Analyzing Features of Multi-Robot Systems An Initial Step for the RoboCare Project *

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Sommario

La ricerca sui sistemi multi robot (MRS) ha avuto negli ultimi anni un impulso significativo, nel settore della Robotica e della Intelligenza Artificiale, ed un numero crescente di sistemi prototipali è riportato in letteratura. Questo lavoro descrive una classificazione degli MRS che mette in risalto le relazioni tra MRS e i sistemi multi agente (MAS). Vengono quindi discusse le tendenze che emergono da un'analisi della letteratura, con lo scopo di evidenziare i temi di ricerca che hanno ricevuto particolare attenzione nel recente passato. Infine, viene presentato l'approccio seguito nello sviluppo di un MRS per il progetto RoboCare che ha l'obbiettivo di svolgere alcune mansioni di ausilio agli anziani.

Abstract

Research on Multi Robot Systems (MRS) has significantly increased in the last years, being investigated both within Robotics and Artificial Intelligence, and a growing number of prototype systems have been recently presented in the literature. In the present work we present a taxonomy for classifying MRS, which highlights the relationship between MRS and Multi Agent Systems (MAS). We then discuss the trends of the literature on MRS trying to highlight the areas which received significant attention in the recent past. We finally present the main goals of RoboCare a recently started project which addresses the use of a MRS to support elderly people.

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1 Introduction

The research on Multi Robot Systems (MRS) has been developed in the recent past both from a biologically inspired perspective and from an engineering standpoint. While in the former case the goal is to develop real systems that are capable of showing various types of collective behaviour typical of animal species, in the latter case MRS are designed and realized in order to improve the effectiveness, performance and robustness of a robotic system.

In this paper we are more concerned with engineering motivated approaches to MRS whose goal is the improvement of the performance in accomplishing a give task, or in the robustness and reliability of the system [1]. The increase of performance not only means accomplishing goals that cannot be achieved by individual robots, but also improve the efficiency of the system by increasing the number of robots with similar capabilities [2].

There is a large variety of tasks that can be accomplished by the MRS. According to [3], they can be grouped in the following categories: *foraging and coverage*, where the basic behaviour is to collect objects scattered in the environment, with a variety of applications including search and rescue, de-mining, toxic waste cleaning and service robots; *multi target observation*, with applications in security, surveillance and recognition problems; *box pushing and manipulation*, with applications on stockage, truck loading and unloading, and cooperative transportation; *exploration and flocking*, with application on formation maintenance, map building, cooperative localization and mapping (SLAM), exploration of dangerous environments.

MRS have been used in several environments: military and security applications [4, 5], rescue operations

[6], space applications [7], large scale assembly [8], and many others. The increased availability and performance of robotic bases, tasks and behaviours of MRS has provided for applications and experimental scenarios that are more and more complex. In particular, special attention is given to MRS developed to operate in dynamic environments, where uncertainty and unforeseen changes can happen due to the presence of robots and other agents that are external to the MRS itself.

A significant boost to the work on MRS has recently been given also by Robotics competitions, such as AAAI robotic contexts and RoboCup [9]. In fact, the design and the realization of MRS is regarded as one of the major scientific challenges and robotic contexts are extremely useful for comparing and analyzing different strategies and techniques by providing a common testbed for experiments. Moreover, these competitions offer new challenges in the design of MRS: for example in the RoboCup soccer domain, as compared with other domains for MRS, the environment is highly dynamic and includes an opponent team.

In our current work we are considering the scenario of a residence for the elderly people, where a MRS can accomplish a number of tasks including: object transportation, search, surveillance and guidance. In such an application the presence of several robots is motivated by the objective of accommodating the needs of several people, as well as by the variety of functionalities to be provided. The main aim of this paper is to address the most recent developments of MRS by highlighting the relationship between MAS and MRS, specifically focusing on the coordination aspects and on the team work capabilities of the MRS. Subsequently, we focus on the cooperation in exploration, which is one of the main requirements for the MRS we are developing within the RoboCare project.

The paper is organized as follows: in Section 2 we present the taxonomy which addresses the recent work in MRS from the standpoint of MAS; in Section 3, we discuss the new trends arising in the recent research on MRS; finally, in Section 4 we describe the main features of the *RoboCare* project, that motivates the development of a MRS targetted to a residence for the elderly.

