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A Modular Architecture for Developing Robots for Industrial Applications

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Abstract

This chapter is concerned with proposing ways to make feasible the use of robots in many sectors characterized by dynamic and unstructured environments. In particular, we are interested in addressing the problem through a new approach, based on modular robotics, to allow the fast deployment of robots to solve specific tasks. A series of authors have previously proposed modular architectures, albeit mostly in laboratory settings. For this reason, their designs were usually more focused on what could be built instead of what was necessary for industrial operations. The approach presented here addresses the problem the other way around. In this line, we start by defining the industrial settings the architecture is aimed at and then extract the main features that would be required from a modular robotic architecture to operate successfully in this context. Finally, a particular heterogeneous modular robotic architecture is designed from these requirements and a laboratory implementation of it is built in order to test its capabilities and show its versatility using a set of different configurations including manipulators, climbers and walkers.

Keywords: Modular robots, industrial automation, multi-robot systems.

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1.1 Introduction

There are several industrial sectors, such as shipyards or construction, where the use of robots is still very low. These sectors are characterized by presenting dynamic and unstructured work environments where the work is not carried out in a chain production line, but rather, the workers have to move to the structures that are being built and these structures change during the construction process. Basically, these are the main reasons to explain the low level of automation in these sectors. Despite this, there are some cases in which robot systems have been considered in order to increase automation in these areas. However, they were developed for very specific tasks, that is, as specialists. Some examples are robots for operations such as grit-blasting [1, 2], welding [3], painting [4, 5], installation of structures [6, 7] or inspection [8, 9]. Nevertheless, their global impact on the sector is still low [10]. The main reason for this low penetration is the high cost of the development of a robot for a specialized task and the large number of different types of tasks that must be carried out in these industries. In other words, it is not practical to have a large group of expensive robots, each one of which will only be used for a particular task and will be doing nothing the rest of the time.

In the last few years, in order to increase the level of automation in the aforementioned environments, several approaches have been proposed based on multi-component robotics systems as an alternative to the use of one robot for each task [11–13]. These approaches seek to obtain simple robotic systems capable of adapting, easily and quickly, to different environments and tasks according to the requirements of the situation.

Multi-component robotic systems can be classified into three categories: distributed, linked and modular robots [14]; however, in this work, only the last category will be taken into account. Thus, we explore an approach based on modular robotics, which basically seeks the re-utilization of pre-designed robotic modules. We want to develop an architecture that with a small set of modules can lead to many different types of robots for performing different tasks.

In the last two decades, several proposals of modular architectures for autonomous robots have been made [15, 16]. An early approach to modular architectures resulted in what was called ‘modular mobile robotic systems.’ These robots can move around the environment, and they can connect to one another to form complex structures for performing tasks that cannot be carried out by a single unit. Examples are CEBOT [17] or SMC-Rover [18]. Another type of modular architecture is lattice robots. These robots can form compact three-dimensional structures or lattices over which one module or a set of them can move. Atron [19] and Tetrobot systems [20] are examples of this architecture.

A different approach to modularity is provided by the so-called chain-based architecture, examples of which are modular robots such as Polybot [21], M-TRAN [22] or Superbot [23]. This kind of architecture has shown its versatility in several tasks such as carrying or handling payloads, climbing staircases or ropes or locomotion in long tests or in sandy terrains [24–26]. In addition, some of them were designed specifically for dynamic and unstructured environments. This is the case of the Superbot system, which was developed for unsupervised operation in real environments, resisting abrasion and physical impacts, and including enhanced sensing and communications capabilities.

However, and despite the emphasis on real environments, they are mostly laboratory concept testing approaches with an emphasis on autonomous robots and self-reconfigurable systems rather than on. That is, these architectures were not designed to work in industrial settings and, consequently, their components and characteristics were not derived from an analysis of the needs and particularities of these environments. In fact, they are mostly based on the use of a single type of module to simplify their implementation. Additionally, these homogeneous architectures lead to the need of using a large number of modules to perform some very simple tasks.

On the other hand, we can find another expression of modular robotics, which appears as a result of the addition of modularity to robot architectures. An example is modular manipulators which have mostly been studied for their use in industrial environments. These types of manipulators can be re-coupled to achieve, for example, larger load capacities or to extend their workspace. Most of them can obtain a representation of their morphology or configuration and automatically obtain their direct and inverse kinematics and dynamics. There are homogeneous architectures and there are also architectures with modules specialized in different movements but mainly with rotational joints. Nevertheless, they are usually aimed at static tasks [27, 28] and are much less versatile than real complete modular architectures. In this line, companies such as Schunk Intec Inc or Robotics Design Inc. are commercializing products inspired by this last approach. Both companies have developed modular robotic manipulators with mechanical connections, but these manipulators still need an external control unit configured with the arm's topology.

Currently, new research lines have emerged proposing models that take characteristics of the two areas commented above. For example, some research groups have begun to propose complete versatile heterogeneous modular systems that are designed with industrial applications in mind. An example of this approach is the work of [29] and their heterogeneous architecture. These authors propose a heterogeneous architecture, but in its development, they concentrate on using spherical actuators with 3 degrees of freedom and with a small number of attachment faces in each module. Similarly, other authors have proposed the use of a modular methodology to build robots flexibly and quickly with low costs [30]. This architecture is based on two different rotational modules and several end-effectors such as grippers, suckers and wheels or feet. It has shown its strong potential in a wall-climbing robot application [31]. These approaches are quite interesting, but they still lack some of the features that would be desirable from a real industrially usable heterogeneous modular architecture. For instance, the actuator modules in the first architecture are not independent; they need a power and communications module in order to work. The second system only allows serial chain topologies, which reduces its versatility, or the robot is not able to recognize its own configuration in both architectures.

