International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 11 (2016) pp 7348-7354

Comparison of Control Methods For Modular Robotic Systems

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Abstract
This article reviews the state of art regarding control methods applied in modular reconfigurable robotic systems. Several approaches for design of control algorithms are presented, such as the use of oscillators to simulate Central Pattern Generators (CPGs), trajectory-tracking control, and the morphogenetic approach. A comparison between centralized and decentralized controllers is made, leading to the observation that decentralized control algorithms and methods such as CPG y morphogenetic approaches are currently the most studied cases.

Keywords: Central Pattern Generators; Morphogenetic control; trajectory-tracking control; chain-based modular robots; lattice-based modular robots.

INTRODUCTION

Although Modular Self-Reconfigurable Robots (MSR) can be classified in many ways such as2-or-3 dimensional systems, legless or propelled, their design is generally divided into two basic types: chain-based modular robots and lattice-based modular robots**[1]**. The first type concerns modules connected in series with locomotion capabilities as the main purpose, and the second type concerns modules with the capacity of changing the lattice structure. Hybrids of these two types also exist, capable of both reorganizing their shape and locomotion.

Efficiency of modular robotic systems is related totwo key implementation elements: the hardware's mechanical design, which aims to reduce module constraints related to movement and reconfiguration and implementation of a self-reconfiguration algorithm, allowing the system to achieve arbitrary complex configurations in order to adapt itself to dynamically changing environments**[2]**.

Despite growing interest in research of modular robots without a fixed structure, control systems and techniques for said robots have remained mostly equal; in other words, greater attention has been paid to mechanical issues rather than control considerations **[3][4]**.

As noted in**[5]**, control methods for whole-body locomotion are more difficult than for an ordinary robot, since a modular robotic system can form several configurations with a varying number of degrees of mobility. Therefore, diverse approaches have been adopted to control the movement and behavior of modular robotic systems, as Central Pattern Generators (CPG), trajectory-tracking controls and morphogenetic control, among others.

In addition, control algorithms for homogeneous and heterogeneous modular robotic systems are different. Homogeneous systems are composed by modules with the same characteristics, whereas heterogeneous systems are made by modules with different features, sensors and actuators. Heterogeneous systems introduce additional control considerations due to the modules 'different characteristics and interactions. Furthermore, the type of modules and achievable system positions and gaits will have direct implications upon the controllers' design**[6][7]**.

The main considerations of control algorithms for homogeneous and heterogeneous modular robots are: synchronization (modules moving in the proper order and time intervals to achieve a new locomotion configuration), communications (sharing information between modules, regardless of whether the modules are physically coupled or not), control and specification of necessary joint activation sequences. In the case of heterogeneous systems, identification and movement of modules according to their features is an additional consideration.

CENTRALIZED CONTROL VS DECENTRALIZED CONTROL

According to **[8]**,**[9]**, **[10]** and **[11]**, decentralized control methods are better for reaching high robustness and robot expandability. In this situation, each module is involved in control of the system as a whole; computational power of each individual module is used and less communication bandwidth is required**[12]**.

According to **[13]**, "a pure centralized control structure is not suitable for modular robots". Centralized control is followed by **[14]**, where is developed a self-reconfigurable lattice robot whose modules are controlled each one by a host PC. Although this approach has advantages such as simple hardware and software design, also has many disadvantages, like connecting each sensor and actuator to the main controller, rewiring cables when new devices are connected, which implies a too much time, and the number of new

devices that can be connected is limited by the ports of the processor.
Modularity not only covers mechanical and electrical functions, but also control tasks, like position control, sensing control and docking control between modules**[15]**. In this way,**[13]**proposes an hybrid architecture that combines the features of centralized and distributed control system, in which the first one acts as a supervisory controller of whole body motions and keeps the system consistency, and the distributed module controllers are in charge of basic joint tasks.
A similar approach is followed by **[16]**. They adopt a master/multi-slave structure, in which a module is the brain of the system, and other modules act in a semi-independent mode, such as in figure 1. But this approach has a problem, which is the existence a central point that can unfit all the system. This is another feature of a centralized control method. Italso implies that the system has a concentrated weak point, which is the leader or the place from where the whole system is controlled.