2 MAS and MRS

Despite the significant body of research on MRS, it is difficult to identify reference techniques and approaches and the proposed solutions often have a significant degree of specialization for the intended application domain. A first observation is that, a MRS cannot be simply regarded as a generalization of the single robot case and the proposed approaches need to be precisely characterized in terms of assumptions about the environment and in terms of the internal system organization. As for MAS, one of the characterizing features of the MRS is the kind of cooperation/competition that takes place among the robots. However, a MRS can not be simply considered as a special case of a Multi-Agent System, because of the issues arising when dealing with a physical environment, such as uncertainty and incompleteness on acquiring information from the environment. This notwithstanding, in this paper we provide a classification of MRS, by highlighting their relationship with MAS. This has two consequences: the first one is that we focus on the cooperation/competition among the robots, the second one is that we classify the MRS system features in rather abstract terms.

Coordination Dimensions	*System Dimensions*
Cooperation	*Communication*
Knowledge	*Team Composition*
Coordination	*System Architecture*
Organization	*Team Size*

Table 1: Classification dimensions

A classification that highlights the cooperation in MRS is the one given in [10]; other classifications are more focussed on different perspectives of the field, thus dealing with the cooperation aspects in less detail, while addressing in greater detail other issues such as communication and computation [2, 11], group architecture [12], research topics [13] or learning [14]. In the following, we sketch the taxonomy proposed in [10], and discuss some issues and techniques that are of interest for the tasks addressed within the RoboCare project.

The taxonomy that we propose for classifying the work on MRS is constituted by two groups of dimensions: *Coordination Dimensions* and *System Dimensions* (see Table 2). Generally speaking, the first group of dimensions aims at characterizing the type of team work that is achieved in the MRS, while the second group of dimensions includes the system features that influence team work. More specifically, a hierarchical structure of the coordination dimensions is given in Figure 1.

The first level is concerned with the ability of the system to cooperate in order to accomplish a specific task. At the *Cooperation Level* we distinguish cooperative systems from not cooperative ones. A cooperative system is composed of "robots that operate together to perform some global task" [15]. In this work we are interested only in cooperative MRS. Therefore, in the following, the term MRS will refer to a team of cooperative robots. The second level of the proposed hierarchical structure concern the knowledge that each robot in the team has about its team mates. *Aware* robots have some kind of knowledge of their team mates while *Unaware* robots