In this chapter, we are going to address in a top-down manner the main features a modular robotic system or architecture needs to display in order to be adequate for operation in dynamic and unstructured industrial environments. From these features, we will propose a particular architecture and will implement a reduced scale prototype of it. To provide an idea of its appropriateness and versatality, we will finally present some practical applications using the prototype modules.

The rest of the chapter is structured as follows: Section 2 is devoted to the definition of the main characteristics the proposed architecture should have to operate in industrial environments and what design decisions will be taken. Section 3 contains different solutions we have adopted through the presentation of a prototype implementation. Section 4 shows different configurations that the architecture can adopt. Finally, Sections 5 and 6 correspond to the introduction of this architecture in real environments and the main conclusions of the chapter, respectively.

1.2 Main Characteristics for Industrial Operation and Design Decisions

Different aspects need to be kept in mind to decide on a modular robotic architecture for operation in a set of industrial environments. On the one hand, it is necessary to determine the types of environments the architecture is designed for and their principal characteristics, the missions the robots will need to perform in these environments and the implications these have on the motion and actuation capabilities of the robots. Obviously, there are also a series of general characteristics that should be fulfilled when considering industrial operation in general. Consequently, we will first start by identifying here the main features and characteristics a modular architecture should display in order to be able to handle a general dynamic and unstructured industrial environment. This provides the requirements to be met by the architecture so that we can address the problem of providing a set of solutions to comply with these requirements. An initial list of required features would be the following:

- Versatility: The system has to allow to easily build a large number of different configurations in order to adapt to specific tasks;
- Fast deployment: The change of configuration or morphology has to be performed easily and in a short time so that robot operation is not disrupted;
- Fault tolerance: In case of the total failure of a module, the robot has to be able to continue operating minimizing the effects of this loss;
- Robustness: The modules have to be robust to allow working in dirty environments and resisting external forces;
- Reduced cost: The system has to be cheap in terms of manufacturing and operating costs to achieve an economically feasible solution;
- Scalability: The system has to be able to operate with a large number of modules. In fact, limits on the number of modules should be avoided.

To fulfil these requirements, a series of decisions were made. Firstly, the new architecture will be based on a modular chain architecture made up of heterogeneous modules. This type of architecture has been selected because it is well known that it is the general architecture that maximizes versatility. On the other hand, using homogeneous modules is the most common option in modular systems [15, 16, 21–23], because it facilitates module reuse. However, it also limits the range of possible configurations and makes the control of the robot much more complex. In the types of tasks we are considering here, there are several situations that would require a very simple module (e.g., a linear displacement actuator), but which would be very difficult (complex morphology), or even impossible in some cases, to obtain using any of the homogeneous architectures presented. Thus, for the sake of flexibility and versatility, we have chosen to use a set of heterogeneous modules (specialized modules for each type of movement). This solution makes it easier for the resulting robots to perform complex movements as complex kinematic chains can be easily built by joining a small set of different types of modules. Moreover, each module was designed to perform a single basic movement, that is, only one degree of freedom is allowed. This permits using simple mechanisms within the modules, which increases the robustness of the system and reduces the operating and manufacturing costs.

Having decided on the nature of the architecture, now the problem is to decide what modules would be ideal in terms of having the smallest set of modules that covers all possible tasks in a domain. In addition, it should be taken into account that the number of different types of modules needs to be low in order to accomplish the scalability and reduced production cost requirements. To do this, we chose to follow a top-down design strategy. To this end, we studied some typical unstructured industrial environments (shipyards) and defined a set of general missions that needed automation. These missions were then subdivided into tasks and these into operations or sub-tasks that were necessary. From these we deduced the kinematic pairs and finally a simple set of actuator and end-effector modules that would cover the whole domain was obtained. This approach differentiates the architecture presented here from other systems, which are usually designed with a bottom-up strategy (the modules are designed as the first step and then the authors try to figure out how they can be applied).

We have only considered five general types of modules in the architecture:

- Actuators: Modules with motors to generate the robot's motions;
- Effectors: Modules to interact with the environment such as magnets, suckers or grippers;
- Expansion: Modules that increase computational capabilities, memory or autonomy through batteries;
- Sensors: Modules to measure and obtain data from the environment such as cameras and infrared or ultrasonic sensors;
- Linkers: Modules used to join other modules mechanically.

The architecture incorporates these five types of modules, but in this work, we have focused only on the actuator modules. They are the ones around which the morphological aspects of the robots gravitate, and we only employ other modules when strictly necessary to show application examples. Therefore, each module includes a processing unit, one motor, a battery, capabilities to communicate with other modules and the necessary sensors to control its motions. This approach permits achieving a fast deployment of functional robots and their versatility as compared to cases where they require external control units.

The process followed to decide on the different actuator modules corresponds with a top-down design process as presented in Figure 1.1. As a first step, we have considered three basic kinds of general mission the modular robot could accomplish. These are the surface, linear and static missions (top layer). Surface missions are those related with tasks requiring covering any kind of surface (like cleaning a tank). Linear missions are those implying a linear displacement (like weld inspection) and Static missions are those where the robotic unit has a fixed position (like an industrial manipulator).

