On the need of Hybrid Intelligent Systems in Modular and Multi Robotics[1]

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Abstract. The area of cognitive or intelligent robotics is moving from the single robot control and behavior problem to that of controlling multiple robots operating together and even collaborating in dynamic and unstructured environments. This paper introduces the topic and provides a general overview of the current state of the field of modular and multi robotics taking both of these subareas as different representations of the same problem: how to coordinate multiple elements in order to perform useful tasks. The review shows where Hybrid Intelligent Systems could provide key contributions to the advancement of the field.

Keywords: Intelligent robotics, multi-robot systems, modular robotics.

1 Introduction

The classical concept of general purpose industrial robot, both in the case of manipulators and mobile robots, makes sense when the task to be carried out takes place in static or controlled completely structured settings. However, when the environments are highly dynamic and unstructured and when the tasks to be performed are seldom carried out in the same exact way, it is necessary to make use of robotic systems that require additional properties depending on the task. Examples of these environments are shipyards, plants for constructing unique or very large structures, etc. In these environments, work is not generally carried out as in traditional automated plants, but rather, a series of individuals or groups of specialists perform the tasks over the structure itself in an ad hoc manner. Consequently, it is necessary to seek new approaches that permit automating processes in this type of environments based on design specifications such as modularity, scalability, fault tolerance, ease of reconfiguration, low fabrication and maintenance costs and adaptation capabilities.

Thus, structures that can adapt their hardware and capabilities in a simple manner to the task in hand are sought. At the same time these structures, as they are designed for operating in dynamic environments, must be endowed with capabilities that allow them to adapt to their environment in real time. Obviously, they must continue to

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operate even when failures occur in some of their components, that is, they must degrade in a non catastrophic way. All of these requirements imply the construction of a modular architecture, an standardization of the interfaces between modules and an appropriate organization of perception, processing and control for these types of structures that implies the reconfiguration of the system in an intelligent manner for the completion of the mission.

Hybrid intelligent systems are characterized by the composition of the different available computational tools (Bayesian reasoning, neural networks, fuzzy systems, statistical classifiers, evolutionary algorithms, etc.) in a way that is adapted to the particular problem to be solved. They are aimed at achieving the highest degrees of flexibility and adaptation. Until now, most multirobot or modular robotic systems are characterized by the simplicity of their control systems, which are often handcrafted for the particular task that must be demonstrated. We believe there is an open wide application field for hybrid approaches to this type of systems.

2 Approaches to Modular Robotics and Multi-robot Systems

Three different approaches to modularity and multirobotics may be found:

1. Modularity of a continuous robot. It deals with the creation of modules, usually homogeneous, that through their connection into different configurations permit the creation of a single and physically continuous robot. This is the idea of the so called polybots.
2. Modularity of a distributed robot. In this case, the designers seek modules, generally inhomogeneous, and where each one of them is specifically designed for a given part of the global task. They may or may not be physically connected.
3. Distributed cooperative robotic systems. This concept arises from traditional robotics where the cooperation of independent robotic units is sought for performing joint tasks. Their differential characteristic is that the robotic unit is independent and does not require the others in order to perform the task. Cooperation allows them to carry out tasks of a larger scope or complexity.

From now on, and for the sake of simplicity, we will only consider two categories. The first one will refer to systems that present modular solutions, whether continuous or distributed. The second one considers systems that encompass several independent robots.

2.1 Modular Robotics

In general, modular robots can be taken as robotic structures that are made up of multiple, generally identical, modules. The underlying idea of modular robotics takes inspiration mainly from cellular automata and social insect theories. Through cooperation, social insects such as ants, bees or termites, perform tasks that would be impossible for a single individual. This way, modular robots use the emergence and holistic principles that are quite popular in current science. This principles state that there are behaviors or properties of the systems that are intrinsic to the whole system and cannot be found in any of its constituents, that is, they emerge from the interaction of the system parts. Using similar principles, modular robots autonomously self-organize and change their shape in order to adapt to different tasks or classes of terrain. For instance, some modular robots may transform into snakes in order to follow a tunnel and then may transform into quadrupeds to go up stairs. Another important feature of modular robots is their potential for self repair. As the modules making a unit up are usually identical, it is possible to eliminate the damaged module and substitute it using another one, if available. Notwithstanding these comments, most developments in modular robotics are not classified as self organizing systems. This is due to the fact that in most cases, one module is used as the general coordinator and the rest as slaves and these roles can be interchanged.

