

2.3.3 Robotics Institute at Carnegie Mellon University

In CMU's (Carnegie Mellon University) Robotics Institute Kevin Downling studied apodal robots. In his doctoral thesis[27], financed by the NASA, developed a framework environment for the automatic gait generation for snake robots. He was one of the pioneers in applying genetic algorithms to find solutions for the locomotion of these robots.

Investigations on snake robots are being carried out in the bio-robotics laboratory[2] directed by Professor Howie Choset. The principal lines of investigation are mechanical and locomotion at both inferior and superior levels. In the area of mechanics new articulations are being developed[123] to attain snakes in 3D, as well as actuators that permit optimum climbing ability[24].

His investigations of the superior level have concentrated on planing movements, developing locomotive algorithms and positioning in what is known as hyper-redundants[16][15].

Some very interesting results are being obtained for the inferior level. The videos of the robots can be seen on *You Tube*[3]. The prototypes designed (see Figure 2.3) are based on Mark Yim's modules, described in more detail in the section 2.5. They use aluminium modules with a degree of freedom, activated by what is known as Super-servo. These are commercial servos that have been modified, adding their own electronics, sensors and communications bus [150]. Different types of 'skins' are

[2] http://download. srv.cs.cmu.edu/~biorobotics/
[3] Youtube channel: http://www.youtube.com/user/CMUBiorobotics

Figure 2.4: The prototypes Amphibot I and II of the EPFL bio-inspired group. The author of this thesis appears at the lower left, together with Alexander Crespi, author of Amphibot, when attending Clawar 2006 in Brussels.

used to cover the modules and allows the snake to move in all kinds of terrain, including aquatic environments.

The latest prototypes consist of 16 modules and can move in a straight line, sideways, climb on the inside or outside of a tube, swim and roll[81]. At this low level of locomotion the robots are tele-controlled by an operator, who constantly indicates the movements that the robot must carry out.

2.3.4 Bio-Inspired Robotics groups at EPFL

The bio-inspired robotics group at EFPL (*Ecole Polytechnique Fédérale de Lausanne*) has developed the amphibious robot **Amphibot**[21][4] that is capable of moving on ground and in water. It consists of 8 modules that move parallel to the ground and uses bio-inspired controls for locomotion, based on the CPGs (*Central Pattern Generators*) models of the lampreys, developed by Ijspeert[59].

The first prototype, **Amphibot-I**[22][20] could swim by means of undulations of the body, as well as move along the ground as snakes do, for which some passive wheels, similar to those of ACM, situated on the abdomen were included. In the second version, **AmphiBot II**[23], the modules were made more compact and feet were added. This robot could also move on the ground and swim like salamanders do, combining body and foot movement. For the control model the lamprey CPG models were used and demonstrated how the speed and direction of movement can be quickly adjusted, on the ground and in the water[58].

[4]More information is available on the web http://birg.epfl.ch/page53468.html

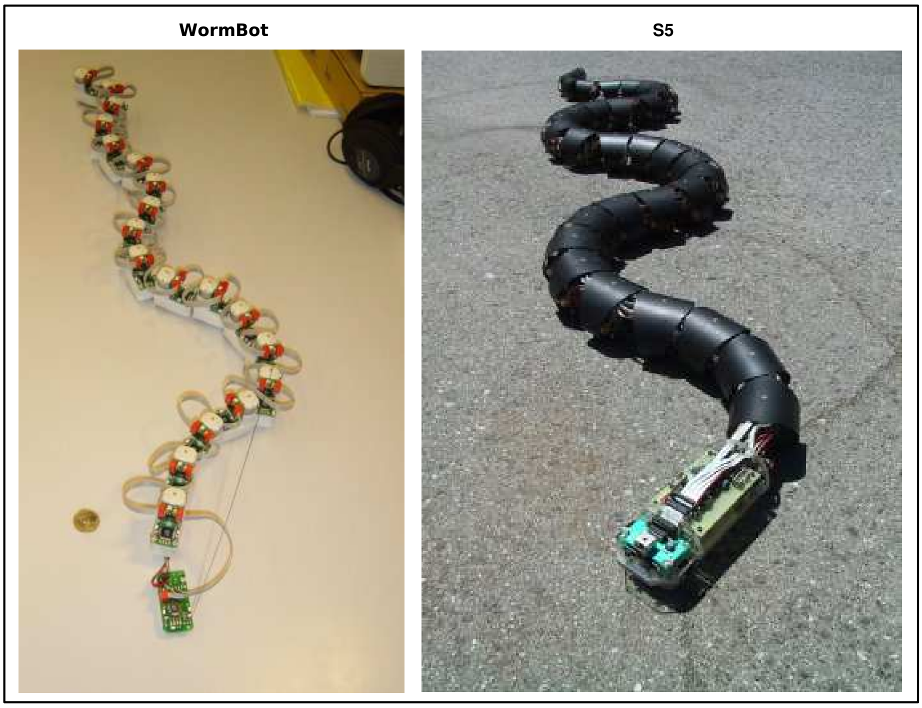

Figure 2.5: Left: Wormbot, designed by Conrad[19]. Right: S5, Miller[90]

2.3.5 Others

One of the most realistic snake robots obtained is the prototype **S5**[5] developed by Miller[90]. It is made up of 64 articulations with the relationship between the length and width of the section nearing the proportions of real snakes. It is the fifth generation of snake robots.

The **WormBot**[6] of Conrad et al.[19], developed by the University of Zurich's Neuroinformatics Institute, is a prototype of a snake robot that moves by means of undulations of its body and is based on the bio-inspired model of CPGs. It has implemented the lamprey CPGs[18]. The robot is autonomous and an operator can change the parameters of the couplings between oscillators.

A different approach is used in the robot **SES-1** y **SES-2** (Self Excited Snake Robots) developed by Ute et al[145] in the Tokyo Institute of Technology. In a prototype of 3 segments and 2 motors, movement is obtained through the principle of self-excitation. According to this principle springs are placed in parallel to the actuators. The torque of each motor depends on the angle of the adjacent motor, obtained by means of negative feedback. With this principle very quick and efficient movements are obtained. The first version SES-1 is formed exclusively of analogic circuits.

The figure 2.5 shows the Wormbot and S5 prototypes.

[5] More information on the web: http://snakerobots.com
[6] http://www.ini.ethz.ch/~conradt/projects/WormBot/

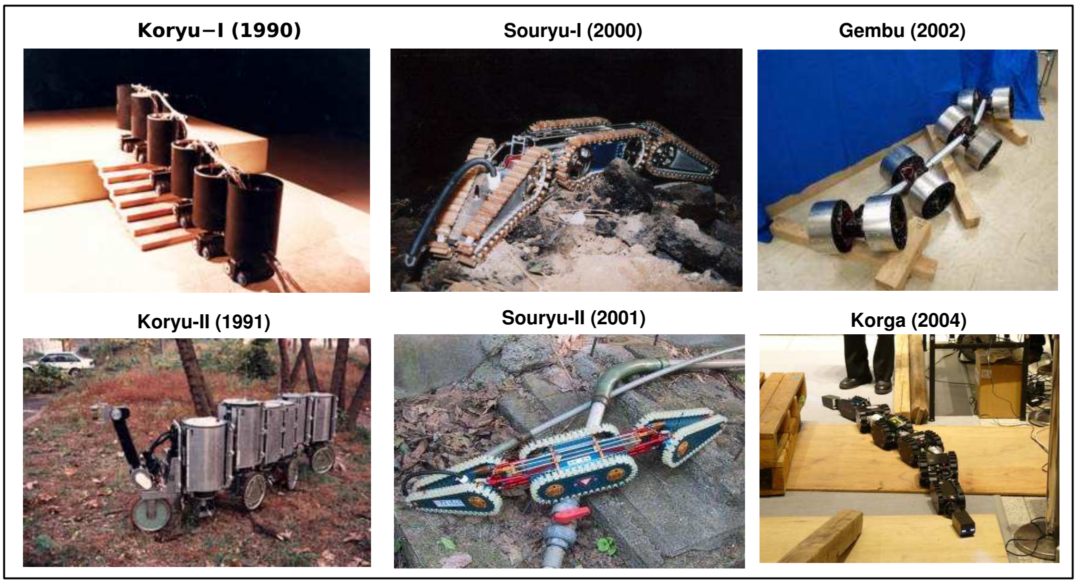

Figure 2.6: Self-propelled robots (serpentine robots) in the Hirose-Fukushima Robotics Lab

2.4 Self-propelled apodal robots

In contrast to the apodal robots that accomplish their locomotion by means of body motions, the self-propelled apodal robots displace themselves by means of active wheels or caterpillar tracks on the different parts that make up the robot. Though they have the form of a snake, they are not bio-inspired robots. This type of locomotion is not found in nature. Nevertheless it is included in this study because most of them are modular robots, formed by similar modules joined in a chain.

This kind of modular robots have also been named[43] as **serpentine robots**.

2.4.1 Hirose Fukushima Robotics Lab (TiTech)

Professor Hirose also pioneered this class of robot. From ACM-III structures were developed with self-propelled modules joined in a chain[51], these are known as **articulated bodies**[7]. Outstanding among the advantages of this type of robot is its ease of transport: the modules are separated one from the other and later joined together again, they can carry a load distributed on all the robot, they can move along narrow and twisting paths and the system is 'redundant', that is if one module fails another takes its place.

To explore the locomotive capabilities of their articulated bodies the **KORYU I** prototype[52] was developed, formed of 6 cylindrical bodies and propelled by caterpillar tracks. Each module has 3

[7] More information in the link: http://www-robot.mes.titech.ac.jp/robot/snake_e.html

degrees of freedom: vertical movement (axis z), turning movement (parallel to the plane xy) and wheels to propel it. It was noted that this robot could turn, climb obstacles and even stairs. The cylinders can also move vertically, which permits the robot to negotiate irregular surfaces. The second prototype, **KORYU-II**[53] uses, instead of caterpillar tracks, independent wheels which allows it to move with ease on sloping terrain. Experiments were carried out both in the city and the countryside.

The Japonese live in a seismic zone where earthquakes are frequent. Because of this the application of search and rescue are of special interest for them. After an earthquake people can be trapped in the rubble and they have to be rescued immediately. To develop a robot capable of manoeuvring in this type of environment, find the victims or survivors, using cameras and microphones, would be a great help.

The first prototype proposed was **Souryu-I**[138], made up of three segments. Each one is propelled by caterpillar tracks, but they are not independent, there is one motor that drives them all. The first one carries a camera and a microphone, and the rear one a radio receiver. The modules at the extremities can carry out pitch and yaw symmetrically. The robot has only three degrees of freedom. The following version **Souryu-II**[140] is similar but its modules are easily separated to facilitate transport and add special intermediate modules.

The **Genbu** (I, II y III)[66] generation of robots is formed by chains whose modules have two independent, active wheels and are joined by passive articulations. It has been developed to deal with fires. The motors are hydraulic and a hose-pipe can be fitted along the central axis of the robot to pump water and reach places inaccessible to the firemen.