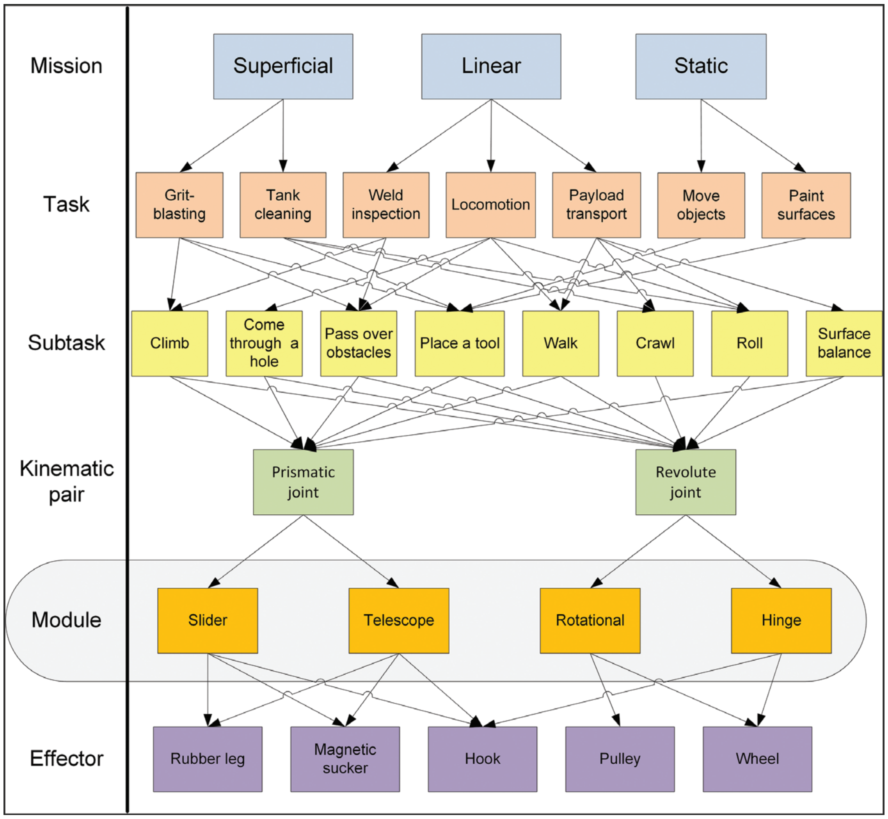

Figure 1.1 Diagram of the selected missions, tasks and sub-tasks considered, and the required actuators and effectors.

The next layer shows the set of possible particular tasks we have considered as necessary according to the previous types of mission, such as grit-blasting, tank cleaning etc. The sub-task layer represents the low-level operations the modular system must carry out to accomplish the task of the previous layer. The next layer represents the kinematic pairs that can be used to perform all the sub-tasks of the last layer. As mentioned above, these pairs only have one degree of freedom. In this case, we have only chosen two kinds of kinematic pairs: prismatic and revolution joints. Nevertheless, each joint was implemented in two different modules in order to specialize the modules to different motion primitives. For the prismatic joint, we have defined a telescopic module with a contraction/expansion motion and a slider module with a linear motion over its structure. The revolution joint also leads to two specialized modules: a rotational module where the rotational axis goes through the two parts of the module, like in wheels or pulleys, and a hinge module. Finally, in the last layer we can see five examples of different effector modules.

Once the actuator modules have been defined, we have to specify the shape or morphology and the connecting faces of each module. Also, and again to increase the versatility of the architecture, each module has been endowed with a large number of attachment faces. This also permits reducing the number of mechanical adapters needed to build different structures. The distribution of the attachment faces will be located on cubic nodes or connection bays within each module. This solution allows creating complex configurations, even closed chains, with modules that are perpendicular, again increasing the versatility of the architecture.

These mechanical connections have to be easily operated in order to allow for the speedy deployment of different configurations. To this end, each attachment face has been provided with mechanisms for transmitting energy and communications between modules in order to avoid external wires. We have also included mechanisms (proprioceptors) that allow the robot to know its morphology or configuration, that is, what module is attached to what face. This last feature is important because it allows the robot to calculate its direct and inverse kinematics and dynamics in order to control its motion in response to high-level commands from an operator.

The robots developed have to be connected to an external power supply with one cable to guarantee the energy needed by all the actuators, effectors and sensors. Nevertheless, the energy is shared among the modules to avoid wires form module to module. In addition, each module contains a small battery to prevent the risk of failure by a sudden loss of energy. These batteries, combined with the energy bus between the modules, allow the robot to place itself in a secure state, maximizing the fault tolerance and the robustness of the system.

Finally, for the sake of robustness, we decided that the communications between modules should allow three different communication paths: a fast and global channel of communications between all the modules that make up a robot, a local channel of communications between two attached modules and a global and wireless communication method. These three redundant channels allow efficient and redundant communications, even between modules that are not physically connected or when a module in the communications path has failed.

Summarizing, the general structure of a heterogeneous modular robotic architecture has been obtained from the set of requirements imposed by operation in an industrial environment and the tasks the robots must perform within it. It turns out that given the complexity of shipyard environments, on which the design was based, the design decisions that were made have led to an architecture that can be quite versatile and adequate for many other tasks and environments. In the following section, we will provide a more in-depth description of the components of the architecture and their characteristics as they were implemented for tests.

1.3 Implementation of a Heterogeneous Modular Architecture Prototype

In the previous section, the main features and components of the developed architecture were presented. Here we are going to provide a description of the different solutions of actuator modules we have adopted through the presentation of a prototype implementation. Throughout this section, the design and morphology of the modules will be explained as well as the different systems needed for it to operate, such as the energy supply system, communications, control system, etc.

