The 7th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications
12-14 September 2013, Berlin, Germany

Designing a Modular Robotic Architecture for Industrial Applications

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***Abstract* – This paper considers the issue of increasing the number of robots working in sectors characterized by dynamic and unstructured environments. Specifically, the paper deals with a new approach, based on modular robotics, to allow the fast deployment of robots to solve specific tasks. Some authors have proposed modular architectures, mostly in laboratory settings, but their design was usually based and what could be built instead of what was necessary for industrial operations. Here we consider the problem by defining the industrial settings the architecture is aimed at and extract the main features that would be required from a modular robotic architecture to operate successfully in these kinds of environments. These requirements are then taken into account to design a particular heterogeneous modular robotic architecture 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**

I. INTRODUCTION

The use of robots in some industrial sectors, such as shipyards or construction, is still very low. The main reason is that these sectors present dynamic and unstructured environments and 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 change during the construction process. Some authors have proposed developing robots for specific tasks, that is, specialists, in order to increase automation in these areas, but their global impact on the sector is still low [1]. 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.

Here, we explore another approach based on modular robotics which basically seeks the re-utilization of pre-designed robotic modules in different robot configurations in order to easily and quickly produce different robots adapted to the different tasks. That is, a small set of modules can lead to many different types of robots for performing different tasks.

Several proposals of modular architectures (in particular chain based architectures) for autonomous robots have been made in the last two decades. Some examples are Polybot [2], M-TRAN [3] or Superbot [4]. Some of them, such as the Superbot system, were designed specifically for dynamic and unstructured environments. The Superbot system 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, 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. They are mostly laboratory concept testing approaches with an emphasis on autonomous robots and self-reconfigurable systems rather than industrial operation. In fact, to simplify their implementation, they are mostly based on the use of a single type of module (homogeneous architectures), which implies the need to use a large number of modules to perform some very simple tasks.

On the other end of the spectrum when adding modularity to robot architectures, we can find modular manipulators. These system have mostly been studied for their use in industrial environments, but they are usually aimed at static tasks [5, 6] and are much less versatile than real complete modular architectures. These types of manipulators can be re-coupled to achieve, for example, larger load capacities or to extend their work space.

Recently a convergence of the two areas has started to take place and 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 [7] 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 attachment faces in each module. The approach is quite interesting, but it still lacks, like many other architectures, some of the features that would be desirable from a real industrially usable heterogeneous modular architecture. For instance, their actuator modules are not independent, they need a power and communications module in order to work, or the robot is not able to recognize its own configuration.

In this paper 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 this features we will propose a particular architecture and will implement a a reduced scale prototype of it. To provide an idea of its appropriateness and versatility we will finally present some practical applications using the prototype modules.

II. MAIN CHARACTERISTICS FOR INDUSTRIAL OPERATION AND DESIGN DECISIONS

To decide on a modular robotic architecture that is appropriate for operation in a set of industrial environments it is necessary to determine the types of environments the architecture should be designed for, 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 so as 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 comply with the versatility requirement, we selected the concept of chain modular architecture as a base to develop the new architecture, as it is the general architecture that maximizes versatility. As commented in the introduction, most modular systems, are made up of homogeneous modules [2, 3, 4]. This facilitates module reuse, but it 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. Furthermore, in order to make the structures more fault tolerant while preserving the heterogeneous nature of the architecture, each module is only allowed one degree of freedom. This permits using simple mechanisms within the modules, which increases the robustness of the system and reduces the operating and manufacturing costs.

In order to decide what modules would be ideal in terms of having the smallest set of modules that covered the possible tasks in a domain (the number of different types of modules needs to be low in order to accomplish the scalability and reduced production cost requirements), 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 (those that generate motion), effectors (magnets, grippers, etc.), expansion modules (computational capabilities, memory or autonomy through batteries), sensors (cameras, ultrasonics, etc.) and linkers. However, in general our work is focused on the actuator modules, which are the ones around which the morphological aspects of the robots gravitate, and we only employ other modules when strictly necessary for the application. In addition, robots can be completely functional with actuator modules as each one includes a processing unit, one motor, a battery, capability 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.

Figure 1 shows a diagram of the process followed in this top-down design process. The top layer of the diagram shows the three basic types of general missions the modular robot could accomplish in this first approach. 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 welding inspection) and Static missions are those where the robotic unit has a fixed position (like an industrial manipulator). The next layer in Figure 1 (Task) shows the set of possible particular tasks we have considered as necessary according to the previous types of mission. The Sub-task layer represents the low level operations the modular system must carry out to accomplish the task. The next layer represents the kinematic pairs that can be used to realize all the sub-tasks of the last layer with the limitation to those with one degree of freedom. Then, we obtain the particular modules required to solve the primitive operations. Both kinematic pairs (prismatic and revolution) were implemented in two different modules to specialize the modules to different motion primitives. To this end, we 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 to 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.

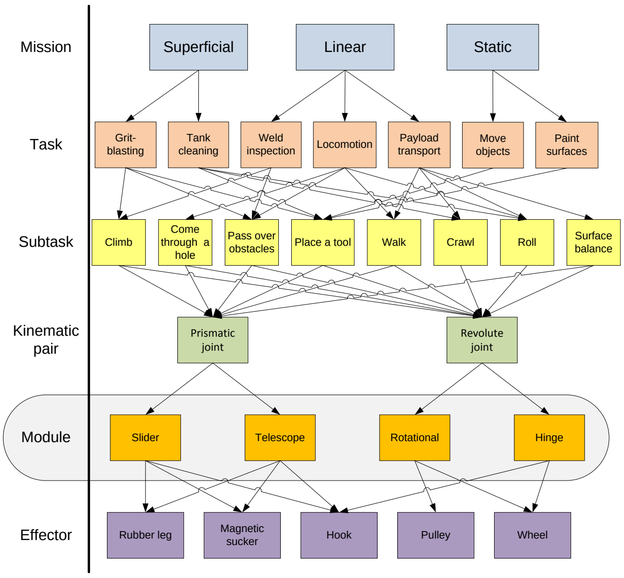

Figure 1. Diagram of the selected missions, tasks and sub-tasks considered, and the required actuators and effectors.