Even though this research area has progressed very fast since its beginnings in the early nineties, modular robots have achieved their objectives only in very controlled laboratory environments. In reality, the control systems within the modules are created ad hoc for the task to be carried out. There is hardly any instance of this type of systems that presents the capability of autonomously deciding the configuration change or the necessary adaptation parameters. The introduction of advanced (hybrid) intelligent systems may be the key for achieving these properties.

Modular robots present structural degrees of freedom in order to adapt to particular tasks. One of the first implementations is a sewer inspection robot [1] although the idea of reconfigurable modular robots starts with the designs by Yim [2-6] of a polypod robot that is capable of adapting its structure in order to produce different gaits for moving over different terrains. In [7] this philosophy is applied to the design of flexible fabrication cells. A robot for operating in vertical surfaces is presented in [8]. The work in [9] discusses the limitations of metamorphic robots based on cubic modules. Different modular configurations are being proposed even nowadays, examples are [10-14]. New classes of robots are introduced in [15] where Campbell et al. present robots that are configured as power buses while performing the assigned task. In [16] Carrino and col. present modules for the construction of feed deposition heads in the generation of composite materials.

The idea that robots should be able to self-configure is introduced in [17-20] over one type of modular robot called M-TRAN [21,22]. In its current state the transitions between configurations are carried out manually and a few configurations for particular tasks are obtained through genetic algorithms and Sefother global random search methods. The idea of self-configuration over Yim´s polybots is proposed in [23]. Liping et al. [24] propose a coupling method that is based on position sensors and in [25] Patterson and col. propose another one based on magnetic couplings that may lead to new proposals of self-configurable robots. An area of active interest is that of the application of intelligent (hybrid) systems for the autonomous on line reconfiguration of this type of robots. It would really be necessary to reformulate the problem as a distributed optimization problem with partial information and combine estimation methods (Bayesian or neuronal) with robust optimization methods (evolutionary or graduated convexity).

Papers [26-29] study kinematic calibration methods and ways for obtaining the inverse kinematics and the dynamics of modular and reconfigurable robots in order to solve the problems introduced by tolerances in the fabrication of the modules. On the other hand, [30] presents a methodology for the dynamic modeling of multirobot systems that facilitates the construction of simulators that may be used in order to accelerate the development of intelligent control systems through virtual experiments.

Regarding the automated design of modular robots, some work has been carried out in the application of evolutionary algorithms that seek the minimization of a criterion based on the variety of the modules employed for a given task that is cinematically characterized [31] or on the mass, ability and workspace [32]. In [33] Zhang and col. provide a representation of the robot and the environment that permits the application of case based reasoning techniques to the design of a modular robot. For the automation of the design of the configurations of modular robots, including self-reconfigurable robots, [34] proposes a representation of the potential connection topologies among the modules. Saidani [35] discusses the use of graph theory and cellular automata as a base for the development of design and reconfiguration algorithms. However, this type of systems will not be really autonomous until these design and analysis tasks are carried out in an autonomous and distributed manner over the robot modules themselves. Again, robust estimation and modeling methods that are still not in general use are required.

An aspect we are interested in is that of the need to organize the sensing of the robot so that the different sensors are integrated in order to obtain the desired information. A primitive example is the application of Bayesian decision theory for door detection as presented in [36]. A decentralized Bayesian decision algorithm that may be used for the fusion of sensorial information in sensor networks is introduced in [37]. This algorithm indicates the path to follow for the application of hybrid intelligent techniques to this problem.