Figure 1.2 displays some of the different types of modules that were developed. On the left part, it presents some of the effectors, on the top a linker, a slider on the right and a rotational module, a telescopic module and a hinge in the center. The different modules (actuators, linkers and effectors) have been fully designed and a prototype implementation has been built for each one of them. They all comprise nodes built using fiber glass from milled printed circuit boards (PCBs). These parts are soldered to achieve a solid but lightweight structure. Each module is characterized by having one or more

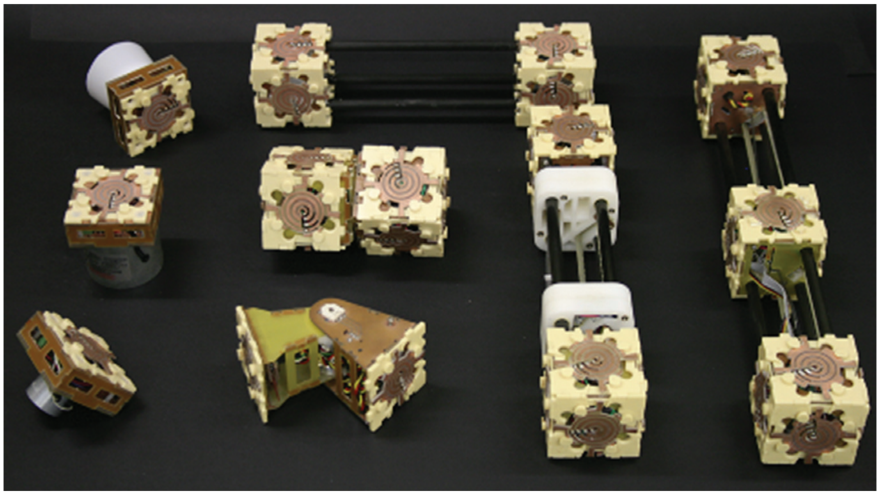

Figure 1.2 Different types of modules developed in this project: three effectors on the left part, a linker on the top, a slider on the right, and in the middle there is a rotational module, a hinge module and a telescopic module.

nodes, which act as connections bays. The shape of the nodes varies depending on the type of module (e.g., it is a cube for the nodes of the slider and telescopic modules). All of the free sides of these nodes provide a connection mechanism that allows connecting them to other modules. The size of the nodes without the connection mechanism is 48x48x48 mm; it is 54x54x54 mm including the connectors.

1.3.1 Actuator Modules

To develop the prototype of the architecture, four different types of actuator modules have been built in accordance to the main features of the architecture described in the previous section. The modules only present one degree of freedom in order to increase robustness and they have different types of joints so that it is easy to build most of the kinematic chains used by real robotic systems in industry. To this end, two linear actuators (slider and telescopic modules) and two rotational actuators (rotational and hinge modules) have been developed. In the case of linear actuators, the slider module has a central node capable of a linear displacement between the end nodes. Any other module can be connected to this central node. The telescopic module only has two nodes and the distance between them can be modified.

On the other hand, the rotational modules have two nodes and allow their relative rotation. These modules are differentiated by the position of the rotation shaft. Whereas the rotational axis of the rotation module goes through the center of both modules, in the hinge it is placed in the union of both nodes and perpendicularly to the line connecting their centers. The main characteristics of the actuator modules are described in Table 1.1.

1.3.1.1 Slider module

This module has two end nodes that are joined together using three carbon fiber tubes and an additional node that slides along the tubes between the end nodes. The distance between the end nodes is 249 mm and the stroke of the slider node is 189 mm. One of the end nodes has a servo with a pulley, which moves a drive belt. The node on the other end has the return pulley and the slider node is fixed to the drive belt. The central node contains the electronics of the module, with power and data wires connecting it to one of the end nodes. There is also a mechanism that coils the wires to adapt them to the position of the slider node.

1.3.1.2 Telescopic module

The telescopic module has two nodes and the distance between them can increase or decrease. Each node has two carbon fiber tubes attached to it. There is an ABS plastic part at the end of the tubes. These parts have two holes with plain bearings to fit the tubes of the other node. One node contains a servo with a drive pulley and the return pulley is in the ABS part of this node. The drive belt that runs in these pulleys is connected to the ABS part of the opposite node. The other node has the electronic board.

1.3.1.3 Rotational module

This module has two nodes that can rotate with respect to each other. A low friction washer between the nodes and a shaft prevents misalignments. One

Table 1.1 Actuator Modules

	Slider	Telescopic	Rotational	Hinge
Type of movement	Linear	Linear	Rotational	Rotational
Stroke	189mm	98mm	360º (1 turn)	200º
Nº nodes	3	2	2	2
Nº connection faces per node	5–4-5	5–5	5–5	1–1
Weight	360g	345g	250g	140g

node carries a servo with a gear that engages another gear coupled to the shaft. The reduction ratio is 15:46. The servo is modified and its potentiometer is outside attached to a shaft that is operating at a 1:2 ratio with respect to the main shaft. This configuration permits rotations of the module of 360º.

1.3.1.4 Hinge module

This module does not have any connection bay in its structure, only one connection mechanism in each main block. A shaft joins two main parts built from milled PCBs. These parts rotate relative to each other. The reduction of the servo to the shaft is 1:3. The potentiometer of the servo is joined to the shaft to sense the real position of the module.

1.3.2 Connection Mechanism

Different types of physical couplings between modules can be found in the literature, including magnetic couplings, mechanical couplings or even shape memory wires. In this work, we have decided to use a mechanical connection due to the high force requirements in some tasks and due to the power consumption of other options, like in the case of magnetic couplings.

