First Steps towards a Heterogeneous Modular Robotic Architecture for Intelligent Industrial Operation

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***Abstract*— This paper is concerned with the issue of producing robots whose morphology helps to simplify the control requirements with the objective of obtaining more efficient and intelligent structures. Thus, we find ourselves in the realm of morphological intelligence. In particular, the paper describes current work we are carrying out in addressing one of the problems in this field, which is what the building blocks should be in order to allow us to produce morphologically adapted robots in a simple and automatic manner. In this line, we propose a heterogeneous modular architecture for the construction of robotic structures that can be applied in unstructured industrial environments. The resulting modules are completely developed and described in the paper. Additionally, their validity for achieving the objective of facilitating the combination of an appropriate morphology with simple control mechanisms is shown through two experiments.**

I. MORPHOLOGICAL INTELLIGENCE

THE relationship between intelligence and embodiment, a topic that was already pointed out in the early fifties by Turing [1], among others, and to a certain extent abandoned by the AI community for decades, has again become popular in recent years. Authors such as Rodney Brooks [2] or Maes [3] have brought the body-mind or body-control coupling problem in autonomous robots back into the limelight and in the last twenty years it has become the topic of many papers and discussions in the autonomous robotics community [4] [5]. Basically, the authors had a robot and an environment and wanted to obtain a simple control system that was able to make use of the specific corporal characteristics of the robot and the particular environmental set up to achieve the desired goal.

Much more recently, C. Paul [6] introduces the term “morphological computation”, and Rolf Pfeifer and Fumiya Iida [7], among others, became strong advocates of this approach, which is reflected beautifully in Pfeifer and Bongard’s book [8]. These authors showed that the body or morphology of robots is a part of their computational or intelligence system. The complex computational and control mechanisms required for robots to really be able to operate and interact with dynamic and unstructured environments can be certainly facilitated if both the body and the control system are designed jointly within the environment benefitting from the morphological computational capabilities, however limited, that a body can provide. That is, taking into account the fact that morphology is involved in computation. This may theoretically permit designing robots with reduced control requirements that are more adapted to their environments and tasks or, in other words, more intelligent. This implies designing the body and control simultaneously, in other words, co-designing both aspects with the objective of achieving the perfect computational equilibrium.

Thus, the real intelligence of the robot lies not only on its control system, but on the coupling of this control system within a body that is adequately designed for the robot’s context and tasks. The main problem with this approach is to find ways to identify and exploit the morphological traits that provide the maximum degree of morphological intelligence to the system given a task and a context. This is especially so if one would like this process to take place automatically or without a direct human designer of the morphology so that the systems can eventually adapt by themselves to different environments or requirements.

To address these issues in a practical and applicable way, at least two aspects must be considered. On one hand, as it would be quite difficult to automatically design and construct any free form morphology, it is necessary to define a finite set of building blocks (modules) that are appropriate for the construction of any relevant morphology within a given domain. On the other, a procedure has to be established that allows determining in an automatic way the morphology-control structure a given robot must have in order to perform a particular task or achieve a specific goal within an environment. This paper is focused on the first one in the context of unstructured industrial environments.

In particular, we consider the design and implementation of a heterogeneous modular architecture as a base for the construction of a wide range of robotic morphologies. This architecture is complemented by a constructive evolutionary approach described elsewhere [9], and which will only be used here in order to be able to provide some application cases. This evolutionary tool makes use of the modular architecture in order to coevolve the morphology and the simple control structures of robots that must perform some tasks.

II. MODULAR ROBOTIC ARCHITECTURES

Modular robotic systems present several features such as scalability, fault tolerance or reconfiguration simplicity that

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make them highly suitable for industrial environments and morphologically intelligent design. Modular systems are based on blocks with limited capabilities that, through a connection mechanism, can produce robotic units with different physical and functional properties, that is, they permit adapting the morphology to the task.

Several proposals of modular architectures for autonomous robots can be found in the last two decades such as Polybot [10], M-TRAN [11], CONRO [12] or ATRON [13], mainly designed for laboratory experiments. Regarding dynamic and unstructured environments like those considered here, the Superbot system [14] must be pointed out. It has been developed for unsupervised real environment operation, resisting abrasion and physical impacts, and it includes enhanced sensing and communication capabilities. Since the middle 90's one can find industrial modular manipulators able to operate in hard conditions [15] [16], but always in structured and controlled tasks and environments, consequently, out of the scope of this work.