Another robot is **Kogha**[61], developed for search and rescue operations. It has 8 modules connected in series with two caterpillar tracks, except the first and last ones. The connections between two modules dispose of two degrees of active freedom that allow them to climb obstacles and 3 degrees of passive freedom that allow them to adapt to the terrain.

Some of the prototypes are shown in the figure 2.6. In [49] a more detailed review of some of the robots developed by the Tokyo Institute of Technology can be found.

2.4.2 German National Research centre (GMD)

The GMD has developed two prototypes of self-propelled apodal robots. One is the **GMD-SNAKE**[68] (prototypes 1 & 2). This is made up of 12 driving wheels on each module. It has 6 modules, plus one at the head. The principal application for which it was designed is the inspection of tubes, though in [105] application to the inspection of buildings is being studied.

The other is the **Makro**[111] robot for inspecting drains of 30 to 60 cm diameter. It has 6 modules and the joints between them have 3 degrees of freedom. Each module has two wheels to drive it. At the head two cameras are fitted as infra-red sensors to detect obstacles. Though the robot is tele-directed, a software has been proposed to make it autonomous[135].

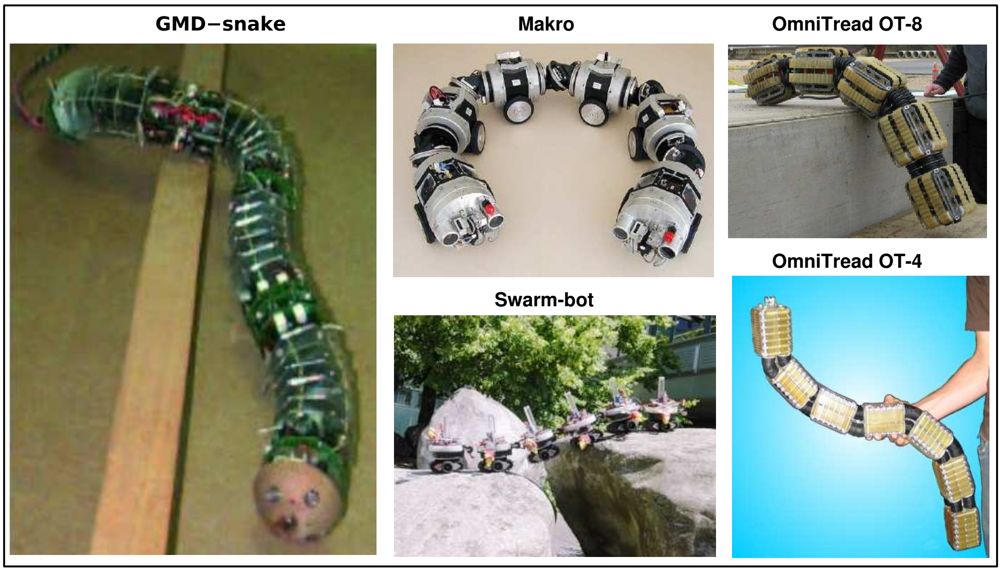

Figure 2.7: Different prototypes of self-propelled apodal robots (serpentine robots): GMD-snake Makro, Swarm-bot, OmniTread OT-8 y OT-4

2.4.3 University of Michigan: OmniTread

One of the most advanced self-propelled apodal robots is **OmniTread**[8] developed by Granosik et al.[43] at the Laboratory of mobile robotics in the University of Michigan, for task of industrial surveillance. This robot is very robust and flexible. It uses pneumatic joints which gives it a lot of strength. The first version omnitread **OT-8** is composed of 5 hexahedral modules. Two caterpillar tracks have been placed on the four external faces of the robot. The inconvenience is that the air compressor is placed outside the robot, which necessitates a hose.

In the following version, **OT-4**[4] the robot has been reduced in size and electric micro-compressors have been added, thereby eliminating the need of a hose. It has an autonomy of around 75 minutes. (Figure 2.7).

2.4.4 EPFL Intelligent Systems Laboratory: Swarm-bot

The **Swarm-bot** robot[9] has been developed at the EPFL Intelligent System Laboraty for the study of 'the intelligent beehive': colonies that are capable of self-organisation. The prototype developed[94] is formed by small mobile robots that have the capacity to assemble themselves to make bigger structures and therefore carry out other tasks. For example, if they have to cross a crevasse, they can organise themselves into a chain[93][44].

[8] More information in the web: http://www.engin.umich.edu/research/mrl/00MoRob_6.html
[9] More information http://www.swarm-bots.org/

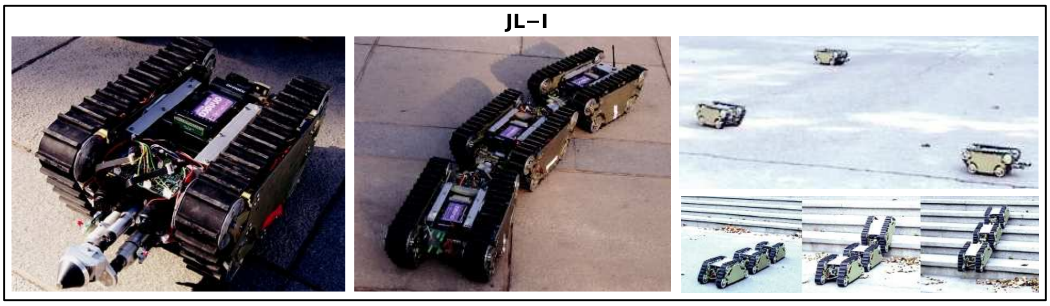

Figure 2.8: The robot JL-I

Each one of these modules is called **s-bot** and is totally autonomous. They use caterpillar tracks to move and are supplied with sensors (Figure 2.7).

2.4.5 Institute of Robotics at Beihang University (BUAA): JL-I

The Beihang University (Beijing China) Robotics Group started the design of this type of robot in 1999, with a two module design[146]. Each one has two caterpillars and an articulation with 2 degrees of freedom as well as a CCD camera and sensors. The articulations can also extend, allowing the robot to increase or shorten its length.

Based on this initial prototype, Houxiang et al designed the **robot JL-I[171]**. At present this is formed by 3 identical modules. It has 3 degree of freedom articulations, which gives it a vast capacity of movement. Not only can it climb obstacles, among other characteristics, but also stairs and recover itself if it turns over[170].The robot is planned for military applications[175].

2.5 Modular robots and locomotion

2.5.1 A new approach to the problem of locomotion

In every discipline an investigator appears who revolutionises this area of knowledge, proposing new ideas and giving new insights. Such is the case with **Mark Yim**, who can be considered the father of **modular self-configuring robotics**. His work has inspired hundreds of investigators (Some of his articles have been referenced more than 250 times!).

In his 1995 doctoral thesis Mark Yim proposed a new approach to the locomotion problem[155]. The traditional solution, described in the section 2.2.3 is focused on designing a specific robot based on the analysis of a terrain's characteristics. What Yim proposed was using robots based on modules with the capability of re-assembling themselves into different forms. In this way, these new modular robots could change their form adopting different configurations and gaits according to the terrain where they were operating at a particular moment.

To illustrate it, he proposed the scenario described in the introduction to this thesis. The question was asked what would the robot have to be like to be able to go from the Stanford Robotics Laboratory to a building on the other side of the street. The robot had to be capable of moving along level ground, cross the laboratory's porch, pass under a railing, go down some 60 cm steps and move across a rough piece of ground, covered in herbage.

To resolve the problem the best configurations for each type of terrain would have to be determined, using a self-reconfigurable modular robot. Initially, therefore, the robot would use a wheel type configuration to cross the porch (it was shown that this gait was the most efficient for level ground), next the "wheel" would open and the robot would transform itself into a worm that allowed it to pass under the railing and descend the steps. Finally it would change into a four footed spider, a configuration characterised by its greater stability, to cross the broken ground.

The advantage, therefore, of these self-configuring modular robots is their **great versatility**. What is more they can employ the most efficient configuration and gait for each class of terrain. That is to say, they combine the best features of apodal robots and robots with feet.

2.5.2 Polypod

This idea of self configuring robots would not have been such an innovation if Yim had not demonstrated their viability. It was not until some years later, after the publication of his thesis, that his idea took off and produced the boom in modular robots.

For the experiments of his thesis the first robot that was developed was **Polypod**. Though what was being proposed was the birth of self configuring modular robots, Polypod was manually self-reconfigurable, but it was used to implement distinct configurations and demonstrate the viability of his ideas. The Polypod´s modules were mechanically complex and possessed two degrees of freedom. All the technical details are included in his thesis[155]. An amplified summary (in Spanish) can be found in [38].

2.5.3 Polybot

After finishing his doctoral thesis Mark Yim started to work as an investigator in the PARC (*Palo Alto Research Centre*) where he developed his famous robot **Polybot**[157][10]. In reality it is not a robot, in the traditional meaning of the term, but the word covers various generations of modules from which modular robots can be created.

[10]Information about Polybot is available on http://www2.parc.com/spl/projects/modrobots/chain/polybot/

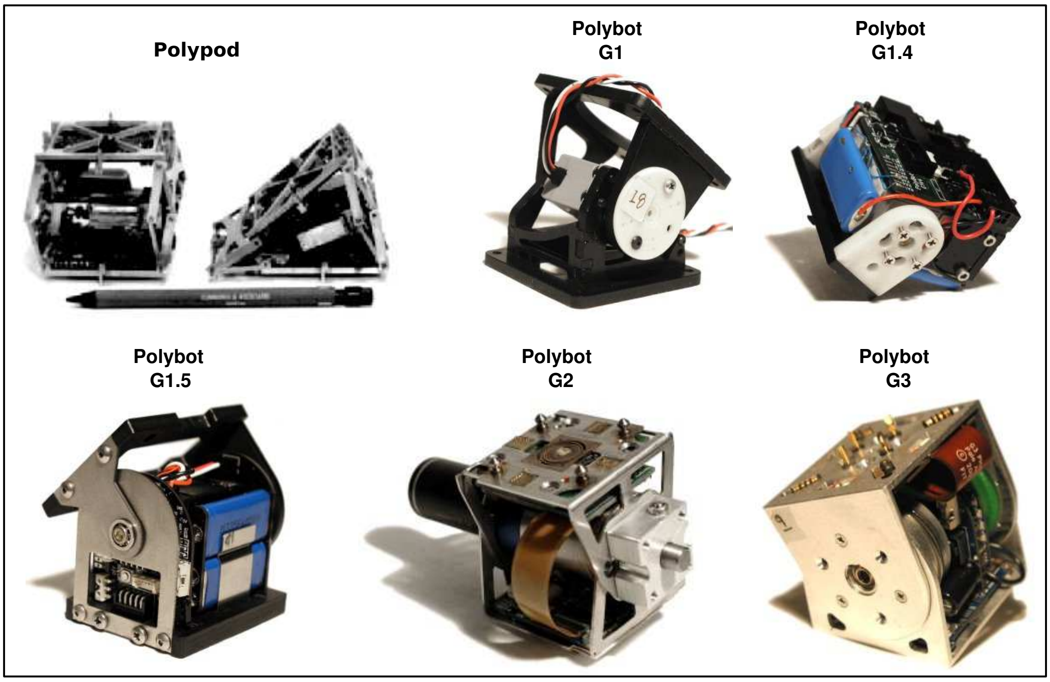

Figure 2.9: The modules of Polypod and Polybot

According to Yim the three promises of modular robotics[166] are versatility, reliability and low cost. **Versatility** is due to the fact that these robots can change their form and move in diverse kinds of terrain. **Reliability** lies in their self-repairing capacity. If one of the modules develops a fault it eliminates itself or is substituted by another. Finally the **low cost** is obtained by applying mass production of the modules. Large scale production leads to reduced costs.