Several mechanical connectors have been developed for modular robots, but most designers focus their efforts in the mechanical aspects, paying less attention to power transmission and communications between modules. Here we have designed a connection mechanism that is able to join two modules mechanically and, at the same time, transmit power and communications. Currently, the connector is manually operated, but its automation is under development.

The connector design can be seen in Figure 1.2 and it has two main parts: a printed circuit board and a resin structure. The resin structure has four pins and four sockets to allow four connections in a multiple of 90 degrees like in [16] and [27]. Inside the resin structure, there is a PCB that can rotate 15 degrees. The PCB has to be forced to fit inside the resin structure, so the PCB remains fixed. When two connectors are faced, the rotation of the PCB of one connector blocks the pins of the other one, and vice versa. The space between the pins of the two connectors is the same as the thickness of the two connector PCBs.

The PCB has four concentric copper tracks on the top side. A mill breaks these tracks in order to provide a cantilever. A small quantity of solder is deposited in the end of the cantilever track. When two connectors are attached, this solder forces the cantilever tracks to bend, so a force is generated. This force maintains the electrical contacts fixed even under vibrations.

Two of the tracks are wider than the other two because they are employed to transmit power (GND and +24V). The other two tracks are employed to transmit data: a CAN bus and local asynchronous communications. The local asynchronous communications track in each connector is directly connected to the microcontroller, while the other tracks are shared for all the connectors of the module. To share these tracks in the node, we choose a surface mount and insulating displacement connector placed at the bottom of the PCB. This solution is used to serially connect the PCBs of the node together in a long string and it allows two modules on the same robot to communicate even in the case of a failure in a module in the path of the message.

1.3.3 Energy

A need for the modular system to require a wire or tether to obtain power or perform communications would limit the resulting robots' motions and their independence. Therefore, one aim of this work is for the architecture to allow for fully autonomous modular robots. This is achieved by means of the installation of batteries in each module and, when the robot needs more power, expansion modules with additional batteries can be attached to it. However, in industrial environments it is often the case that the tools the robots need to use do require cables and hoses to feed them (welding equipment, sandblasting heads, etc.) and, for the sake of simplicity and length of time the robot can operate, it makes a lot of sense to use external power supplies. For this reason, the architecture also allows for tethered operation when this is more convenient, making sure that the power line reaches just one of the modules and then it is internally distributed among the rest of the modules.

The modules developed in this work are powered at 24V, but each module has its own dc converter to reduce the voltage to 5V to power the servomotors and the different electronic systems embedded in each module.

1.3.4 Sensors

All of the modules contain specific sensors to measure the position of their actuator. To this end, the linear modules have a quadrature encoder with 0.32 mm accuracy in their position. The rotational modules are servo controlled, so it is not necessary to know the position of the module. But, in order to improve the precision of the system, we have added a circuit that senses the value of the potentiometer after applying a low pass filter.

Furthermore, all the modules have an accelerometer to provide their spatial orientation. In addition, the local communications established in each attachment face permit identifying the type and the face of the module that is connected to it. This feature, combined with the accelerometer, allows determining the morphology and attitude of the robot without any external help.

All the above-mentioned sensors are particular to each individual module. It means that they only get the data from the module as well. Nevertheless, to perform some tasks (welding, inspection, measuring, etc.), it is necessary to provide to the robot with specific sensors such as camera, ultrasound sensor or whatever. These specific sensor modules are attached to the actuator module that requires it. They are basically nodes (morphologically similar to the rest of the nodes in most modules) with the particular sensor and the processing capabilities to acquire and communicate the data from the particular sensor.

1.3.5 Communications

One of the most difficult tasks in modular robotics is the design of the communications systems (local and global). On the one hand, it has to ensure the adequate coordination between modules, and on the other hand, it has to be able to respond quickly to possible changes in the robot's morphology. That is, it has to adapt when a new module is attached, unattached or even when one module fails. The robot's general morphology has to be detected through the aggregation of the values of the local sensing elements in each module as well as the information they have on the modules they are linked to. For this, we use an asynchronous local communications line for inter-module identification (morphological proprioception).

On the other hand, a CAN bus is used for global communications. It allows performing tasks requiring a critical temporal coordination between remote modules. Also, a MiWi wireless communications system is implemented as a redundant system that is used when we have isolated robotic units or when the CAN bus is saturated.

Additionally, all the modules, except the rotational one, have a micro-USB connection to allow communications to an external computer. This feature and a boot loader allow us to employ a USB memory to load the program without the use of a programmer for microcontrollers. Figure 1.3 shows the printed circuit board (PCB) of the slider module containing all the communications elements.

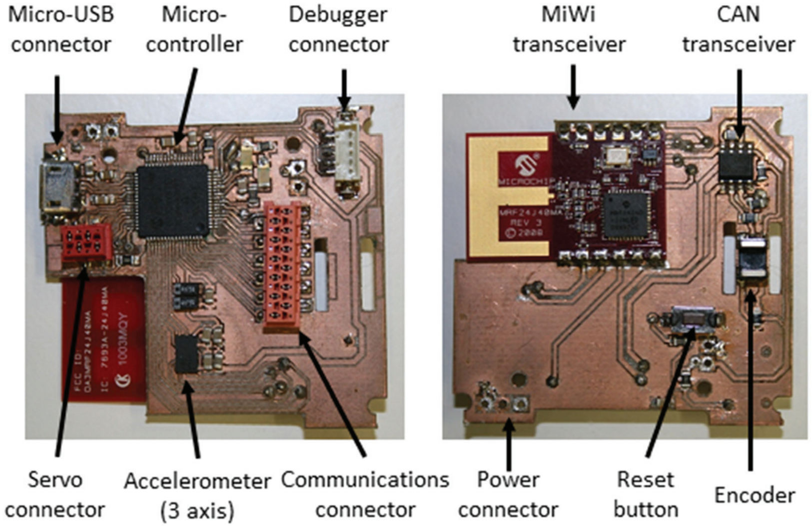

Figure 1.3 Control board for the slider module and its main components.