On the other hand, the existing modular robotic architectures have been designed with the scientific purpose of exploring the domain of modular robotics and obtaining some basic principles on design and construction, but with very little consideration of the concepts of morphological intelligence. In fact, most of these systems imply using homogeneous modules, which complicates, both structurally and design-wise, the production of useful body-control systems due to the complexity of the control required for performing very simple tasks. In this paper we will concentrate on presenting a heterogeneous modular architecture. This architecture will facilitate the design and implementation of morphologically intelligent systems in terms of making the control much simpler than using a homogeneous approach as well as facilitating the automatic design of robotic structures through evolution. Recently, new proposals of heterogeneous modular systems have arisen like [17] and [18], although at the moment quite limited in the type of implemented modules.

The whole line of research considered here is still in its infancy, especially when considering real robots that must adapt to real industrial environments. Therefore, we will be dealing with simplified problems for the final systems that do not take into account all the complexities of real life operation with the objective of gleaning from them information and knowledge that will permit advancing towards the final goal. However, in the development of the modular architecture, which is the main focus of this paper, we have taken care to consider all of the aspects that impact on its performance and provided real modules that can operate in real environments. An example of these simplifications is that, for these first studies, we have only considered actuation, such as, coordinated robot motion, without taking into account any sensing related problems. Summarizing, the modules developed are complete (including sensing and actuation), but must be considered as a prototypical version of the modular system we will develop in the future.

III. MODULE SPECIFICATION

A. *Overview of the architecture*

Most modular systems, as mentioned in the previous section, consist of a homogeneous set of modules [10-14]. This facilitates module reuse, but limits the range of possible configurations and makes control tasks much more complex. In the type of tasks we are considering here, there are several situations that would require a very simple module (for example, a linear displacement actuator), but which would be very difficult (complex morphology), or even impossible in some cases, to obtain using any of the homogenous architectures presented. Thus, for the sake of flexibility and simplicity, we have chosen to use a set of heterogeneous modules that are simple from a mechanical point of view, that is, they can be taken as mechanical primitives. Four general types of modules can be considered:

- *Actuators*: those that generate motion, through pneumatic or electrical motors.
- *Effectors*: coupled to the actuator module they provide it with new functionalities, like legs, wheels or tools.
- *Sensors*: they provide external or internal information, like cameras, battery meters, etc.
- *Linkers*: they join other modules.

In this initial configuration of the architecture we will concentrate on actuator modules. We have selected four simple actuators to obtain basic motion primitives: slider, telescope, rotational and hinge (see Table 1).

	Slider	**Telescope**	**Rotational**	**Hinge**
Type of movement	linear	linear	rotational	rotational
Nº connectors	14	10	10	2
Max Force/ Torque	115 N	115 N	3.4 Nm	3.3 Nm
Stroke	189 mm	98mm	360º (1 turn)	200º
Weight	360g	345g	250g	140g

Table 1. Main characteristics of the four types of modules.

B. *Mechanical design*

The four actuator modules have been fully designed and a prototype has been fabricated. Two of them produce linear motions (slider and telescopic modules) and the other two produce rotational motions (rotational and hinge modules). There are several shared features among the four modules (see Figures 1-4). All of them present a fiber glass part built from milled printed circuit boards (PCBs). These parts are soldered to achieve a solid but light-weight structure. The slider, telescope and rotational modules contain cube shaped structures called nodes. These nodes act as a connection bays. The free sides of the nodes correspond to connection mechanisms. The size of the nodes without the connection mechanism is 48x48x48 mm; it is 54x54x54 mm including the connectors. The motion in all the modules is generated by HS-5245MG servo motors. The linear modules have a pulley-drive belt system to transform the rotational motion into translation motion.

Table 1 summarizes the main mechanical design characteristics of the four types of modules. The particularities of each one will be described in the following subsections:

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. Fig. 1 displays a prototype of this module. 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 in 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 a mechanism that coils the wires to adapt them to the position of the slider node.