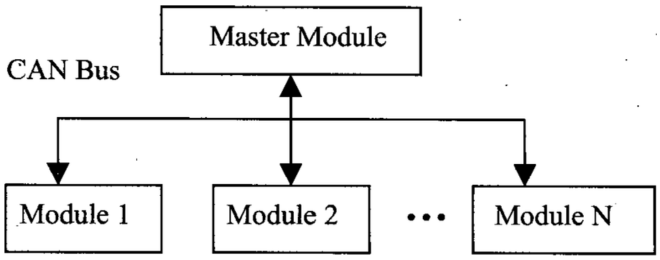
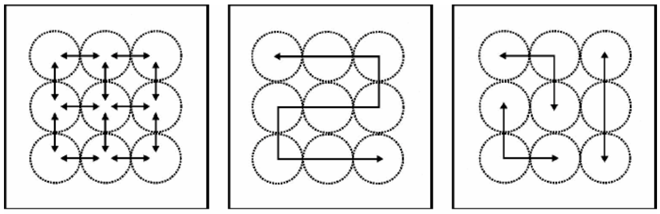


Figure 1: master/multi-slave control structure**[16]**

In **[17]**, an algorithm called PacMan is developed, which is a distributed simple scheme for planning and actuation for self-reconfiguring homogeneous modular robots. With this method, modules act in parallel, using local information and communication, and the method operates in two stages: the first one determines the differences between the current shape and the desired one, and in second stage is planned the paths to be followed by the modules that are not part of the desired shape.
The election of a centralized or decentralized control method also affects other decisions that have to be taken in order to define the design of the module. One of these features is the communication method between modules. There are two main alternatives: global and local communications, as can be seen in figure 2. According to **[18]**, a global communication is better for centralized control approaches, while local communication is convenient for distributed control methods. However, both approaches may be used in the same system and applied in different situations. In addition, another issue to be resolved is the technology to implement the physical layer. Most used are Bluetooth, Zigbee protocols and infrared transceivers **[19]**. In the same way, as well as the communication system is closely related to the control algorithm, the mechanical docking system of modules plays an important role in fulfilling the promises of modular robotics, such as versatility and robustness.**[20]**



(a) Local Buses. (b) Global Bus. (c) Extended Buses.

Figure 2: communication alternatives between modules of a modular robotic system **[18]**

CENTRAL PATTERN GENERATORS (CPGS)

An example of a modular robot controlled by CPGs is presented in **[21]**, where Amphibot has a bioinspired behavior. A bioinspired behavior depends both on the mechanical structure of the robot, and its control algorithm. This system has an anguilliform swimming and ondulatory locomotion on ground. These movements are based on elongated vertebrates, using a nonlinear oscillator chain that simulates the Central Pattern Generators of vertebrates.
Using CPGs, gaits are not predefined in advance, they are generated during locomotion, and this approach does not need an explicit model of the robot. This behavior can be observed in UBot **[22]**, in which the number of CPG oscillators varies depending on the locomotion mode used.
There are different approaches to the use of CPGs: nonlinear oscillators such as in **[23]**, phase oscillators and neural network oscillators. The use of nonlinear oscillators carries several advantages, as reducing the number of state variables and parameters in the models, and thus, the possibility to develop smaller controllers to be used in simpler microcontrollers, which less memory and computer speeds. Nonlinear oscillators have the characteristic to deal with transient perturbations.
To get a specific gate pattern, a group of several oscillators are connected together, in this case, one per element of the Amphibot, which results in a CPG composed by a chain of oscillators.
The use of CPGs can be also applied to modules with more than one degree of mobility, like the M-TRAN II, according to the CPGs outputs. The interactions between CPGs allow the cooperative movement between modules. In this case, CPGs are nonlinear again, and they have four state variables. When they are disconnected, CPG oscillate independently, and when they are connected begin to oscillate together and converge to a specific patron determined by the mechanical connection of the modules, known as locking phenomenon or entrainment among connected nonlinear oscillators. The objective described in that paper was the automatic generation of a locomotion pattern, for which they made a dynamic model of M-TRAN II module, they used a decentralized locomotion controller based on CPGs, and finally apply an optimization method of the CPGs net using genetic algorithms (GA).
They used three types of CPGs connections: excitatory connection, inhibitory connection or without connection, in order to allow GA to find efficiently a CPG net for the locomotion.