Polybot is a platform for experimenting focused on the promise of versatility. Up to now five different types of modules have been created, grouped in three generations: G1, G2 and G3 (see figure 2.9). One of the aims of their design was simplicity, that is why they have all been given only one degree of freedom.

The **G1 generation** is not self-configuring, as the modules do not have the capacity to automatically join themselves together. Nevertheless it is possible to produce various manual configurations and test them. Three different modules have been designed. The first was made of plastic and employed a commercial servo as articulation. Mechanically it is much simpler than the modules developed for Polypod. A novel idea was introduced, that the base of each module should be square, enabling them to be connected one to the other, in different ways. In this way robots with joints that move on one plane, and others perpendicularly to them could be formed. Outstanding among the experiments is **the first example of simple re-configuration**, in which 12 modules adopt, initially, the form of a wheel. These move along a level surface until they arrive at some stairs. The robot opens up and converts itself into a worm that can descend the stairs. It was the first experiment in which a robot carried out

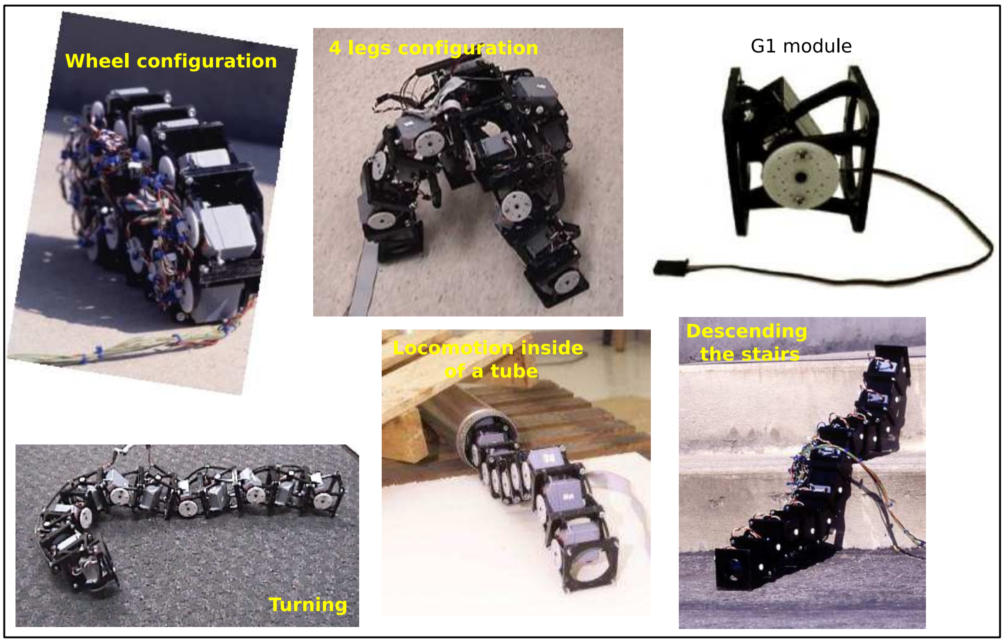

Figure 2.10: Polybot. Different configurations of Polybot G1

a re-configuration[158]. Besides this different locomotive configurations were experimented with a four footed spider and a worm configuration, movement through a tube and turns (Figure 2.10).

Having proved the viability of modules, sensors were introduced in the version **G1v4** to implement applications in closed loop. Experiments were carried out of climbing worms. Not only to climb walls and barriers (lineal configuration) but also to climb stairs (wheel configuration)[161][160]. One of the strangest experiments was imitating the human 'undercarriage' (hips and legs) making them move by pedalling a tricycle[166]. It is a further example of the versatility of modular robotics: configurations can be created that allow objects made for humans to be manipulated[11].

The G2 and G3 generations have the ability to join themselves together and separate[167], which permits the construction of authentically self-configuring robots. The **G3 generation** is a redesigned G2 to obtain a more compact module: Its dimensions allow it to fit in a 5 cm cube. This innovation was produced in the previous version. The first dynamic self-reconfiguration experiment was carried out successfully with the **G2 modules**[159]. The first part of the experiment demonstrates the simple re-configuration, in which Polybot adopts the form of a wheel with 12 modules. Following that it adopts a lineal configuration. In the second part the conversion from worm to a four legs spider is carried out. Both extremities fold inwards, parallel to the ground with the robot adopting the form of ∞, coupled to both sides of the central module. The exterior modules separate so that the robot forms an *X*. Now the robot has 4 feet, each one formed by three modules. Finally the robot raises itself. The

[11] It is interesting that – diverging from the theme – in his science fiction novels Isaac Asimov argue that the future of robotics lay with humanoid robots. All the tools that had been designed for humans could be used by robots, avoiding the need to redesign them.

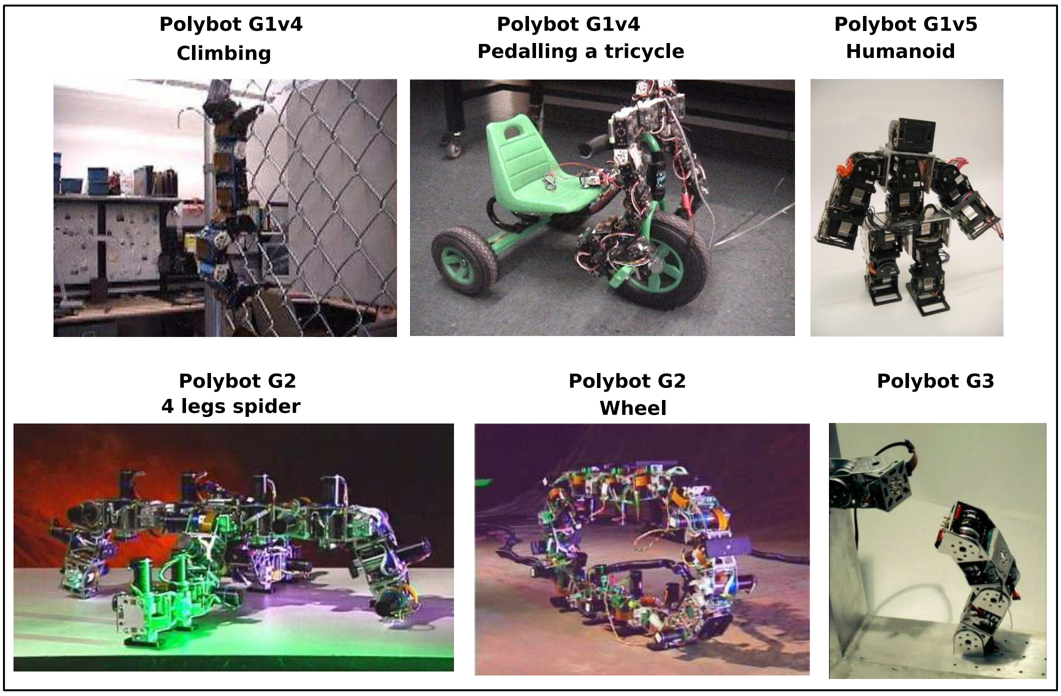

Figure 2.11: Different configurations of Polybot

great contribution obtained is the ability to automatically join modules using infrared rays as guides [112].

The **G1v5 modules** are the latest to be developed. They are not re-configurable, nevertheless they are designed using the lessons learned from all the previous modules. They are very robust and are prepared for commercialisation. The Polykinectis environment[37] has been developed to program and drive them. This includes programming in a scripting language to control the various configurations based on XML[172]. This environment was tested in a workshop given in the International Congress of Intelligent Robots and Systems in 2003 (IROS)[12]. The experience was a success and the possibilities of modular robotics in the field of education was demonstrated.

The theoretic model for the programming of modular robots is known as phase automata[173][174]. It is based on the idea that principal movements are periodical. This periodicity is ruptured when certain events from the sensors occur. The other idea is that the signals that control the modules are the same, but with a time lag.

In the figure 2.11 the different configurations of the Polybot G1v4, G1v5, G2 y G3 generations are shown.

[12]The tutorial is available in the link: http://www2.parc.com/spl/projects/modrobots/chain/polybot/parc/doc/ tutorial/index.html

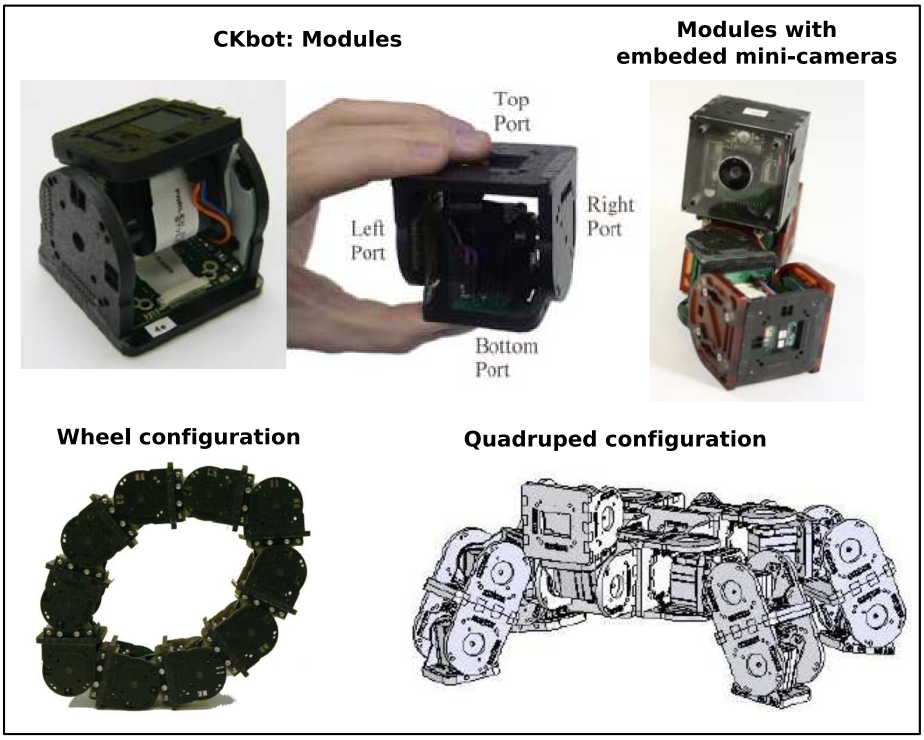

Figure 2.12: Modules and various configurations of Ckbot

2.5.4 Ckbot

In 2006 Mark Yim moved to the University of Pennsylvania where he founded the **ModLab**[13], where investigations in the field of Modular robotics are carried out.