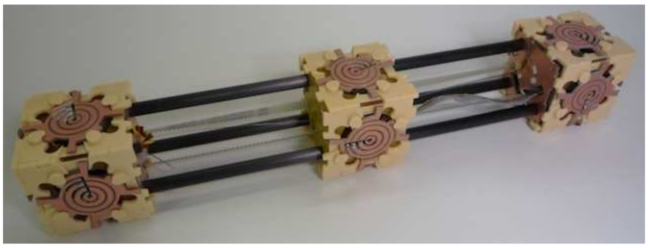

Fig. 1. Slider module. The right node contains the servo with the drive pulley, the central node contains the electronics of the module and the left node contains the return pulley and the mechanism to coil the power and data wires.

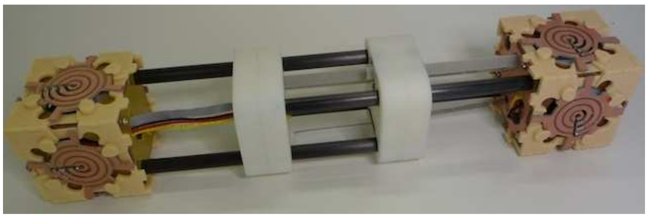

Fig. 2. Telescope module. The servo node is at the right and its drive belt goes to the left white ABS part. The electronic node is at left an its ABS white part, at right, is joined to the drive belt.

2) *Telescope Module*

The telescope module (Fig. 2) 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.

3) *Rotational Module*

This module has two nodes that can rotate with respect to each other (see Fig. 3). A low friction washer between the nodes and a shaft prevents misalignments. One 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.

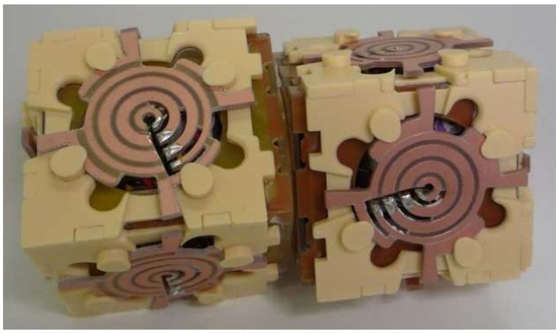

Fig 3. Rotational module. The left node contains the servo and the right node contains the electronic board.

4) *Hinge Module*

Fig. 4 displays a photograph of the hinge module. It 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.

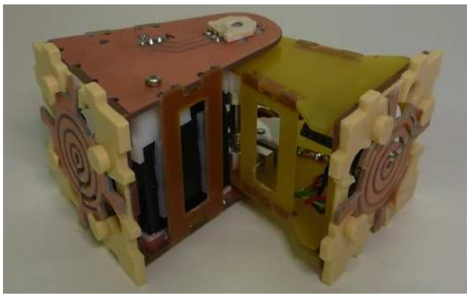

Fig. 4. Hinge module. A shaft joins two main parts that rotate relative to each other.

C. *Connection mechanism*

To facilitate the operation of a heterogeneous modular architecture and the construction of robots using it, it is obvious that standard connectors must be designed to connect the different modules Such connections must provide not only a mechanical coupling but also a path for data and energy transmission.

We can find different types of physical coupling between modules 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 because of 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 on the mechanical aspects paying less attention to power transmission and communications. 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 Fig. 3 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 [10] and [17]. 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 communication lines. The local asynchronous communications track in each connector is directly connected to the microcontroller while the other tracks are shared by all the connectors of the module. To share these tracks in the node we chose 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.

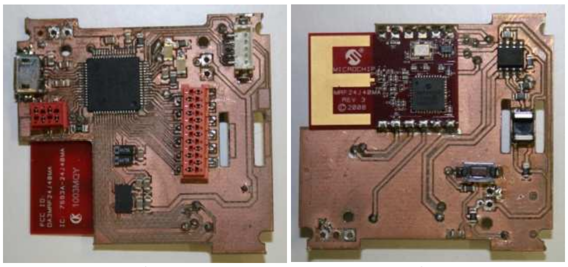

Fig. 5. Both sides of the slider module PCB. The left photograph shows the microcontroller, the connectors for the local communications, the micro-USB connector, the accelerometer and the debugging connector. The IEEE Std. 802.15.4™ Compliant RF Transceiver module and the quadrature sensor can be observed in the right image.