What they did with GA was find the weight and initial values of CPGs, because weights determine the differences between joints of each module, so that modules move as faster as possible in a straight line with the less consumption of energy. And the initial position of modules affects the locomotion pattern chosen by the GA.
Central Pattern Generators can also be simulated by sine waves, such in **[24]**, where each joint of a snake-like modular robot is controlled by the variation of four parameters of the signal: amplitude, frequency, phase and offset. The values of these parameters determine the kind of gait, the direction and velocity of the robot. The gaits that the can be obtained varying these parameters are: forward and backward, side-winding, rotating, rolling and turning.
It has been also developed a generalized method to coordinate any kind of swarm or modular robots, the Robot Formation Language, proposed by **[25]**. It is a method for describing swarm or modular systems, and through it modules can be organized, connect, disconnect, take a specific topology, or go back to swarm mode.

MORPHOGENETIC APPROACH

The morphogenetic approach is a robotic field based on the embryonic development of multicellular organisms. It is based on the process by which living organism take their shape, and uses it to propose algorithms for modular robots. The idea of a system that learns by itself a pattern to move is one of the most challenging issues in the field of modular robots.
Two important features that a modular system should have in order to be controlled by a morphogenetic approach are: 1)the system must have a decentralized control, and 2)the morphology that the system adopts should be the result of module to module interactions and module to environment interactions **[26]**.
To reach this state, it has been used genetic algorithms (GA), such as in **[7]**, where is presented an offline GA-based optimization algorithm "for computing the optimal modular configuration of the robot and its locomotion parameters in different situations". The algorithm, with a previous knowledge of the kinds of modules of the system, calculates the optimal position of them for a specific task and also the optimal locomotion parameters.
The idea of self-adaptive, self-regulative and self-developing modular robots, that simulate multicellular beings, comprising many small robotic elements that can act as one structure with the ability of interchange electric energy and information, that can repair themselves and can adapt their structure according to the environment, is a vision of robot organisms **[27]**
As an example of this kind of control method, there is M-Cubes **[28]**, which uses a self-organizing algorithm for lattice-based systems. The model used for the modular system is Cellular Automata (CA), which are discrete dynamical systems governed by simple local relations. Each module evaluates the same geometric rules with respect to its neighbors to decide what action to take.
In a deeper way, **[29]** follows a modular approach that decompose a modular system in a hierarchy of anatomically-inspired parts such as muscles, bones and joints. By this way, they control the anatomical parts or the system rather than each module. The relation between control and structural layers can be seen in figure 3.