1.3.6 Control

The system control is responsible for controlling and coordinating all the local tasks within each module, as well as the behaviour of the robot. To do this, in this work, each module carries its own electronics board with its micro-controller (PIC32MX575F512) and a DC/DC converter for power supply. The micro-controller is responsible of the low-level tasks of the module: controlling the actuator, managing the communications stacks and measuring the values of its sensors. As each actuator module has its own characteristics (number of connection faces, encoder type, etc.) and the available space inside the modules is very limited, we have developed a specific PCB for each kind of actuator module. As an example, Figure 1.3 shows the top and bottom side of the control board for the slider module.

Besides the low-level tasks, this solution permits choosing the type of control to be implemented: centralized or distributed. While in a distributed control scheme, each of the modules contributes to the final behaviour through the control of its own actions depending on its sensors or communications to other modules. In a centralized control scheme, one of the modules would be in charge of controlling the actions of all the other modules, with the advantage of having redundant units in case of failure. Additionally, all modules employ the CAN bus to coordinate their actions and to synchronize their clocks. Obviously, this architecture allows for any intermediate type of control scheme.

1.4 Some Configurations for Practical Applications

In this section, we will implement some example configurations using the architecture to show how easy it is to build different types of robots as well as how versatile the architecture is. For the sake of clarity and in order to show the benefits of a heterogeneous architecture, we will show simple configurations developed with only a few modules (videos of these configurations can be found in vimeo.com/afaina/ad-hoc-morphologies).

All the experiments were carried out with the same setup. First, the modules were manually assembled in the configuration to test and we connected one cable for power supply and an USB cable to connect one module to a laptop. After powering up the system, the module that communicates to the laptop is selected as a master module. This master module uses the CAN bus to find other connected modules. Then, it uses the asynchronous communications and the orientation of each module to discover the topology of the robot.

1.4.1 Manipulators

One of the most important pillars of industrial automation are manipulators. Traditional manipulators present a rigid architecture, which complicates their use in different tasks, and they are very heavy and big to be transported in dynamic and unstructured environments. Nevertheless, modular manipulators can be very flexible as they can be entirely reconfigured to adapt to a specific task and the modules can be transported easily across complex environments and then they can be directly assembled on the workplace.

The configuration choice of the manipulator is highly application dependent and it is mostly determined by the workspace shape and size, as well as other factors such as the load to be lifted, the required speed, etc. For instance, the different types of modules in the architecture can also be used to easily implement spherical or polar manipulators. These type of manipulators present a rotational joint at their base and a linear joint for the radial movements as well as another rotational joint to control their height. Thus, a spherical manipulator is constructed using just five modules as shown in the pictures of Figure 1.4. This robot has a magnetic effector to adhere to the metal surface: a rotational module, a hinge module and a prismatic module for motion and a

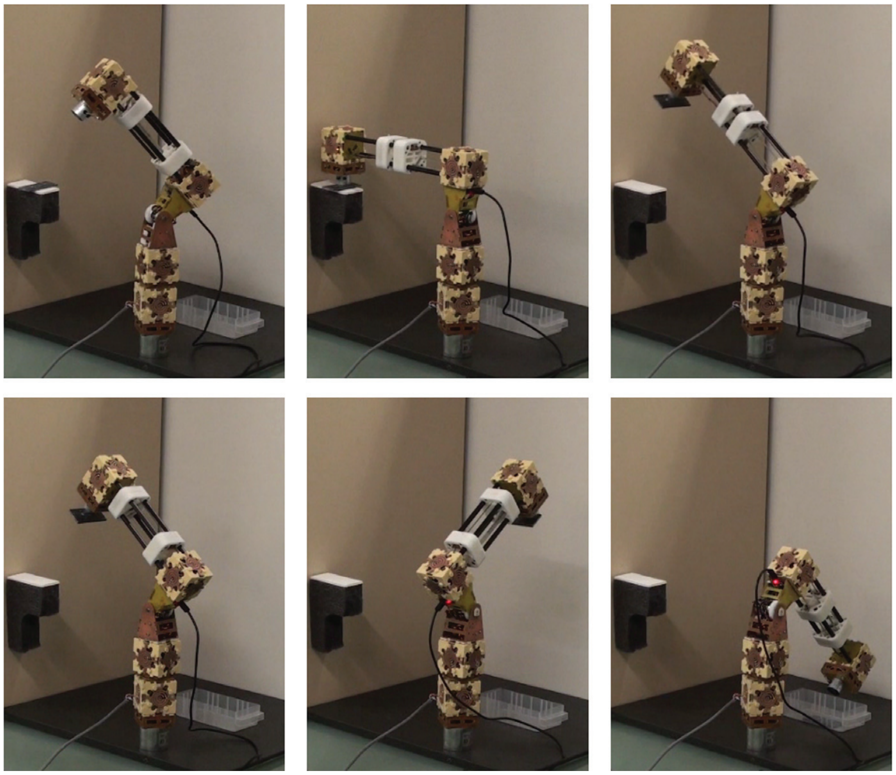

Figure 1.4 Spherical manipulator moving a load from one place to another.

final magnetic effector to manipulate metal pieces. We can see how the robot is able to take an iron part using the electromagnet placed at the end of the manipulator and carry it to another place. The whole process takes around 10 seconds.