2.2 Multi-robot Systems

The second category of interest are robot swarms [38,39]: groups of robots that collaborate to achieve an objective, for example, rescue tasks [40], material handling in flexible fabrication cells [41]. Possibly, the RoboCup robotic football championship is the most important concept testing ground in this field.

The biological foundations of the idea of robot swarms are reviewed in [42], including a prospective of their application in [43]. Different studies of complexity have been carried out over these types of systems. They include the characterization of chaotic behaviors [44]. Dynamic studies have also performed out over simple models such as foraging [45,46]. The negotiation method [47] proposed for self-reconfigurable robots could also be applied to swarms. On another tack [48] shows how a swarm may be converted into a self-reconfigurable robot. In [49] Fukuda and col. discuss the advantages and disadvantages of multiagent robotic systems as compared to single robots. The individuals considered are in general very simple in their internal dynamics and, consequently, the introduction of sophisticated approximate reasoning systems would permit an extension of the range of behaviors and their robustness to changing situations.

One of the critical aspects of this type of systems is the communication between the members of the swarm [50]. It is usually carried out using radio-links. In [51] Dumbar and Esposito study the problem of maintaining communications among the robots performing tasks. Dongtang et al. [52] study the need of optical communications and evaluate a system based on photo sensors and laser. In [42, 53-55] different authors use the pheromone metaphor as a means of communications in, among other, applications for the detection of damaged components. Another line of research where hybrid intelligent systems are becoming necessary is that of stigmergy based communication, that is, communication through the environment [56].

The production of consistent information on the environment in a distributed manner is another challenge for this type of system. In [57] Kumar and Sahin consider this problem in the realm of detecting mines. Pack and Mullings [58] introduce metrics so as to measure the success of a joint search performed by a swarm as well as a universal search algorithm. More elaborate representation methods that include training algorithms for the adaptation of the agents to their environment and tasks are needed.

Obtaining decentralized control that provides interesting collective behaviors is a central problem [39,47,59-65]. In [62] Peleg presents a universal architecture for the decentralized control of groups of robots. A review of the state of the art of decentralized control is given in [63]. Wessnitzer and Melhuish [66] integrate behavior based control strategies with swarm control systems in a task having to do with the elimination of underwater mines. Dorigo, within his swarmbots project [68] presents a hunting behavior as a collective decision making process. In general, the formulation of decentralized control implies the need to work with incomplete or temporally inconsistent information. Hybrid intelligent systems should help to improve the robustness of these control systems.

Marco Dorigo´s group [68] has been very active in this field, developing the idea of swarm-bot [43]: In [69] they discuss a transportation behavior that is similar to that of ants. In [70,71] they present a hole avoiding behavior. A Review of their work can be found in [64]. Finally, in [72] they study the application of evolutionary techniques for obtaining distributed control methods. Again, these evolutionary techniques are run based on the global information available about the system and are not implemented on the agents. Thus, these systems are still far from being autonomous

An interesting application is that of positioning and map generation through robot swarms [73]. A precedent may be found in [74], and in [75] Di Marco et al. consider the simultaneous localization and map generation problem (SLAM) for a robot team. In [76] a group of cooperating robots creates a map by integrating the particular maps of each robot using an information theoretical approach. On the other hand, Stroupe and Balch [77] try to estimate the best next move of a group of robots in order to obtain the map. The techniques are based on variations of Kalma filters, which can clearly be improved through the application of techniques from the hybrid intelligent systems tool box and thus things such as inverting the observation prediction functions could be avoided.

3 Conclusions

The two most important approaches to the construction of multi or modular robots have been reviewed. As a general comment it must be pointed out that this type of systems still lack the desirable level of autonomy. The application of hybrid intelligent systems for the construction of truly autonomous control systems or for the interpretation of the sensing data are open fields of great potential. A systematic need of working with imprecise and incomplete information that may be temporally inconsistent is detected when contemplating distributed implementations of control and sensing. Sensor fusion, whether from several sensors from the same robot or from different robots, requires robust and efficient modeling techniques. It is with the hybridization of different approaches that this may be achieved.

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