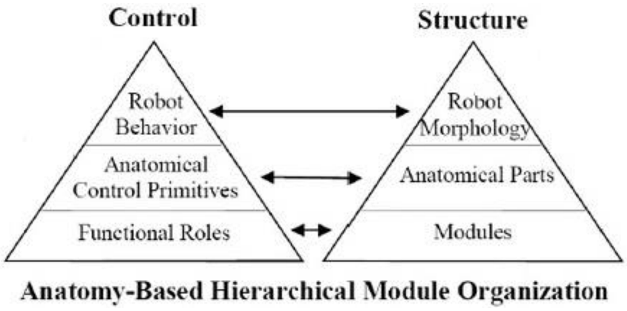


Figure 3: relation between control and physical layers of CATOM modules**[29]**

A similar approach is followed by Crossball, **[2]** which uses three layers to control modules reconfiguration. A first layer is in charge of generating the adequate mechanical configuration depending of environmental conditions; a second layer makes the configuration physically, and a third layer controls the movements of each Cross-ball module.
This is the same approach taken by **[30]**, where is developed a set of mechatronical independent modules, which can connect, disconnect and climb over adjacent modules. A metamorphic system can dynamically reconfigure its locomotion configuration, so they can be viewed as a group of swarm robots. The modules presented are hexagonal and planar, and are controlled by an external and internal processor.
CONRO **[31]** applies other concept brought from biology, the use of a "hormone", which is a message that triggers different actions in different modules. The idea can be applied to both homogeneous and heterogeneous systems. The characteristics of a hormone message is that it has a lifetime, has no particular destination and floats in a distributed system, which means that modules have to interchange information.
The approach followed by **[32]** consists in a continuous cycle between swarm and organism mode, which is shown in figure 4. A group of heterogeneous modular robots begins to explore the environment in swarm mode, guided by its sensors. At one point, they have to achieve a goal, for which they go to the aggregation phase to form a structure and adopt a special locomotion configuration. Finally, when they have reached their goal, go again to swarm mode and continue with the exploration of the terrain.

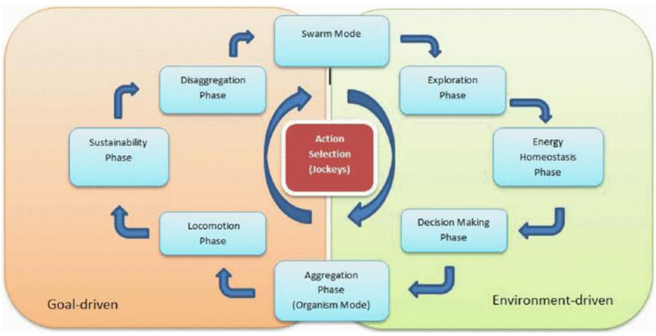


Figure 4: transition diagram between swarm and organism mode**[32]**

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 11 (2016) pp 7348-7354

There is also a morphogenetic approach that uses genetic algorithms to generate decentralized controls, such in **[12]**. They generate software that controls the modular robotic system in a decentralized manner, appropriate to different types of tasks, and robust against failures or unknown environmental conditions.

TRAJECTORY-TRACKING CONTROL

This approach analyzes and manages the behavior of each joint of the modules controlling their position with different methods, such as control tables, adaptive control or PIDs.

This approach is used either in mobile modular systems, such as in **[33]**,**[34]** and**[35]**,in modular systems that can become both a modular manipulator and a mobile modular system, such as in **[36]**, and in modular robot manipulators, such as in **[37]**,**[38]**, **[39]**,**[40]** and**[41]**, in which is designed a control method based on human immune system, and **[42]**, where is developed a distributed control method based on torque sensing, using a spring and a brake in each joint module. In**[43]** it is presented a control method for modular manipulators, where it is designed a neurofuzzy control architecture to adapt the proportional-integral-derivative parameters. The advantage of the method presented is that is not necessary a priori knowledge of the system model, which in the case of reconfigurable modular robots, may be many configurations each one with an unique dynamic-model parameters.

The neurofuzzy hierarchical architecture to control modular and reconfigurable robots of **[43]** comprises five levels: first one represents the mechanical system, namely, the joints of the manipulator; second one is the execution, and it represents the PID parameters; third level includes fuzzy-gain-adaptation module and neural-network-online—learning unit; fourth level updates the parameters of fuzzy module, and fifth level deals with task planning. The levels are presented in figure 5.