Another very common type of manipulator is the cartesian robot. They are constructed using just linear joints and are characterized by a cubic workspace. The ease with which it is possible to produce speed and position control mechanisms for them, their ability to move large loads and their great stability are their major advantages.

An example of a very simple and fully functional cartesian robot is displayed on the left image of Figure 1.5. It is constructed using only two linear modules and a telescopic module for the implementation of its motions, two magnetic effectors to adhere to the metal surface and a smaller magnet that is used as a final effector. The two large magnets used to adhere the robot

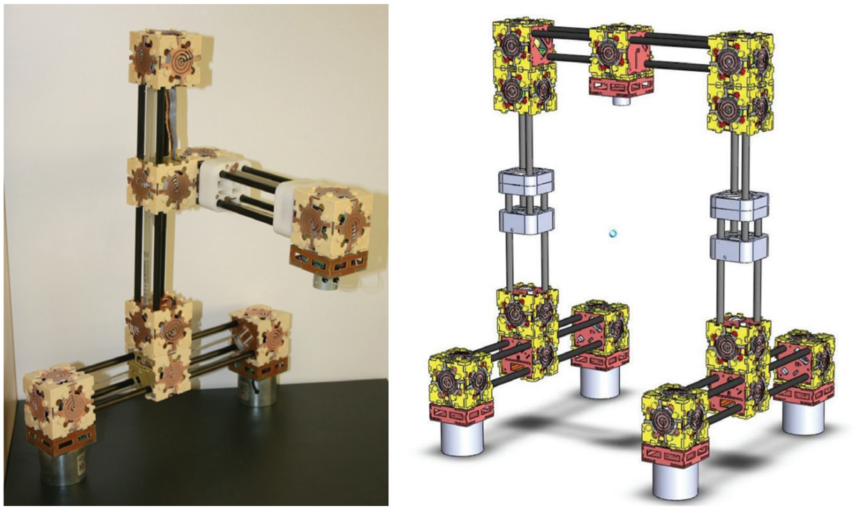

Figure 1.5 Cartesian manipulators for Static missions.

to the metal surface provide better stability than the previous spherical robot and reduce the vibrations on the small magnetic end-effector. In addition, we could implement a gantry style manipulator, as we can observe on the right image of Figure 1.5. This gantry manipulator has great stability as it uses four magnets to adhere to the surface and provides a very stable structure to achieve a high accuracy positioning of its end-effector. Furthermore, this implementation can lift and move heavier loads as it has two pairs of modules working in parallel.

1.4.2 Climber and Walker Robots

The most appropriate configurations to carry small loads or sensors and to move the robots themselves to the workplace are the so-called climber or walker robot configurations. Modular robots should be able to get to hard to reach places and, more importantly, their architecture should allow for their reconfiguration into appropriate morphologies to move through different types of terrains, different sized tunnels or over obstacles. This reconfigurability allows reaching and working in areas where it would be impossible for other kinds of robots to operate. Consequently, being able to obtain simple modular configurations that allow for these walking or climbing operations is important, and in this section we will describe three configurations using our architecture that allow for this.

One of the most prototypical configuration in modular robots is a serial chain of hinge modules. It is called a worm configuration and can be employed for inspection tasks inside pipes using a camera or to pass through narrow passages. Here, we show on Figure 1.6 that we can achieve a working worm type robot using two hinge modules of our architecture. The whole sequence takes around 8 seconds, but the robot's speed could be increased if we use a worm configuration with more modules.

Another example of how using this architecture a functional robot climber can be constructed with just with a few modules is the linear wall climber. This robot consists in a combination of a slider module for motion and two magnet effectors to stick to the metal surface. This simple robot, which is displayed on Figure 1.7. (left), can be used on tasks like measuring ship rib thickness or inspecting a linear weld.

Obviously, the linear climber is unable to avoid obstacles or to turn. Thus, a possibility to achieve configurations with greater capabilities is to use a few more modules. A wall climber robot is shown in Figure 1.7 (right). It can be constructed through the combination of two slider modules, each one of them with two magnetic effectors to adhere to the metal surface, a linear module and

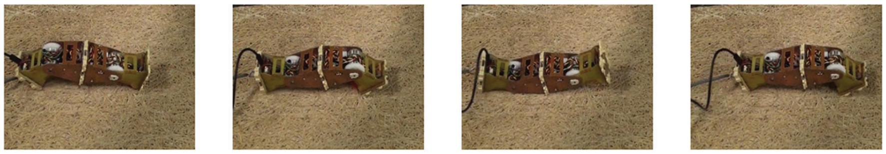

Figure 1.6 A snake Robot that can inspect inside a pipe.