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, allows 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

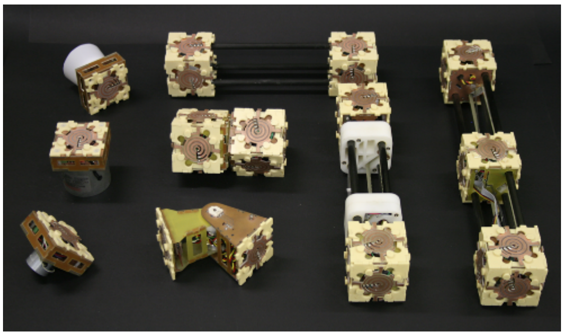

Figure 2. Different types of modules developed: some effectors on the left part, a linker on the top, a slider on the right and a rotational module, a hinge module and a telescopic module in the center.

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.

III. IMPLEMENTATION OF A HETEROGENEOUS MODULAR ARCHITECTURE PROTOTYPE

After presenting the main features and components of the architecture, in this section we provide a brief description of the different solutions we have adopted through the presentation of a prototype implementation.

All of the modules have been fully designed and a prototype implementation has been built for each one of them, see Figure 2. 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 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.

A. 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 the 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.

Table I. MAIN CHARACTERISTICS OF ACTUATOR MODULES

	Slider	**Telescopic**	**Rotational**	**Hinge**
Type of movement	linear	linear	rotational	rotational
Stroke	189mm	98mm	360°(1 turn)	200°
N°nodes	3	2	2	2
N°connection faces per node	5-4-5	5-5	5-5	1-1
Weight	360g	345g	250g	140g

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 I.

B. Connection mechanism

A connection mechanism has been designed that is able to join two modules mechanically in a few seconds and, at the same time, transmit power and communications (a CAN bus and a local asynchronous communications line are used for this purpose).

When two connectors are mechanically attached, they maintain their electrical contacts fixed even under vibrations. The local asynchronous communications contact in each connector is directly connected to the microcontroller while the other contacts are shared by all the connectors of the module using buses. This solution 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.

C. Energy

In this work, we aim to design a fully autonomous and flexible modular architecture, without the need for any wire or tether, which would limit the resulting robots' motions and their independence. 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. Consequently, even though the architecture contemplates fully autonomous operation through batteries in each module and expansion modules with additional batteries that can be connected to the system, it 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 power input is 24V and each module has its own dc converter to reduce the voltage to 6V.

D. Sensors

All of the modules contain specific sensors to measure the position of their actuator as well as 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.

Additionally, when a task requires a specific sensor such as a camera, ultrasound sensor, or whatever, a specific sensor module for that sensor is attached to the actuator module that requires it. These sensor modules 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.

E. Communications

In modular robotics, the communications systems (local and global) are fundamental to ensure an adequate coordination between modules. 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 propioception).

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.

F. Control

Each module in the architecture has its own embedded micro-controller (pic32mx575f512). This 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 behavior 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.

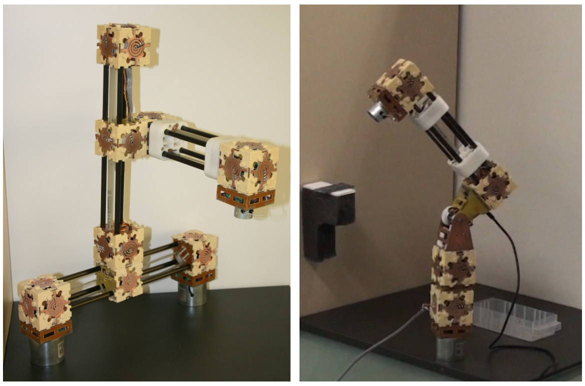

Figure 3. Cartesian and spherical manipulators for static missions.

IV. SOME DIFFERENT CONFIGURATION 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.

A. 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 whereas modular manipulators can be very flexible. They can be entirely reconfigured to adapt to a specific task and even be directly assembled on the workplace. The configuration choice 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. In particular, Cartesian manipulators 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 3. 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 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

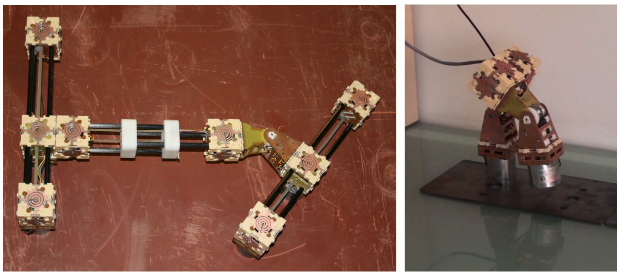

Figure 4. Climber and walker robots for linear and superficial missions.

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 right image of Figure 3. 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 final magnetic effector to manipulate metal pieces.

B. *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 module 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.

An 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 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 show in Figure 4. 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 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.

More complex approximations, with better locomotion capabilities can be created 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 4. 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 an horizontal to a slanted surface.

V. CONCLUSIONS

This paper presents a heterogeneous modular robotic architecture that permits building robots in a fast and easy way. The design of the architecture is based on the main features that we consider a modular robotic system must have in order to work in industrial environments in a top down fashion. 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 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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