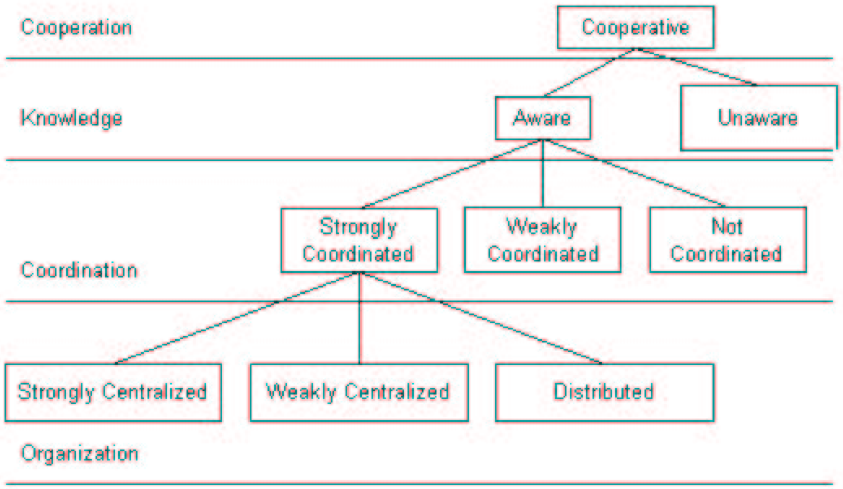

Figure 1: MRS Taxonomy

act without any knowledge of the other robots in the systems. The *Coordination Level*, is concerned with the mechanisms used for cooperation. Following [16] we consider *Coordination* as: "cooperation in which the actions performed by each robotic agent take into account the actions executed by the other robotic agents in such a way that the whole ends up being a coherent and high-performance operation". However, there are different ways a robot can take into account the actions of the other members of the team. The underlying feature is the *coordination protocol*, that is defined as a set of rules that the robots must follow in order to interact with each other in the environment. Therefore, we can further classify the coordinated MRS based on the type of coordination protocol. We consider *Strong (Weak) coordination* as a form of coordination that relies (does not rely) on a coordination protocol. The fourth level of our hierarchical structure is concerned with the way the decision system is realized within the MRS. The *Organization Level* introduces a distinction between centralized approaches and distributed ones [12]. In particular a *Centralized* system have a robotic agent (leader) that is in charge of organizing the work of the other robots; the leader is involved in the decisional process for the whole team, while the other members act according to the directions of the leader. On the other hand a *Distributed* system is composed by robotic agents which are completely autonomous in the decisional process with respect to each other; in this class of systems a leader does not exist. The classification of centralized systems can be further refined depending on the way the leadership of the group is played. Specifically, *Strong centralization* is used to characterize the MRS in which decisions are taken by the same pre-defined leader agent during the entire mission duration, while in a *weakly centralized* MRS the leader can dinamically change during the mission.

Along with the classification introduced to characterize the form of team work, there are a number of system features that are relevant to the team work ability of the system that we have grouped in the system dimensions. They include: communication, team composition, system architecture and team size.

Cooperation among robots is often obtained by a communication mechanism that allows the robots to exchange messages among each other. For a detailed analysis of the various technical problems related to communication see [16]. We roughly distinguish two different types of communication depending on the way the robots exchange information. All the communicating systems can use either direct or indirect communication. Direct communication makes use of some hardware on board dedicated device, while indirect communication makes use of stigmergy

According to team composition MRS can be divided in two main classes, heterogeneous and homogeneous (see for example [67]). Homogeneous teams are composed by team members that have exactly the same hardware and control software, while in heterogeneous team, the robotic agents differ either in the hardware devices or in the software control procedures.

System architecture is an important feature for clas-

Coord. Dim.	Foraging	Box pushing	MTO	Exploration	Soccer
Unaware Systems	[17]	[18, 19, 17]			
Aware not Coord.		[20]		[21, 22]	
Weakly Coord.	[23, 24]	[25, 26, 27]		[28, 29, 30]	[31]
Strongly Coord. Strongly Centr.	[32]			[33, 34, 35]	[36]
Strongly Coord. Weakly Centr.		[8, 37]		[38]	
Strongly Coord. Distributed	[39, 40, 41, 42] [43, 44, 17]	[45, 46, 47] [48, 49, 50]	[51, 52] [53]	[54, 55, 56, 57] [58, 59, 60, 61]	[62, 63, 64] [65, 66]

Table 2: Summary of classification

sifying MRS. In this work we will refer always to the architecture of the whole MRS and not to the architecture of the single robotic agent. A precise characterization of MRS with respect to reactive or deliberative is presented in [10]. We consider a team architecture as deliberative if it allows the team members to cope with the environmental changes by providing a strategy that can be adopted to reorganize the overall team behaviours. On the other hand, in reactive team architectures each robot in the team copes with the environmental changes by pursuing an individual approach to reorganize its own task in order to accomplish the goal assigned to it. The main difference between deliberative and reactive team architectures relies on the different modalities applied by the MRS to recover from an unpredicted situation: in a deliberative MRS a long term plan involving the usage of all the available resources to collectively accomplish a global goal is provided; in a reactive MRS a plan to cope with the problem at hand is provided by the robotic agent directly involved with it.

Finally, the team size is becoming a relevant issue in MRS development, and several works address large scale MRS [3]. Rather than a quantitative measure of the size of the MRS we distinguish those approaches that explicitly consider as a design choice the opportunity to deal with a large number of robots, from those that do not address explicitly the problem of coordination for a large team.

3 Trends in MRS

In this section we summarize the results of our analysis of the works on MRS that have recently been proposed in the literatuure. We first present a summary of the classification of some works according to our taxonomy and then look at specific issues and discuss trends.