The modular robot **CKBOT** [107] (*Connector Kinetic roBot*) has been developed there to be used as a platform for his investigations. The modules of Ckbot have been inspired by the Polybot version G1v5: dynamically they are not reconfigurable, but they do permit the creation of different types of configuration to explore their locomotive capabilities. In the figure 2.12 the modules and some of the configurations that have been tested are shown.

Though Modlab is not very old, its contributions are very innovative. One of them is a new application baptised by Yim as '**self-reassembly after explosion**' (SAE) [164][165]. The aim is to begin to explore the second of the modular robotics promises: **robustness** and **self repairing ability**. The following problem is still to be resolved: the starting point is a modular robot with a specific configuration. At a particular moment it suffers an impact and all its modules or parts of the robot are scattered over the immediate area. The robot must be able to put itself together again and continue with the task that it was doing.

[13]The web page is: http://modlab.seas.upenn.edu/index.html (Modular Robotic Lab)

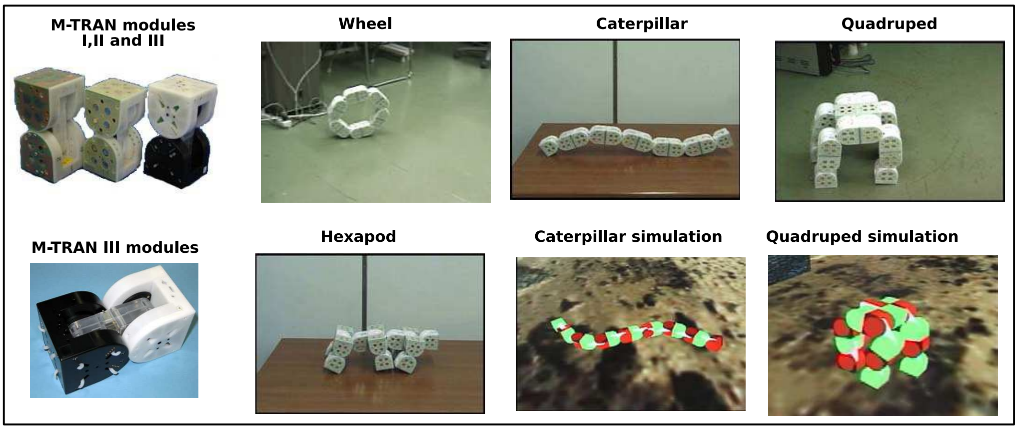

Figure 2.13: Modules and different configurations of the robot M-TRAN

To test the viability of the system, a configuration in the form of a humanoid robot has been created, made up of three groups of modules (known as *clusters*). Each cluster consists of 3 modules Ckbot and a module with a mini-camera[128]. The mechanical union between the three clusters is by means of permanent magnets, while the internal modules are joined by screws. In the experiment realised in [165], the humanoid configuration is walking. One of the investigators hits it and the three clusters are scattered across the ground. By means of the mini-cameras the different parts are capable of recognising each other and moving until they reconstruct the humanoid original and continue the task.

Besides this different gaits and configurations, for example a type of wheel movement[121] or the creation of a centipede robot from modules that add exterior feet[122], are continuing to be studied and analysed.

2.5.5 M-TRAN

One of the most advanced modular robots that exist at the moment is the **M-TRAN** (Modular TRANformer)[99][14] developed in the National Institute of Advance Industrial Science and Technologies (AIST) in Japan. In the figure 2.13 the modules and different configurations of the robot are shown.

The present version has been the result of more than 10 years of investigation. It is a hybrid modular robot (see paragraph 2.7) that can configure itself to form chain topologies or lattices. Three generations of modules have been developed: M-TRAN I, II & III.

The project started in 1998, with **M-TRAN I**[104]. Faced with the search for simplicity in Polybot and Ckbot, the M-TRAN module has two degrees of freedom and a novel system of coupling between modules based on permanent magnets and SMA (*Shape Memory Alloy*) springs for separation. They

[14] More information is available in the link: http://unit.aist.go.jp/is/dsysd/mtran3/

are based on Profesor Hirose's principal of internally balanced magnetic units[50]. The modules are joined to each other by means of permanent magnets. The system's novelty is in the SMA springs that are activated by electric current to disconnect the modules. In the first experiments it was shown that the permanent magnets had sufficient force for one module to lift another. Also the viability of various configurations in movement was explored: wheel, worm, quadruped, and dynamic configuration [65]. As well as the mechanical and electronic design of the module, a powerful simulation system was developed[75] that was used to explore the modules' possibilities, causing a block of 12 modules to pass over obstacles and simulate different algorithms of planned movements[169] and simulations of self-reparation[103].

In 2002 the second generation: **M-TRAN-II**[102] was developed. The idea of the module is the same, improvements have been made in the mechanics and the hardware. The module was reduced in size by approximately 10%, and consumed less, which led to better autonomy, and the hardware allowed for wireless communication. The innovations that were introduced were in the field of the automatic generation of gaits, using CPGs and genetic algorithms [73]. Genetic algorithms are run in a PC and then the pattern of movements are down-loaded to the modules, either to the actual robot or to the simulation. More information can be found in [63]. Nevertheless, one of the most novel experiments that was done was the reconfiguration of a quadruped into a worm [73], something that had not been seen before. To achieve it, it is necessary to plan the steps that the modules have to follow to reach the goal [168]. Due to these experiments the M-TRAN became the most advanced modular robot.

The present generation, **M-TRAN III**[62] incorporate a new mechanical connecting mechanism, that replaces the permanent magnets. This has achieved improved energy efficiency and speed in connecting and disconnecting, though at the price of mechanical complexity. These modules, nevertheless, are no longer prototypes, but can be produced industrially. The electronics are much more powerful. Now each module has four microprocessors connected by a bus CAN (Controller Area Network). One is the master and the others slaves. The previous experiments of locomotion have been verified and amplified [76] and reconfigured [74]. One of the new possibilities of these modules is that of incorporating specialised modules, for example mini-cameras [98] to help in the implementation of the reconfiguration.

2.5.6 CONRO

The **CONRO** modules[15] were developed by Castano et al.[8] at the University of South California's ISI (Information Science Institute) for the implementation of what are called **metamorphic systems**: robots that can change their shape. What Yim called self-configuring (the denomination that has prevailed). These modules have two degrees of freedom and self-coupling ability. In the initial experiments a snake and a hexapod were formed[7]. The coupling system was tested, though in the first version it has not been integrated into the modules yet.

[15] More information on the web: http://www.isi.edu/robots/conro/

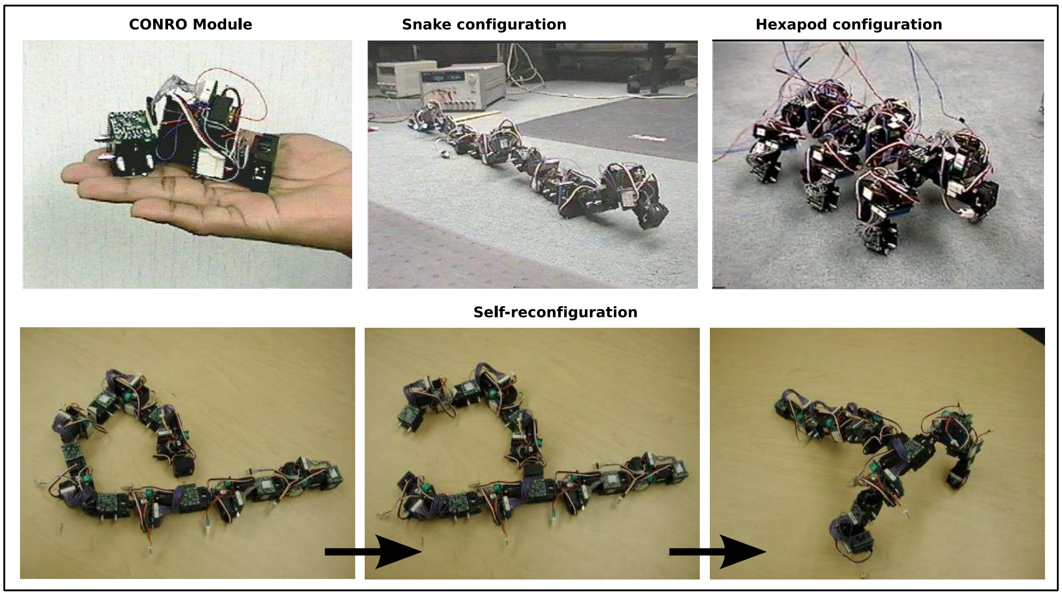

Figure 2.14: Conro module and different configurations

To represent the configuration of a re-configurable robot graphs are used to determine if two robots have the same configuration[9]. Also it is possible to locate special modules, for example a mini-camera [6].

In later studies a new bio-inspired system was proposed so that the modules could discover the changes in topography and could collaborate with other modules to carry out movement and self configuration. Two protocols based on the idea of hormones have been developed, one called Adaptive Communication (AC) and the other Adaptive Distributive Control (ADC)[126]. In [114] a system of autonomous coupling between modules is being studied.

The figure 2.14 shows what CONRO looks like as well as various configurations and one of the reconfiguring experiments that was carried out.