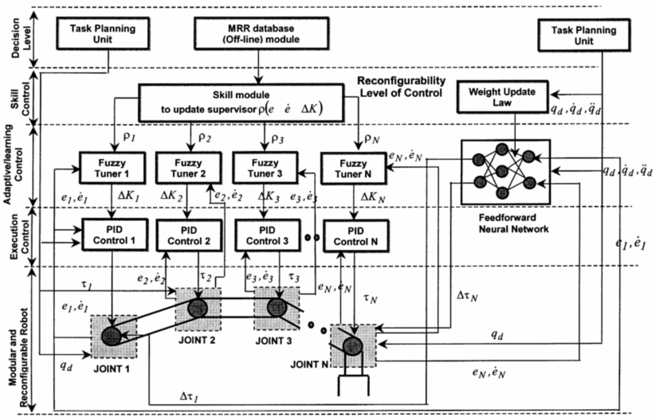


Figure 5: neuro-fuzzy architecture proposed by **[43]**

A different approach was taken by**[44]**, where the locomotion configuration and gait of a modular robot is defined through high-level specific instructions given in English, such as "narrow" or "low", indicating the system that must adopt a configuration for a pipe, for example, in the first case, and for a space with a low ceiling, in the second.

When it is talked about control tables, such as in **[45]**, they are used as high control level method. The tables include the number of segments as columns, the stages through which pass the modules as rows, and the trigger state, that indicates to the controller the appropriate moment to change from one stage to other. One stage could be all modules stretched, and the next one all modules contracted.

In table 1, "′+end" and "-end" means some kind of action with segments' ends, such as stretching right or left one. The trigger state may mean that when all ends have reached the state, the module go to the next stage.

Table 1: example of a control table

Stage	**Segments**				**Trigger state**
	1	**2**	**3**	**4**	
0	+end	+end	+end	+end	1,2,3,4
1	-end	-end	-end	-end	1,2,3,4

In the case of PID, in **[46]** is developed a modular bio-mimetic robotic system to control the position of the finger-like modules and perform complex manipulation tasks.

There are, in the literature, other control methods that not fit pretty well to the mentioned ones previously. In **[47]**, a group of modules are controlled using an unique motor and a set of mechanical joints move through PWM technique.

In **[48]**, the goal is to get the robots to organize in a fixed spatial 2D distribution, such a circle, a paraboloid, among other figures. The approach followed by them consists in a simple set of rules that determine the behavior of each single agent, instead of a central controller. It is similar to a binary decision tree, but more robust and adaptive for big groups of modules.

In **[49]**, it is developed a reactive behavior with a finite state machine as controller for each module, with 10 states and 19 transitions. Each module is autonomous, can move by itself and also attach and detach from other ones to build different locomotion configurations. The control algorithm has three levels of communication between modules, none, minimal and local.

A distributed consensus control method is followed by **[50]**. This control algorithm is based in local information that receives each module from its neighbors, and its main objective is to get the modules reach a state of agreement. At each time step, the modules update their state according to the differences between their state and their neighbors' state.

CONCLUSIONS

As can be seen, control methods for modular robots are a field with less development that the mechatronical characteristics of the systems, and hence, it is not yet a final solution to the main question, such as: how to allow modules to take a determined locomotion configuration according to condition environment?

Regardless the kind of control method used, the approach that is being developed most frequently is decentralized control, because it is more in line with the modular nature of a system of these characteristics. Centralized algorithms restrict the performance of the system because only one agent has to receive all the information and control all the modules. Approaches as master/multi slave control algorithm offer a balanced solution between centralized and decentralized methods.

In the same way, CPGs and morphogenetic approaches are being more investigated than traditional control methods, such as PIDs and control tables, which were used at the beginning of modular robotic research. CPGs simplify the issue of moving modular robotic systems like the real vertebrates do, and morphogenetic approaches look for give to the robotic system intrinsic abilities of living things, such as adapt their locomotion configuration according to the environment, decide how many modules are necessary for a given task, or change or repair any damaged module.

ACKNOWLEDGMENT

This project was funded by Universidad Militar Nueva Granada, as part of the ING-1755 research project.

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