In Table 2 we summarize some of the classified works (namely, those works published since 2000), grouping them according to the tasks performed by the MRS, and their position inside our taxonomy. The analysis performed over the recent MRS literature suggests that while with both *Unaware* and *Aware not coordinated* systems very interesting results can be obtained in the execution of simple and losely coupled tasks, such as *Foraging* or *Box Pushing*, for more complex domains *Weakly Coordinated* and *Strong Coordinated* approaches are preferred. For example tasks such as *Soccer*, where the competing environment requires high efficacy, or *Exploration*, where the unpredictable and uncertain environment requires high robustness, more complex coordination capabilities are required. Although among the *Strong Coordinated* approaches, all the possible organizations have been extensively used, a trend towards the development of distributed ones is rather clear. Distributed approaches are preferred because are generally more flexible, robust and less computational demanding.

In order to analyze the development of some features of MRS during the last years, we have drawn some histograms in which we have grouped the works according to some specific features over the pubblication years from 1997 to 2002. These histograms give only a qualitative indication of the trend of the papers on MRS, since they take into account only a portion of the high number of works on MRS. Nevertheless, the papers that have been considered here represent a substantial coverage of the works on MRS in the last five years and thus the analysis is useful for deriving some interesting insights on the recent developments in the MRS community.

The first histogram in Figure 2a reports on centralized vs. distributed approaches. The trend towards the development of distributed systems with respect to centralized ones in the last years is rather clear. We believe that one of the reasons for the choice of distributed systems is that in order to effectively realize MRS in dynamic and complex application domains, distributed approaches guarantee more robustness and efficency with respect to centralized ones.

The second histogram evaluates the MRS system architectures in terms of their capability of coping with environmental changes in a reactive or deliberative way. Since this characteristic of a MRS has been investigated only recently [10], only a few articles address this issue explicitly, although it is usually possible to characterize them with respect to it. However, the histogram in Figure 2b shows that there is not a precise trend in this feature and that both reactive and deliberative MRS have been successfully implemented in the last years.

In the histogram in Figure 2c we have investigated the communication mechanisms used by these systems. It shows that direct communication is considered an effective way for coordination and even if in the last years there have been some works using stigmergic communication or that do not use communication at all, the use of direct communication allows for simpler but still effective forms of coordination.

The analysis of these diagrams allows for a general view of the trend in the design of recent MRS. In particular, from a coordination point of view, distributed approaches based on explicit communication seem to be suitable and effective for application in several domains. Moreover, the architectural choice in realizing deliberative or reactive MRS has not nowadays a precise trend, since effective solutions have been proposed for both the two approaches.

Looking at the most recent development of the MRS research two main future perspectives seems to be considered as important topics: *Large Scale* systems and *Complex task* execution. Several efforts have been done in the recent work on MRS for building systems that can deal with a large number of robots capable of performing effective coordination in complex tasks. In particular, issues such as cooperative localization, long term autonomy, task assignment and conflict resolutions, have been addressed in large scale MRS. These trends impose clear constraints on the *System* and *Coordination* dimensions of our taxonomy. In particular, research pushes toward *Heterogeneous* teams of robots following *Stron Coordinated* approaches. The complexity of the tasks in which robots are involved (e.g. building patrolling [4, 5], large-scale assembly [8], rescue operations) entails increasingly complex capabilities both in software and in hardware. Thus heterogeneity is a key property in order to exploit different robot capabilities reducing the cost of the overall system development.

Moreover, from our perspective, social deliberative architectures, although more complex to realize, ensure more efficent and effective strategies in uncertain and dynamic environments. In most of the large scale heterogeneous systems developed so far, a *Weakly Centralized* approach has been preferred, where the more capable robot assumes the role of leader for the most complex tasks [4, 5].

4 The RoboCare project

The RoboCare project [1] is funded by MIUR (the Italian Ministry for Education, University and Research (Law 449/97/2000)) and is a three years effort that started in January 2003.

The project focuses on the development of distributed systems in which software and robotic agents contribute to the common goal of generating active services in environments in which humans may need assistance and guidance, such as health care facilities. In particular, RoboCare aims at studying issues and challenges involved in the design of systems for the care of the elderly that adopt both fixed and mobile heterogeneous agents. In general these agents can be robots, intelligent sensors or possibly even humans, but a very relevant challenge is represented by the design and implementation of a multi-robot system to create a *helping environment* for humans. The project is a National initiative that involves both Robotics and Artificial Intelligence researchers and investigates several aspects of the problem from high level problem solving facilities, to sensorized environment networks, to several robotics platforms for specific tasks, to the problem of coordinating multiple robots in the same environment.