2.5.7 SuperBot

SuperBot[16] is a modular robot created in the ISI Robotics Polymorphic Laboratory of the University of South California. The module designed is one of the most modern (2005) and is inspired in all the previous ones: Conro, Polybot, MTRAN y ATRON. It is a project financed by the NASA and the DARPA. and was developed, initially, to be used in space applications[124]. How to employ it as a mobile platform to move on another planet's surface and collect information is being studied[141]. Between 8-10 modules reconfigure to form the needed platform: such as wheel (for efficient movement), spider, snake, communication towers, etc. Another application is what the authors call MULE

[16] More information on: web:http://www.isi.edu/robots/superbot.htm

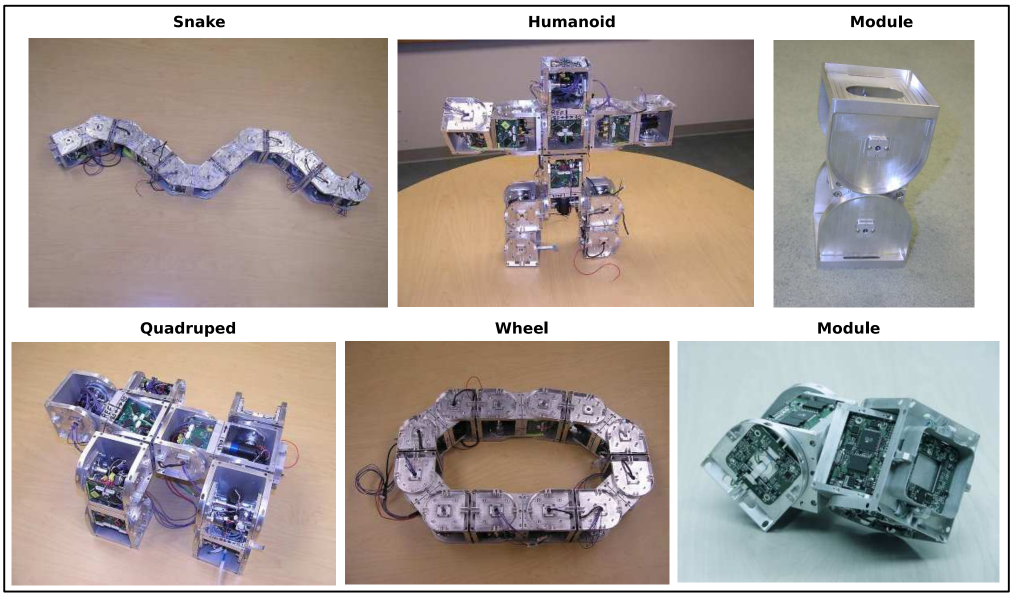

Figure 2.15: Different configurations of the SuperBot module

(*Multi-Use Lunar Explorer*) [79]. The idea is to place more than 100 modules on the chassis of a lunar vehicle and use them to carry out various geological tasks, with or without the help of the astronauts. Weight is very important on space missions. Instead of carrying different apparatus to make measurements, the modules can be reconfigured to form different structures according to need.

The latest application is that called OHMS (*Habitat Operations and Maintenance System*)[77] in which approximately 150 modules are used to obtain various tools: solar panels, cleaning and maintenance of the installations, monitoring and inspection in real time...

The mechanics of the Superbot modules are inspired in MTRAN, but includes an extra degree of freedom. The two extremities turn vertically (pitch) and rotate (roll) between themselves. It has, the same as MTRAN, a total of 6 contact surfaces where other modules can be joined, this allows not only the formation of chain type robots (see paragraph 2.7), but also solid 3D structures[125][118].

The re-configurable systems must resolve various challenges: 1) Distributed negotiation, in such a way that the modules agree on the global task they are to perform. 2) Distributed collaboration, that allows them to translate the global task into local tasks that each module can carry out. 3) Synchronisation, so that each local task is synchronised with the others.

These problems have already been addressed in the CONRO modules, but with the supposition that the topology did not vary while a task was being carried out. In [120] an algorithm is proposed to resolve these problems, allowing the topology to change. This is inspired in the concept of hormones[119].

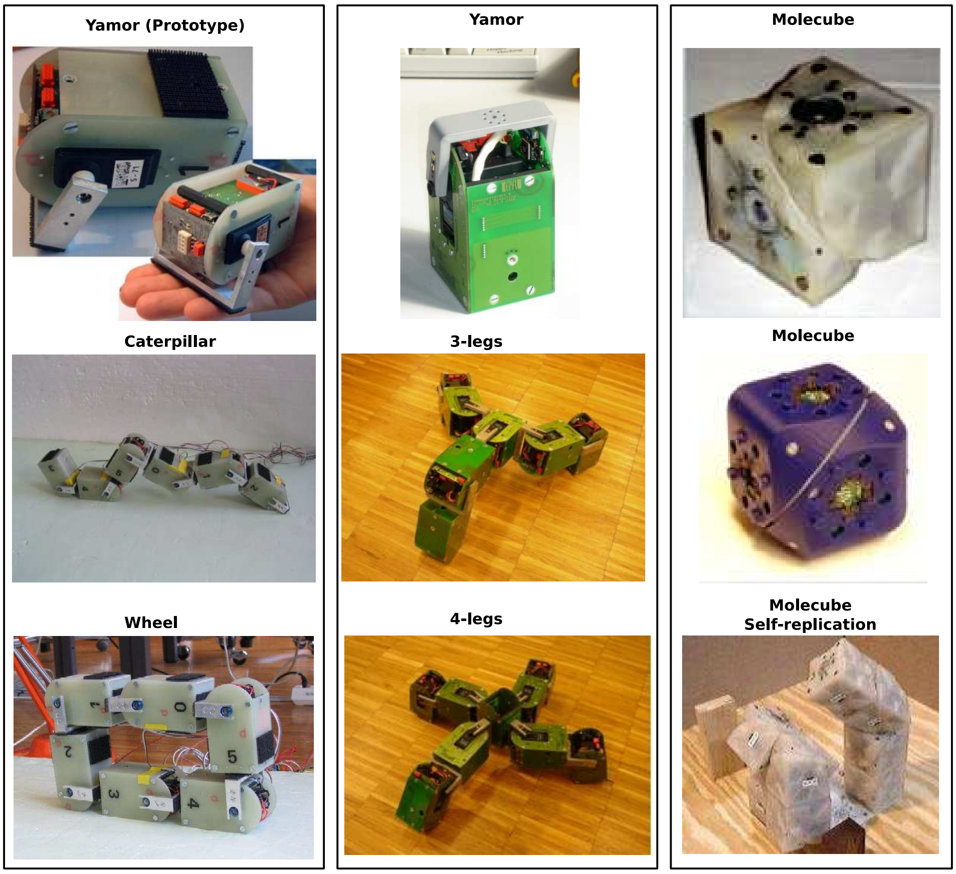

Figure 2.16: The modular robots Yamor and Molecube

2.5.8 Yamor

Yamor[17] (*Yet Another Modular Robot*) is the modular robot developed in the bio-inspired robotics laboratory of EPFL, to study adaptive locomotion[92]. The developed module has one degree of freedom activated by a servo and the communication between modules, and the modules with the PC is by Bluetooth, which means that there are no wires. The control hardware includes FPGAs (Field Programmable Logic Arrays) which gives the system greater versatility for the implementation of specific controllers. The software developed allows the generation of movement functions using a GUI (Graphical User Interface), which is then down-loaded to the hardware[91].

Maye et al.[89] applied the CPG models to the movement of modular robots, carrying out experiments with Yamor, thereby validating the previous simulations. Worm, tripod and quadruped configurations were tested.

Yerly et al.[154] are working on the following generation of modules, adding accelerometers and improving the software.

[17] More information in http://birg.epfl.ch/page53469.html/

In the figure 2.16 the two versions produced of Yamor and the various configurations tested, are shown. In the central part are the following versions of modules and the tripod and quadruped configurations.

2.5.9 Molecube

In the Cornell University CSL (Computational Synthesis Laboratory) the modules known as **Molecubes**[18]**[176]** have been developed. They have one level of liberty and form a cube. They differ from the rest in that they rotate on a diagonal axis, that unites two opposing points of the cube. When a 90 rotation is performed on this axis, another cube is obtained.

These modules are not adapted to resolve locomotive problems, though robots can be created with locomotive capacity. Their original purpose was to build **the first modular system capable of self replication[177]**. In the experiment that was performed, a tower composed of 4 molecubes, duplicated itself. For this another four modules were used as raw material for the duplication. The initial individual deposits its own modules in the places where the replica is to be created. Using the "raw material" supplied it self replicates. The final process ends after two and a half minutes. What is important is that the new copy can also duplicate itself. The new individual can create another, demonstrating that total self replication has been obtained (in behaviour as well as structure).

2.6 Modular Robots and Structures

Other area of investigation on the modular robots is **the capability to form structures that can be reconfigured**. In the figure 2.17 various of these prototypes are shown. The origins go back to 1988 with the proposal of Fukuda et al. **CEBOT**[32] (CEllular RObоT) developed at the Technology Institute of Tokyio. Each Cebot is treated as an autonomous cell that can move and join itself to others. Also the idea of a dynamically re-configurable robotics systems was developed[31]. This is a similar idea to the re-configurable robotics but it is applied to structures, instead of to locomotion. The system can be reorganised to carry out more complicated tasks. Each cell has its own knowledge (known as knowledge cells) and can use the knowledge of others. It is a system of distributed intelligence.

Chirikjian et al., of John Hopkins University PKL (*Protein Kinematics Lab.*) proposed the **metamorphic manipulators**[12]. It is a net of modules arranged in two dimensions that can move through a global structure because they have the ability to couple and uncouple with each other. Compared to CEBOT the modules can not move on their own, only being able to do so when connected to adjacent modules. The kinematics of these manipulators was studied[13] and their use was proposed for capturing satellites in space. Initially the manipulator has an undefined form, like an amoeba. By means

[18] The link for more information: http://www.molecubes.org/

Figure 2.17: Various lattice type modular robots

of the movement of some modules over others some tentacles appear that wrap round the object to be captured. Pamecha et al. implemented it in two modules, the robot was called **Metamorphic**[106]. Each module is of hexagonal shape and can warp by means of 3 actuators.

The idea of metamorphic manipulators was perfected by Murata et al., of the AIST, with the prototype **Fracta**[100]. The 'cells' are much simpler and do not have any actuators which means less consumption. To carry out the displacement and the coupling/uncoupling permanent magnets and electro-magnets are used. The same as Metamorphic, the structures that are formed are two dimensional.

The idea was enlarged with the building of three dimensional structures, and the designing of the robot **3D-Fracta**[101] with a cubic structure and six arms that join the centre with each one of the cube's faces. A total of 6 actuators are used. These investigations together with Mark Yim's idea of modular robotics were the seeds of the hybrid modular robot M-TRAN, that not only can move but also shape three dimensional structures.

Hamblin et al. created **Tetrobot[45]**, formed by a tetrahedral module with spherical articulations. The system is reconfigured manually. Experiments have been done with arms and walking robots.

At the CMU's Advanced Mechatronics Lab Unsal et al. developed the **I-CUBE** robot[54] formed by two elements: cubes (passive) and active segments. The segments have three degrees of freedom and are used as arms that hook onto the cubes. Different three dimensional structures can be built and they have the ability to modify themselves[19].

In the PARC, Suh et al. developed the **Telecubes** robot[137][20]. It is a cube with 6 prismatic articulations that allows it to move all of its faces. What is more all of the faces have a coupling/uncoupling system by which modules can be connected one to another, and disconnected. With this system very compact 3D structures can be created and can re-configure themselves.

The distributed robotics laboratory of MIT[21] is also interested in modular robots. Kotay et al. have created **Molecule**[71]. This robot imitates a two atom molecule, joined by a rigid segment. Each atom has 5 connectors to join it to other molecules and two degrees of liberty. The grouping of various molecules permits the creation of structures in two as well as three dimensions. In the first prototype only one molecule was implemented. Further work was done to improve the modules and a two molecule structure was implemented[69][70].

In the same laboratory, Rus et al. worked on **Crystal**[116], a configurable robot made up of atoms that can form two-dimensional structures. The atoms are four faced cubes that can expand. In contrast to other modular robots, where there is translation of the atoms, movement in this one is only obtained by expansion and compression [117].