D. Communications

Communications are mandatory in modular robotics to ensure the adequate coordination between modules. The systems that employ local communications (serial bus, infrared) are able to detect the robot's morphology and coordinate tasks involving just local information. On the other hand, global communications (wireless, CAN bus) allow performing tasks requiring a critical temporal coordination between remote modules [19]. We have decided to use two types of wired communication, a CAN bus for global coordination and an asynchronous local communications line for inter-module identification (morphological propioception), and MiWi wireless communications for global coordination when we have isolated robotic units or when the CAN bus is saturated.

Additionally, all of the modules except the rotational one have a micro-USB connector to facilitate communications to an external computer. Also, this feature and a bootloader allow us to employ a USB memory to load the program without the use of a programmer for microcontrollers. Fig. 5 shows the PCB of the slider module containing all the communications elements.

E. Energy

The energetic considerations in modular systems are very relevant, and most approaches in this line can be grouped into two main trends: systems with external or internal power supply. It is obvious that in the first case a wire is required, which limits the system motion and independence. This is a useful approach in the early stages of development, but it should not be an option to design fully autonomous and flexible modular systems. Consequently, in this work we have selected a battery-based power supply system that will be included in each module in its final version. Anyway, right now, the designed modules use an external power source with a single wire for the whole system. The power input is 24V and each module has its own dc converter to reduce the voltage to 6V.

F. Sensors

The linear modules include a quadrature encoder and end-stroke sensor in order to achieve 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.

The local communications permit identifying the type and the face of the module that is connected to a given side. Additionally, all the modules include an accelerometer to provide their spatial orientation. This feature, combined with local communications, permits determining the morphology of the robot without any external help.

G. Control

The control system of a modular robotic unit can be centralized or distributed. Both approaches present advantages and problems and, consequently, here we have decided that each module must have its own embedded microcontroller (pic32mx575f512) so that both types of control are possible. For example, in the case of using a completely distributed approach, each of the modules contributes to the final behavior by only controlling its own actions. In the case of using a centralized control, one of the modules would be in charge of executing it, 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. Fig. 5 shows the microcontroller placement in the PCB of the slider module.

Gait tables, sinusoidal signals, central pattern generators and hormones are the most common methods to control the low level motion of the modules in most modular architectures. Here we are interested in achieving the highest possible level of morphological intelligence, which translates into the simplest possible control for performing a given task. Although hormones and central pattern generators have provided successful results [12][20], in this work, due to their simplicity, we have used sinusoidal signals for control.

IV. APPLICATION

We provide two examples of robots implemented using this modular architecture as a demonstration of the usefulness of this approach. These two experiments were performed mainly to show the validity of the four modules that were designed in terms of obtaining stable and robust structures through a heterogeneous approach.

The first one is a robot designed for a painting task in a static mission and the requirements were that a structure was needed that was capable of painting a surface using a painting pistol that had to be positioned perpendicular to the wall and 20 cm from it. This robot had to be capable of doing so for surfaces that were not flat. The type of robot required is typical in these types of industrial environments, where painting, sand blasting or structural verification are required and thus so are robots that are able to precisely position a tool and move it over a surface. The solution proposed using the heterogeneous architecture is the one shown in Fig. 6. It consists of only four modules: a rotational module, a slider module, a telescopic module and a final hinge module that supports the tool. It is important to note that this structure is quite efficient and that it would be very difficult to obtain something similar using homogeneous modular systems due to the fact that more modules would be required. The result would imply exerting forces that a single module would not be able to handle (for energetic and cost reasons, most modular systems design their modules to be able to support at most a chain of four other modules in terms of torque).

To provide an example of the automatic production of heterogeneous modular structures with this architecture, we have carried out some experiments that using the components of the architecture evolutionarily construct robots for some simple tasks. Obviously, evolution is carried out over simulations, but the final robots are constructed using the architecture presented in this work. The main idea of the experiments is to force the adaptation of the morphology to the tasks by allowing just a very simple control system in open loop employing sinusoidal signals.