The activities focus on two scenarios, the first being a domestic environment in which domotic technology, robotic components and care-givers contribute to the common goal of assisting an elderly person in his or her daily life. The second scenario is a health-care institution, an environment in which these actors cooperate in order to enact a predefined workflow of activities for the care of the elderly. Both these settings provide a rich set of challenges for the technology, which is the scope of the research teams and is also motivating the development of new solving tools which address the issues connected to improving the level of autonomy for older adults.

The project aims at creating a initial demonstration environment in which multiple robots are able to perform specific services and make them available as e-services to the world. A supervision system, that uses planning and scheduling technology, will be able to compose such services and suggest more complex plans for the environment according to high level goals. The robotic services currently pursued are the following: (i) reminder (i.e. "it is time for your pill"); (ii) entertainment (i.e. "let's have a chess match" or "read me the news") (iii) transport (i.e. "get me a coffee from the coffee-machine"), (iv) examination (i.e. "check the stove"), (v) search (i.e. "look for Mr.Smith"), (vi) escort ("go for a walk with Mrs. Brown").

Once achieved this basic operational environment, the project will deepen the analysis of all the issues that

[1] See `http://robocare.ip.rm.cnr.it`

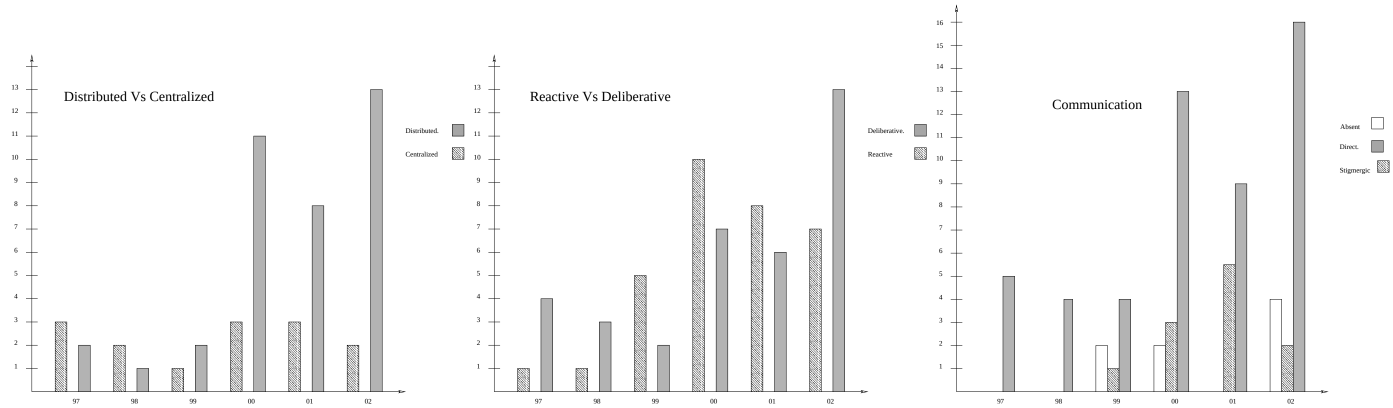

Figure 2: a) Centralized vs. Distributed. b) Deliberative vs. Reactive. c) Communication.

make an intelligent system based on MRS both robust and widely acceptable. A high level goal of the project is to show how intelligent robotic systems (e.g., robotic platform plus high level intelligent functionalities) could represent a viable alternative to physical adaptation of homes proposed by state of the art domotics. The project aims at paving the way for showing how low cost autonomous robot can increasingly perform useful tasks. Additionally we constantly pay attention to the other side of the coin connected to the use of technology aimed at helping people: which is the cognitive impact of this novelty and how we can drive the research to avoid rejection by real users. We also are paying attention to the issue of reliability of the heterogeneous robotic platforms that are planning to use in the project, and are studying the problems connected to their continuous use in an environment.

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