[19] More information in http://www.cs.cmu.edu/~unsal/research/ices/cubes/
[20] More information in http://www2.parc.com/spl/projects/modrobots/lattice/telecube/index.html
[21] More information: http://groups.csail.mit.edu/drl/wiki/index.php/Main_Page

The latest prototype developed in the MIT is **Miche**[34]. The idea is completely different to the rest of the modular robots. It starts from the idea of an amorphous structure, as if it was a marble block in the world of sculpture. The user specifies the 3D form he wants to "sculpture". He makes the calculations and the system disconnects from the amorphous mass all the unnecessary modules. When the object is taken, the unused modules stay on the ground, leaving the created structure. The modules are cubes that only have the capacity to join themselves one with the other (they do not have any degrees of freedom). Among the experiments carried out a dog and a humanoid have been "sculptured".

In Denmark, at the the Maersk Mc-Kinney Moller Institute for Production Technology, work is being done on **ATRON**[60]. Starting with the ideas of CONRO and M-TRAN an spherical module has been created that can rotate around its equator, dividing the module into two semi-spheres that rotate, one in relation to the other. The modules can link together in such a way that the rotation can be made on any one of the three axis: x, y, z. In the latest version 100 of these modules have been created and diverse simulations and experiments have been realised[17].

Goldstein et al., of CMU, are developing the idea of synthesising real structures in three dimensions from virtual modules, within the project **Claytronics**[35][22]. The aim is the development of what is denominated a Claytronics: a computer generated synthetic object, but with a real physical structure. These systems are formed by atoms called **Catoms** (Claytronics Atoms) that can move in three dimensions in all the structure. By the re-combination of these atoms the Claytronic attains the desired shape. In the Miche prototype real structures are also synthesised, but the approach is that of a "sculpturer" that eliminates excess material. In the Claytronics' approach it is its own atoms that reorganise to create the object.

In the first phase work is being done on Catoms restricted to two dimensions [67]. The movement of these catoms is obtained through the correct co-ordination of electro-magnets, in such a way that not one type of actuator is needed. The aim is to be able to miniaturise to achieve nano robots of this type that can be relocated to form the Claytronics.

In the Bio Inspired Robotics Laboratory (BIRG) and learning algorithms (LASA) of EPFL an innovative concept has been suggested. Use three dimensional structures for creating furniture that can be reconfigured. The prototype of the proposed module is **RoomBot**[2][23] and is inspired in Yamor. In the figure 2.18 the shape of some of the furniture, made up of these modules, is shown. The desire is that the furniture forms part of the new centre that is being constructed. They are not only static, but also have the ability to move[24].

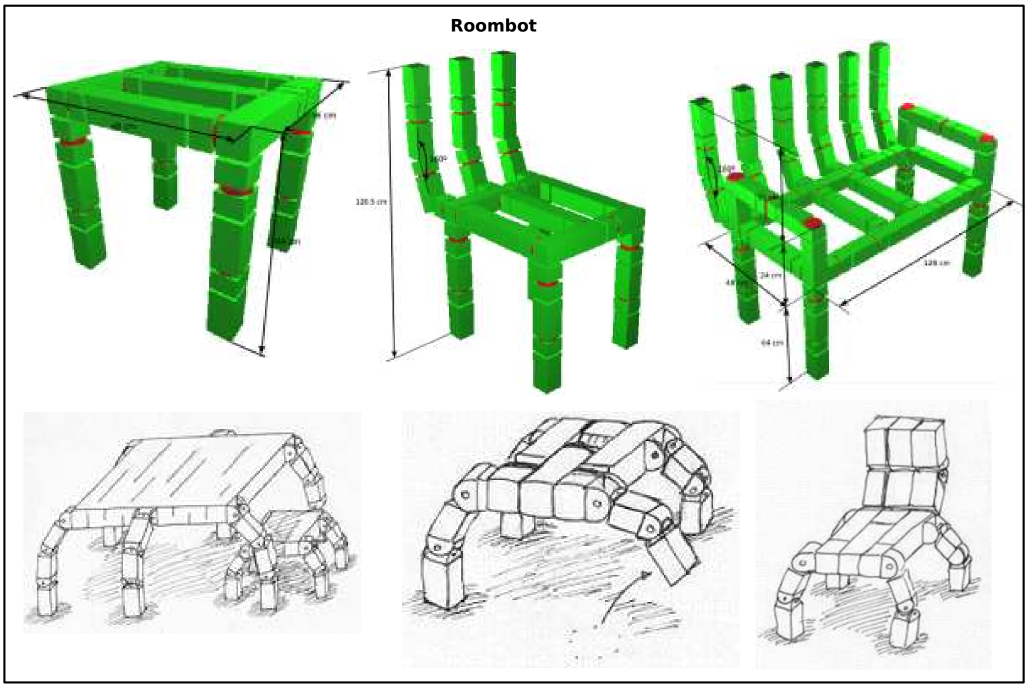

Figure 2.18: RoomBot prototype: a lattice modular robot designed to make re-configurable furniture

2.7 Classification of the modular robots

The figure 2.19 shows a clasification of the modular robots according to their structure and connections, that will be explained below. All the robots presented previously are placed in different groups.

To study the modular robots' locomotive property configurations it is essential to classify them by groups that share the same characteristics. The proposed classification is based on the structure and the connections between the modules. One must emphasise that the re-configurable modular robots can belong to different groups, due to the fact that various configurations can be built with them. For example, with the Polybot modules an apodal robot with connections pitch-pitch can be created; that is included among the robots with one dimensional topology. But also a quadruped with two dimensional topology can be built.

Mark Yim[163] proposes a basic division of three groups: reticule (lattice), chains and hybrids. The **lattice type** modular robots connect with each other to form structures, in the same way that atoms join together to form complex or solid molecules. They are the robots that have been described in the section 2.6. The idea behind all of them is to make structures that can dynamically modify themselves. According to the type of structure, they can be grouped as 2D or 3D. Among the first are

[22] More information in: http://www.cs.cmu.edu/~claytronics/hardware/planar.html

[23] More information: http://birg.epfl.ch/page65721.html

[24] Author's note: I am not very clear what use is this mobile furniture, nevertheless it seems to me an entertaining application. I would like to visit the centre to see the system in action ;-)

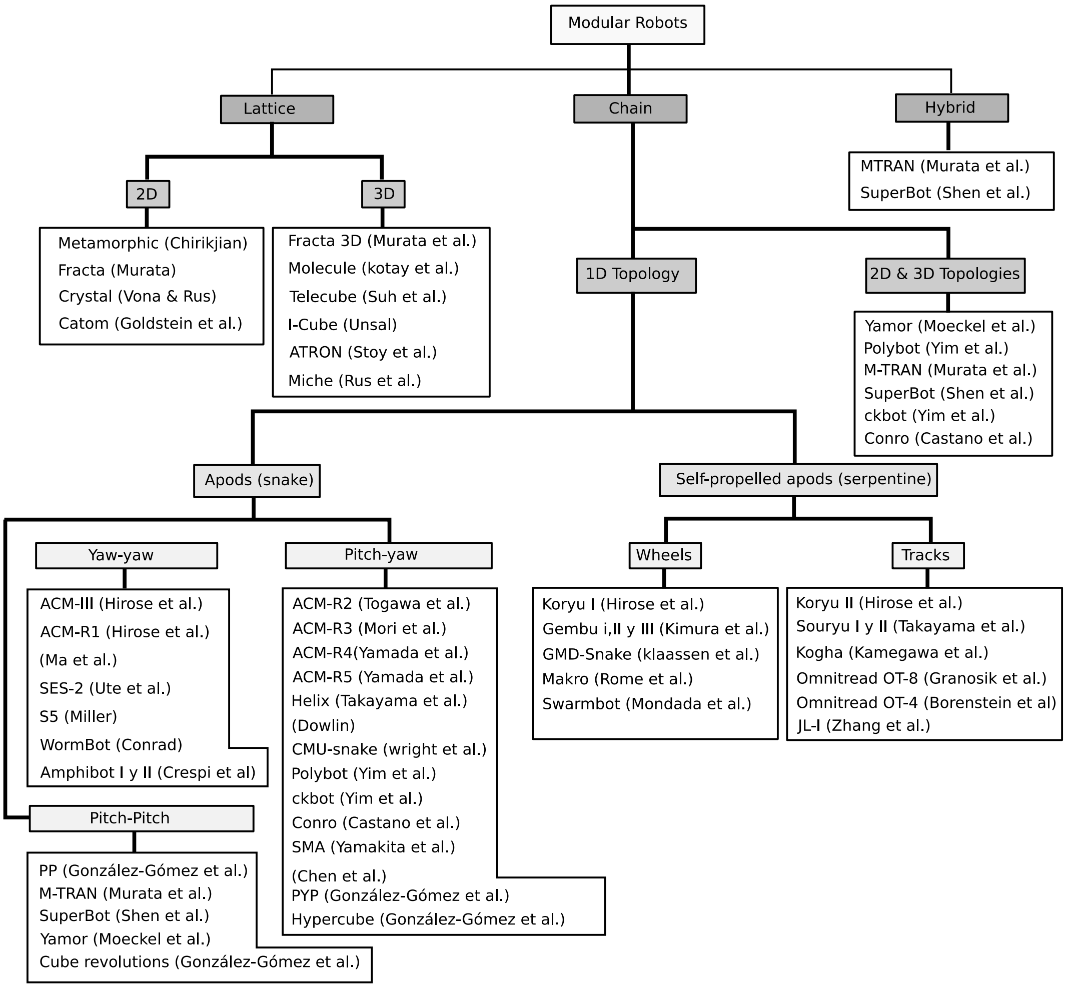

Figure 2.19: Classification of the modular robots

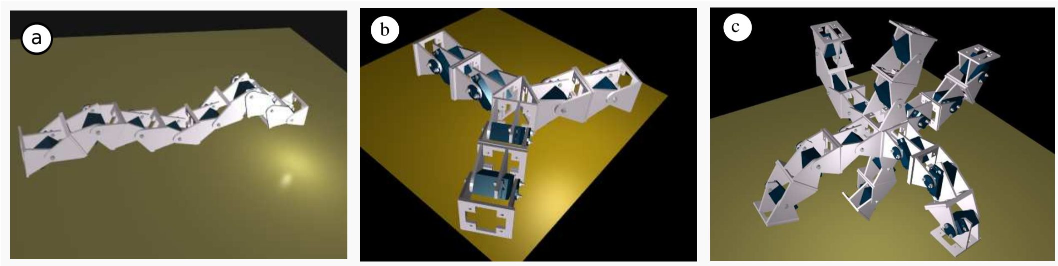

Figure 2.20: Example of the three sub-types of chain modular robots: a)1D Topology; b) 2D Topology 2D; c) 3D Topology 3D

Metamorphic[12], **Fracta**[100], **Crystal**[117] and **Catom**[67]. Among the second **Fracta 3D**[101], **Molecule**[71], **Telecube**[137], **I-Cube**[144], **ATRON**[60] and **Miche**[34].