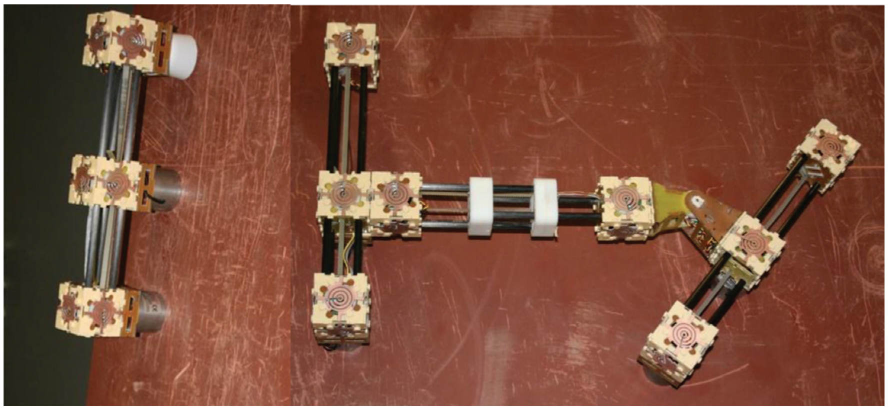

Figure 1.7 Climber and Walker Robots for linear and surface missions.

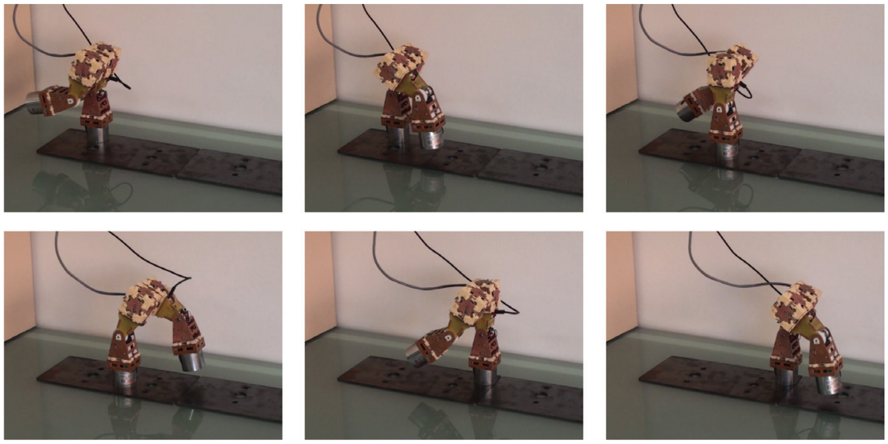

Figure 1.8 A Biped Robot able to overpass obstacles.

a hinge module between them. This configuration allows the robot to move and to turn, making it useful for surface inspection tasks performed with an ultrasonic sensor or other final effectors.

Approximations that are more complex can be created with better locomotion capabilities using other sets of modules. For example, a well-known way to move through an environment is by walking. This way of moving also allows stepping over small obstacles or irregularities. A very simple implementation of a walking robot is shown in Figure 1.8. This configuration is made up of two hinge modules, each one of them with a magnetic effector, joined together by a rotational module. This biped robot is capable of walking over irregular surfaces, stepping over small obstacles and even of moving from a horizontal to a slanted surface.

1.5 Towards Industrial Applications

In this work, we have analyzed the main features and characteristics that a modular architecture should display in order to be able to handle a general dynamic and unstructured industrial environment: versatility, fast deployment, fault tolerance, robustness, reduced cost and scalability. Currently, modular commercial systems have achieved a good fault tolerance, robustness and reduced cost, but they still lack versatility to operate in dynamic industrial environments and their deployment needs at least some hours.

Here, we have developed a new modular architecture taking into account these dynamic environments. An initial analysis has shown that some important features for an architecture of this type is that it should be an heterogeneous modular architecture with a high number of standardized connection faces, different channels of communication, common power buses, and an autonomous and independent control for each module or the robot's ability to discover its morphology. In order to test the architecture in useful tasks, we have implemented some modular prototypes. The results show that we can deploy complex robots for specific tasks in a few minutes and they can be easily controlled through a GUI in a laptop. Furthermore, we can deploy different configurations for similar tasks where we can increase the stability and accuracy of the robot's end-effector using parallel robots.

An industrial implementation of this architecture is still in a development stage, but it will allow working reliably in dynamic and unstructured environments. It will have the same features of our architecture but with an industrial-oriented implementation. The main changes will affect to the robustness of the modules and the connectors. First, modules will be able to support loads and momentums generated by the most typical configurations. In addition, it will be ruggedized to work in real environments, which can present dust or humidity. Regarding the connectors, they will be able to support high loads and, at the same time, they will allow the fast deployment of the robot configurations. We can find one connector with these characteristics in [32] but, additionally, they will have to distribute the energy and communications buses. As the robots have to work in environments with a high presence of ferromagnetic material, such as shipyards, we cannot use the magnetometer values to calculate the relative orientation of the module. Therefore, we will include a sensor to measure the relative orientation between the modules. Finally, one important issue to address is the security of the operators who work near the robots. Most industrial robots are designed to work in close environments with a shield for the worker's protection. Thereby, our modules will have to be compliant for security reasons. This solution is currently used by some companies that sell compliant robots able to work in the presence of humans [33].

1.6 Conclusions

A new heterogeneous modular robotic architecture has been presented which permits building robots in a fast and easy way. The design of the architecture is based on the main features that we consider, in a top-down fashion, that a modular robotic system must have in order to work in industrial environments. A prototype implementation of the architecture was created through the construction of a basic set of modules that allows for the construction of different types of robots. The modules provide for autonomous processing and control, one degree of freedom actuation and a set of communications capabilities so that, through their cooperation, different functional robot structures can be achieved. To demonstrate the versatility of the architecture, a set of robots was built and tested for simple operations, such as manipulation, climbing or walking. Obviously, this prototype implementation is not designed to work in real industrial environments. Nevertheless, the high level of flexibility achieved with very few modules shows that this approach is very promising. We are now addressing the implementation of the architecture in more rugged modules that allow testing in realistic environments.

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