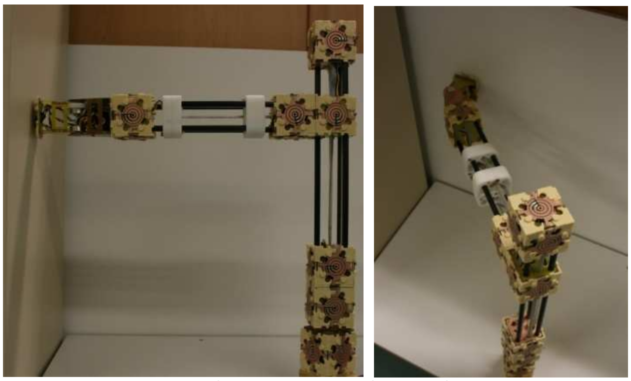

Fig. 6. Morphology of the robotic unit for a surface painting task. The tool has four degrees of freedom employing four modules.

Given the high dimensionality and complexity of the search space, several authors have applied evolutionary techniques to solve this automatic design problem with successful results [20]. In the case of the heterogeneous approach we are following here, the problem is even more complex because the number of possible combinations of modules, connection sides and orientations make the morphological search space huge. In addition, it is not continuous, and a simple change in one module can turn an inadequate structure into a successful one. As a first approach to address these problems, in [9] we proposed an incremental evolutionary design strategy that was validated in a typical benchmark problem.

Here, we will present the modular robot configuration obtained using this evolutionary design system and the set of modules detailed in section III. Specifically, we have considered a difficult task: carrying a payload of 0.6Kg over small obstacles.

An important aspect of the simulation was to provide realistic results that could be directly transferred to real structures using the same modules. For this reason, the modular robots were simulated using Gazebo with its realistic dynamics engine. Models of the four types of modules described in the previous section were created with the mechanical designs of III.B and the parameters displayed in Table 1. In addition to the four basic modules, we defined a rectangular base module as an initial structure and as a base to support the payload. For details about the control adjustment and the behavior of the evolutionary system see [9].

The final morphology obtained in this experiment and four snapshots of the robot motion are displayed in Fig. 7. The structure includes a square base module with two symmetrical branches. These branches are composed by two hinge modules, a slider and a telescope each. The first hinge joins the base and the central node of the slider to tilt the slider module. The slider produces the displacement through friction with the ground of one of its ends and, sometimes, the telescope and the other hinge module. The other slider module is employed to climb the obstacles. Again, through a simple sinusoidal based distributed control strategy and a morphology that is well adapted to taking advantage of the environment, the task is performed appropriately.

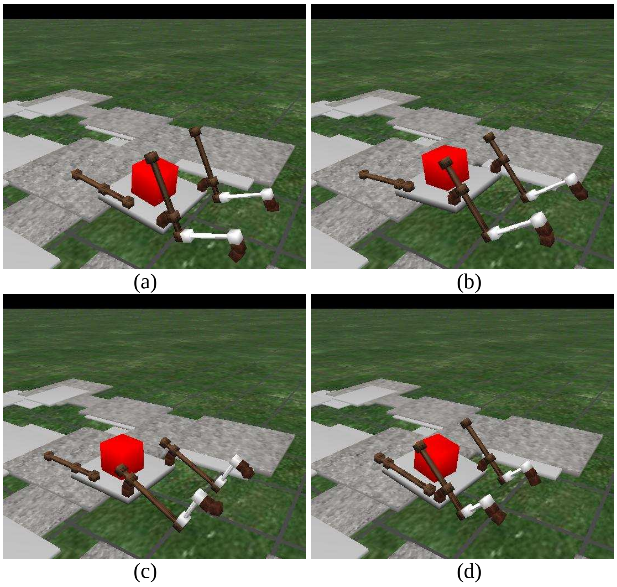

Fig. 7. Four consecutive steps in the movement of the morphology obtained for carrying a payload (red box) using the heterogeneous modules presented here.

V. CONCLUSION

The main contribution of this work is a proposal of a heterogeneous modular architecture as a base or toolbox for the construction of morphologically intelligent industrial robots. The basic architecture was designed with four actuator modules which were developed in their mechanical, electrical and control dimensions in order to produce the basic motion primitives of the robots. Two of these modules perform linear motions and the other two achieve rotational motion. To demonstrate the appropriateness of the architecture for the objectives, we presented two final morphologies with their corresponding control systems. It can be concluded that using simple combinations of modules and an extremely basic control mechanism based on sinusoidal functions allowed performing the tasks in a much simpler way than would have been possible with a homogeneous architecture.