The **chain type** modular robots are formed by uniting different chains of modules. For example the structure of a quadruped robot can be seen as made up of five chains: a central one that acts as the spine and four more for the extremities. The robots of this group are better for locomotion because they reconstruct animal morphology. The chains of modules can act like feet, arms, spine, etc. The lattice type robots, though they can also move, are much slower, as they are based not on the global movement of the structures, but on module to module movement. The **hybrid modular robots** possess the characteristics of both these groups: surfaces can be built with them as well as chain like structures. Within this group are found the most advanced modular robots, **M-TRAN**[102] and **SuperBot**[124].

At the same time, according to their topology, **chain type robots** can be divided. They can have a 1D topology, such as worms and snakes, 2D topologies, quadrupeds, polygonal structures such as stars, pentagons, etc., or 3D topologies such as hedgehogs. In the figure 2.20 can be seen an example of the different topologies. Once more it must be emphasised that the re-configurable robots can have configurations with different topologies, for this reason they can be placed in various groups. The criterion followed in the diagram has been to place the robots according to the experiments that have been carried out with them. For example, with Polybot the experiments have been with the quadruped configuration, therefore it has been included in the 2D topologies group, but it has also been tested with a worm configuration, therefore it is in the 1D topology group.

The **1D topologies** can be worms, snakes, arms, legs, spines, etc. In general these structures are very flexible and can adopt different shapes. They can, for example, be introduced into tubes, intestines or in general tortuous routes. If they are sufficiently long, they can form loops and move like a wheel[64][136].

According to how the propulsion to move the robot is generated, we propose two categories. One is what we call **apodal robots**[25] that comprises all the robots that move by means of body motions.

[25]Clarifying terminology: Granosik et al., proposed calling both groups of snake robots and serpentine robots. The first is what I baptised as apodal robots, and the second as self-propelled apodal robots

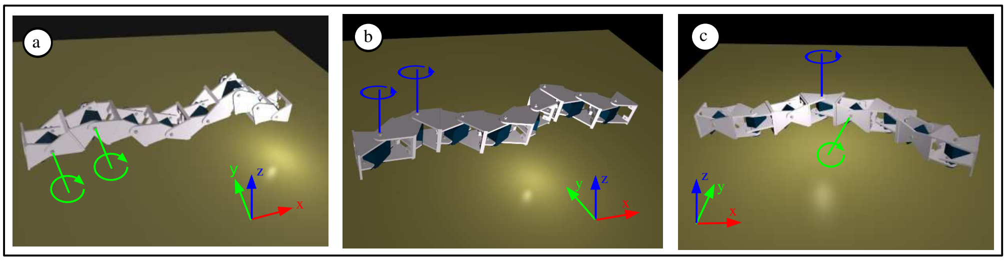

Figure 2.21: Different types of connections in the apodal robots a) Pitch-pitch. b) Yaw-yaw. c) Pitch-yaw.

The modules alone are unable to move, but when they are joined to form a chain and are adequately co-ordinated manage to do so. That would be the case of the biological worms and snakes. In another group are the robots that move by means of active wheels or caterpillar tracks. These are known as **self propelled apodal robots**. In these each module can move as an autonomous unit, using this system of propulsion. This group is employed in applications of search and rescue or inspection of tubes or bridges. Generally they are more industrial. As their mobility is by wheels or caterpillar tracks they can move across a wide variety of terrain. Being of 1D topology they possess the flexibility of this group and therefore can adapt their shape to the terrain, climb obstacles, go through tubes, etc.

Among the **apodal robots propelled by wheels** there is: **Koryu I**[52], **Gembu**[66], **GMD-Snake[68]**, **Makro** [111] and **Swarmbot** [94]. Among the **apodal robots propelled by caterpillar tracks**: **KoryuII**[53], **Souryu I** [138], **Souryu II**[140], **Kogha** [61], **Omnitread OT-8** [43], **Omnitread OT-4**[4] and **JL-I**[171].

In the **apodal robots group**, we propose classifying them according to how the modules are connected one to the other. As can be seen in the figure 2.21, the connection can be of yaw-yaw type (that is to say the modules rotate parallel to the ground), or pitch-pitch (they do it perpendicularly) and pitch-yaw where the modules that rotate parallel to the ground alternate with those that turn perpendicularly to the ground.

The connectivity between modules is a very important characteristic and determines what sort of movement can be carried out. Therefore, the **yaw-yaw group** is that that includes all the robots that move like snakes. This type of movement requires that the friction coefficient in the tangent to the body axis is very small while the normal is infinite (or the greatest possible). The snakes obtain this thanks to their scaly skin. The snake robots use passive wheels to fulfil this requirement. For this reason, this group is special. Not only does it need body movement but also the passive wheels or skins. They are, therefore, specific robots. If one takes generic modules (for example the Polybot) and builds a robot of this group, one cannot obtain locomotion without adding external elements.

Within this group are found all the robots that are developed based on the gait of snakes on the level. They are: **ACM-III**[47], **ACM-R1**[48], **(Ma et. al)**[82], **SES-2**[145], **S5**[90], **WormBot**[19] and **Amphibot I & II**[21].

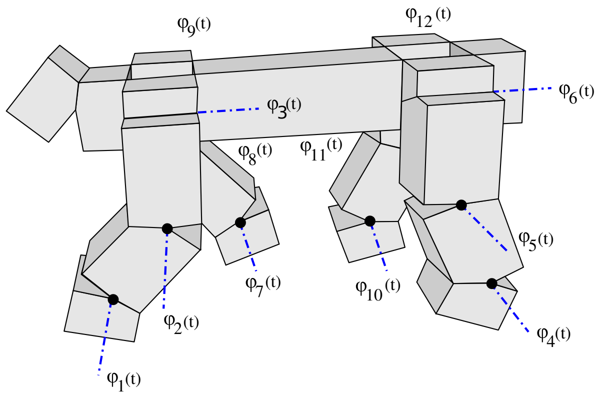

Figure 2.22: An example of the problem of co-ordination in a quadruped robot with 12 articulations. Finding the functions $\varphi_i(t)$ so that the robot can move

The **pitch-pitch group** only allows the robots to move in one dimension, forwards or backwards. It is a movement similar to the worms or caterpillars. They can also turn over on themselves to form a wheel. In this thesis this group of robots is used for a detailed study of one dimensional locomotion. The following robots have been subject to experiments with this type of connectivity: **M-TRAN**[102], **Polybot**[157], **Superbot**[124], **Yamor**[92], **PP**[40] and **Cube Revolutions**[39]. These last two carried out in this thesis.

The **pitch-yaw group** allows the robot to carry out many types of different movements, such as roll, side winding, climb, etc. Some of the robots already mentioned that have this type of connectivity are: **ACM-R2**[142], **ACM-R3**[96], **ACM-R4**[152], **ACM-R5**[142], **Helix**[139], **(Downlin)**[27], **CMU-snake[150]**, **Polybot**[157], **Ckbot**[165], **Conro**[8], **SMA**[153], **(Chen et al.)**[11], **PYP**[40] and **Hypercube**[42]. These last two created by the author in this thesis.

2.8 Co-ordination and locomotion

We have presented the state of the art of apodal and modular robots, and have classified them according to their structure and connectivity. In this section their control will be analysed. We will see what alternatives exist to resolve problems of co-ordination and which is the one we have employed in this thesis.

2.8.1 The problem of co-ordination

When a mobile robot has wheels or tracks, the lower level of locomotion does not present any problems. One only has to make the motors turn to obtain the movement. The difficulties appear in the superior level tasks, such as the planning of routes and navigation.

Nevertheless, if the robot is articulated and it either has feet or it is and apodal robot, the problem of co-ordination arises, even if the movement is on a flat surface without obstacles. It is necessary that all movements of the articulations are synchronised so that the robot can travel. This problem can be stated in the following way:

Co-ordination problem: *Given that a robot with M articulations find the functions $\varphi_i(t)$ that decide how it has to vary with time the angle of each articulation so that the robot manages to move.*

In the figure 2.22 an example of a quadruped modular robot can be seen, with two dimension topology and twelve articulations. The problem of the co-ordination will be solved if the functions $\varphi_1(t),\ldots,\varphi_{12}(t)$ are found and the value of its parameters with which the quadruped is capable of travelling. The solution depends on the gait that one desires to obtain: movement in a straight line, sideways, turns, etc., and in general it will not be the only one.

In the following sections the different ways of addressing the problem are presented.

2.8.2 First approach: Manual solution

To implement easily the locomotion in modular robots, Mark Yim used, in Polypod, what he called '**gait control tables**' [155]. The columns are vectors that contain an articulation's discrete position for each moment. The positions are kept in the files momentarily. The controller revises the tables, sending at each moment the position to the actuators. When it arrives at the last line it starts from the beginning, carrying out a repetitive movement.

When the modular robots do not have many modules and the movements are simple, these tables can be created manually. It permits the definition of sequences of movement "frame by frame", as if it were an animated film. This is the remedy adopted in the robot **Puchobot I**, developed by Prieto-Moreno[108]. Using a software with a graphic interface that runs in the PC, the user establishes the position of the articulations, that are recorded in the control table.

Another example is the hexapod robot **Melanie III** of Alonso-Puig[1]. The application that runs in the PC permits the manual generation of the sequences. The positioning of the articulations can be done either by the graphic interface itself (using sliders) or by using gestural programming, in such a way that the user places the robot's feet in the desired positions and the application records them.

The manual solutions allows for the prototypes of the robots to be tested during their construction and to detect at an early stage of design any possible mechanical problems. Also it allows to explore very quickly possible solutions for the co-ordination. Nevertheless, they lack flexibility. To enable the robot to move in different ways a new control table has to be created. Also, if the robot possesses a lot of articulations, its creation can be tedious and complex.

2.8.3 Approach II: Inverse Kinematics

The classic approach is based on the idea of employing inverse kinematics. The idea is to apply the same techniques used for manipulators, but to the robot's feet. The functions $\varphi_i(t)$ are obtained from the functions of the trajectory of the supporting points. This method has been studied in detail in hexapods by Fligliolini[30] and has been implemented in the Alonso-Puig robot Melanie[1]. The trajectories of the feet's extremities are specified by means of sinusoidal functions. Using inverse kinematics the position of the angles $\varphi_i(t)$ are obtained.

The apodal robots can be considered as hyper hiper-redundant manipulators, formed by infinite articulations. Chirjkjian[14] employs functions to describe the form that the manipulator must adopt and gets the angular expressions. Gonzalez et al.[41] have also explored this type of solution, but using what is denominated the adjustment algorithm, in which it iterates on the articulations and goes finding the angles so that all of them are placed on a curve. With these algorithms the control tables have been automatically created and have successfully moved an eight articulation apodal robot. Spranklin[132], in his doctoral thesis, studies the kinematics and the dynamics of an apodal robot of the pitch-pitch group and proposes a solution using classic controllers.