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REFERENCES

[1] A. M. Turing, “Computing Machinery and Intelligence,” *Mind* 49, pp 433-460, 1950

[2] R.A. Brooks, “Intelligence without Representation,” *Artificial Intelligence*, Vol. 47, pp. 139-159, 1991

[3] P. Maes, P. "Behavior-Based Artificial Intelligence", From Animals to Animats 2: Proceedings of the 2nd International Conference on the Simulation of Adaptive Behavior, pp. 2-10, 1993

[4] G. Baldassarre, S. Nolfi, D. Parisi, “Evolving mobile robots able to display collective behavior,” Artificial Life. Vol. 9, pp. 255-267, 2003

[5] D. Floreano, F. Mondada, “Evolutionary Neurocontrollers for Autonomous Mobile Robots”, *Neural Networks*, Vol. 11, pp. 1461-1478, 1998

[6] C. Paul, “Morphology and Computation,” *Proceedings of the International Conference on the Simulation of Adaptive Behaviour* pp 33–38, 2004

[7] R. Pfeifer, F. Iida, “Morphological computation: Connecting body, brain and environment,” *Japanese Scientific Monthly*, Vol. 58, No. 2, pp 48–54, 2005

[8] R. Pfeifer, J.C Bongard, “How the body shapes the way we think: a new view of intelligence”, MIT Press, 2007

[9] A. Faina, D. Souto, F. Bellas, R.J. Duro, “Towards an Evolutionary Design of Modular Robots for Industry, “, *Proceedings IWINAC 2011*, 2011

[10] M. Yim, D. Duff, K. Roufas, “PolyBot: a modular reconfigurable robot,” *IEEE International Conference on Robotics and Automation*, pp 514-520, 2000

[11] S. Murata, E. Yoshida, A. Kamimura, H. Kurokawa, K. Tomita, S. Kokaji, “M-TRAN: Self-reconfigurable modular robotic system,” *IEEE/ASME transactions on mechatronics* vol 7, pp 431-441, 2002

[12] W.M. Shen, B. Salemi and P. Will, "Hormone-Inspired Adaptive Communication and Distributed Control for CONRO Self-Reconfigurable Robots," IEEE Trans. Robotics and Automation, vol. 18, no. 5, Oct. 2002, pp. 700-712

[13] D. Brandt, D. J. Christensen, H.H. Lund, “ATRON Robots: Versatility from Self-Reconfigurable Modules”, *Conference on Mechatronics and Automation*, pp 26-32, 2007

[14] B. Salemi, M. Moll, W. Shen, “SUPERBOT: A deployable, multi-functional, and modular self-reconfigurable robotic system”, *Proc. Intl. Conf. Intelligent Robots Systems*, pp 3636-3641, 2006

[15] C. J. Paredis, H. B. Brown & P. K. Khosla, “A Rapidly Deployable Manipulator System”, *IEEE International Conference on Robotics and Automation*, pp 1434-1439, 1996.

[16] T. Matsumaru, “Design and Control of the Modular Robot System: TOMMS”, *ICRA*, *pp* 2125-2131, 1995**.**

[17] V. Zykov, W. Phelps, N. Lassabe, & H. Lipson, “Molecubes Extended: Diversifying Capabilities of Open-Source Modular Robotics”, *Self-Reconfigurable Robotics Workshop, IROS* 2008

[18] A. Lyder, R. Garcia, & K. Stoy, “Mechanical design of odin, an extendable heterogeneous deformable modular robot”, *International Conference on Intelligent Robots and Systems, pp* 883 -888, *2008.*

[19] E. Yoshida, T. Arai, M. Yamamoto, J. Ota, and D. Kurabayashi. “Evaluating the efficiency of local and global communication in distributed mobile robotic systems,” *In Proc. IROS*, pp 1661–1666, 1996.

[20] D. Marbach & A. Ijspeert, “Online optimization of modular robot locomotion”, *IEEE International Conference on Mechatronics and Automation*, 248-253 *2005*