The inconvenience of the classic approach based on inverse kinematics is that it requires greater computing power compared with the bio-inspired approach, that will be discussed next. Therefore the bio-inspired controllers generally need less powerful (and cheaper) microprocessors for their implementation.

2.8.4 Approach III: Bio-inspired

Another approach is to use nature as a source of ideas, and try to imitate it. Living beings in the animal kingdom just move. Their brains do not seem to be constantly reading the position of their extremities (x,y,z), nor to use inverse kinematics to constantly contract their muscles.

In nature the vertebrates and invertebrates have special neurones called CPGs (*Central Pattern Generators*). These centres oscillate and produce rhythms that control muscle activity to carry out actions such as breathing, bowel movements, masticating, locomotion, etc. Based on biological studies mathematical models are constructed from these oscillators and they are applied to robots to control locomotion. In this bio-inspired approach the functions $\varphi_i(t)$ to be applied are obtained from the mathematical models of the CPGs. In contrast to the inverse kinematics approach, during the movement a bio-inspired controller does not know the position of its extremities. It only acts on the muscles to obtain locomotion. For this reason the computing power necessary is, in principal, less that that for approach II.

Figure 2.23: The lamprey used by the biologists to study its CPGs

2.8.4.1 CPGs and Biology

One of biology's investigation tasks is the physiology where, among other things, the mechanisms of living beings that carry out the basic functions, are studied, as for example walking. The existence of pattern generators was documented for the first time by Wilson[148] in his study on locust flight. In the experiment carried out by Shik et al. on de-cerebrated cats[127] in 1966, it was observed that a vertebrate's locomotion mechanism is situated in the spinal column, and was also based on pattern generators. The brain stimuli are not in charge of this movement, rather its "modulation". In 1980 Delcomyn[25] coined the term CPG to refer to this group of neurones that oscillate rhythmically.

Within this group of vertebrates, **the lamprey** (see figure 2.23) is the one that is most used to study CPGs, because its spinal column is transparent, contains few cells and lasts at least a week outside of the animal (in a saline solution) without deterioration. This allows the biologists to carry out experiments more easily[113].

Cohen proposed **a mathematical model for the lamprey's CPG**[18] and later Williams et al. carried out various experiments on the different phases observed that generated the patterns[147], and the effects on the co-ordination[129].

2.8.4.2 CPGs and Robotics

The fusion of different fields of investigation always illuminates and permits addressing the problems from another perspective. This has occurred with robotics and biology. One of the pioneers in applying CPG models to robotics has been Ijspeert, of EPFL's Bio-inspired Robotics Laboratory. In his doctoral thesis[55] he proposed neuronal models for the implementation of CPGs for lamprey and salamander locomotion, thereby placing the foundations for its posterior implementation in a real robot. By means of evolutive algorithms parameters are obtained for an optimal locomotion. In later work he continued carrying out simulations of his models[59] and in 2004, together with Crespi, implemented the first prototype of **amphibot**[21] (see section 2.3.4), demonstrating the viability of his bio-inspired model for robot locomotion.

In later work the model was improved and the transition from one of the salamander's gaits to the other has been investigated. This animal's characteristics is that it can swim and also move on land. Both gaits have been modelled, simulated and implemented in amphibot[57]. In [56] the problem of how to make a smooth transition has been studied.

The CPGs model has not only demonstrated its value in specific robot designs, such as amphibot, but is also being successfully employed in the movement of generic modules. The EPFL is leader in these matters. Bourkin carried out simulations of locomotion of a modular robot with different morphologies such as: wheel, worm, quadruped. All of them used CPGs[5]. Further improvements in the simulations were made by Marbach et al.[86][87], and the validations in the robot Yamour were carried out by Sproewitz et al. [133][134] and [89].

The CPGs model has also been successfully applied in the modular robot M-tran. Kamimura et al. used Matsuoka's CPGs model[88] to implement the locomotion of a worm and a quadruped[63].

The CPGs bio-inspired model is not only being used in modular robots, but also in locomotion for quadruped robots [33][130], in the eight footed robot Scorpion, and en in humanoid robots [28].

In the neuro-computation group of the Autonomous University of Madrid's Politechnic School Herrero et al. have modelled and implemented CPGs based on Rulkov's model[115] to control an eight segment worm robot [46]. The experiments were carried out with the Cube Revolution robot, developed in this thesis.

2.8.5 Approach IV: sinusoidal generators

The problem of co-ordination has been resolved by nature. Therefore it is "only" necessary to imitate it to obtain robot locomotion. Nevertheless in the biological mechanisms there is certain complexity as well as a lot of redundancy. Perhaps the answers appear to be very specialised or too "rich" supplying too much information could be unnecessary for robot locomotion.

In the field of neuro-computing all the neurons and CPGs are modelled in detail, the mathematics equations are obtained and then simulated later. Moreover, it is possible to try these models in real robots, with the aim of confirming if they are correct, comparing the locomotion of the artificial animal robots with the real ones. The aim of these experiments, therefore, is to confirm the value of the models. The robot is only a medium towards this end. Nevertheless, from the robotics perspective what happens is the opposite. The aim is to have a robot that can move in the best way possible, with the least consumption of power and resources. The neuro-computing models are used as inspiration and the necessary simplifications are applied.

Due to this, another way of addressing the problem of the co-ordination is **to employ solutions based on the simplest of CPGs models possible**, in such a way that their implementation is simple and needs the least resources. One possible simplification is **to substitute the CPGs by sinusoidal generators** that directly control the position of the robot's articulations, This simplification is workable for the study of robotics locomotion in a permanent regime, in that when the CPGs have reached the stationary regime, they behave like fixed frequency oscillators. What is more, observation of animal locomotion shows that the frequencies of the rhythmic movements are the same and there is no evidence that the different spinal oscillators use different frequencies[55][87].

One of the aims of this thesis is to explore the locomotion of apodal robots of the pith-pitch and pitch-yaw groups, using sinusoidal generators. This idea has been recently used for the movement of one dimensional topology robots to obtain smooth, natural, life like movements, as for example in the latest apodal robots of the CMU [81][150]. Chen et al. are using them to obtain movements that adapt to the surroundings [10]. Also the viability in two dimensional topology robots is being studied. Such is the case of the quadruped **PuchBot II[109]** in which Prieto-Moreno et al. have employed sinusoidal generators for movement in a straight line.

2.9 Modular robots applications

Modular robots have some characteristics that make them unique. Outstanding among them are movement flexibility, self repairing, self reproducing, self configuration and formation of solid structures.

Though these very advanced prototypes exist, as yet the possibility of their practical use is being explored. In the following section some of the references already given will be classified according to the three principal applications that are being evaluated.

- **Search and rescue**: [156][90][149][49][61][171].
- **Inspection of tubes and bridges:** [138][140][111][43][105]
- **Space exploration:** [162][131][124][77][79][141]

2.10 Conclusions

In this chapter we have seen the evolution of apodal modular robots and the latest prototypes that have been created in the most important international investigation centres. **The problem of locomotion** has been presented, and in contrast to the classical solutions using rigid structures with wheels, caterpillars or feet, the idea has arisen of using **self-configuring modular robots**, that are capable, at any moment, of changing their shape to be able to move in the most efficient way. Also modular robots have been developed that are orientated to the creation of two or three dimensional structures, in a similar way to matter being formed by atoms and molecules. This will allow, in future, creation of solid objects that can change their shape.

From the view point of structure, in the last decade interest has grown in **apodal robots**. They have a one dimension topology that gives them a unique locomotive capability, such as the possibility of deforming the body to go through tubes or areas with many nooks and crannies. These robots move by means of body movement, in a way reminiscent of snakes and worms. **Self-propelled apodal robots** have been developed to be used in practical applications, they also have a one dimension topology, but movement is obtained by means of wheels or caterpillar tracks situated on each module and not by means of body movement.

To sum up, **a classification for all the mentioned robots has been established**, using as a yardstick the structures that they can form and the connection between modules. The groups in which this thesis is interested are the **apodal robots of pitch-pitch** and **pitch-yaw type**. The robot group with connection yaw-yaw, similar to real snakes, has been studied fully by other investigators. These robots need special conditions of friction between the body and the surface they travel on, which means that in the existing prototypes passive wheels or artificial skins have been added. Nevertheless, in the other groups locomotion is obtained solely by means of body motions. Their study will permit that any generic modular robot that adopt a one dimensional topology can move without having to use special modules or artificial skins.

When the inferior level of modular robot locomotion is studied **the problem of co-ordination** arises. This consists in calculating the functions and the parameters that must be applied to each of the articulations so that the robot can move. One way of solving the problem and which has led to very good results is the **bio-inspired approach** based on using the **mathematical model of animal CPGs** as control functions.

From the viewpoint of biology the CPGs are studied to understand their functioning and to know more about living organisms. To do this measurements on different animals are carried out, and mathematical equations are proposed to model these CPGs, simulations are made and are recently being implemented in animal robotics to confirm if they are correct, That is to say, **biological knowledge is used as an instrument to validate the robots**. Investigation concentrates on obtaining data and the modelling of the CPGs.

Nevertheless, from the robotics point of view the contrary happens. The aim is to have a robot that can move in the best way possible, with the least consumption of power and resources. The biological models are used as inspiration and the necessary simplifications are applied. The internal parameters of the CPGs and the biological significance does not have such importance. For this reason the other approach to robotics locomotion is that **the robots employ simplified CPGs models**. In this thesis we propose a model for locomotion of apodal robots based on **sinusoidal generators**.

Although other investigators have constructed prototypes of apodal robots of the groups pitch-pitch and pitch-yaw, up to now their locomotion has not been addressed from a general perspective. The problems of direct and inverse kinematics have not been solved, neither has their locomotion been related to the number of the robot's modules. The following questions, therefore, are unanswered: *What is the minimum number of modules that a robot has to have to be able to move in one or two dimensions? What is the minimum number of control parameters necessary to obtain locomotion of the apodal robots, whatever the number of their modules? How to calculate the step that an apodal robot takes in function of the parameters employed in the sinusoidal generators? What amplitudes and differences of phase are to be applied to the modules' oscillations so that the robot fulfils the given restrictions?*

This thesis deals with, from a general perspective, the study of the apodal robot's locomotion, equally in one as in two dimensions. The relationship between the oscillators' parameters and the way in which they move the robot is established. A methodology is proposed to resolve the problems of inverse and direct kinematics and all the ideas are summed up in principals of locomotion. The **minimum configurations** are presented, that is the robots with the least number of modules that can move, with the movements they can make and the necessary control parameters' values. Finally experiments in simulation and with real modules have been carried out, that confirm the principles enunciated.

This thesis confirms the viability of using sinusoidal generators to control the permanent regime of the apodal robots locomotion. This allows the implementation of controllers using less resources than with the classical approaches and therefore they can be integrated into low range microprocessors, or directly as part of an FPGA's hardware.