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Current State of the Art in Multirobot Systems

S. Verret
DRDC Suffield

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Abstract

Since the late 1980s, researchers have been working with teams of robots, both homogeneous and heterogeneous in composition. All have shown different levels of cooperation, coordination, awareness and communication. During that time, research in multirobot systems has progressed along many fronts including architectures, communication methods, coordination efforts, and several more. This paper will give a brief history of robotics and detail some of the inspirations and influences in multirobot systems. Finally, it will conclude with a non-exhaustive but expansive survey of the various research that has been performed in the past two decades.

Résumé

Depuis la fin des années 1980, les chercheurs ont travaillé avec des équipes de robots de compositions à la fois homogènes et hétérogènes. Toutes ces dernières indiquent des niveaux différents de coopération, coordination, reconnaissance et communication. À cette époque, la recherche dans le domaine des systèmes multirobots progressait à de nombreux niveaux dont les architectures, les méthodes de communication, les efforts de coordination et autres. Cet article résume brièvement l’histoire de la robotique et donne quelques détails au sujet des sources d’inspiration et d’influences dans le domaine des systèmes multirobots. Il se termine enfin avec un sondage non exhaustif mais coûteux portant sur une variété de recherches ayant été effectuées durant les deux dernières décennies.

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Executive summary

Current State of the Art in Multirobot Systems

S. Verret; DRDC Suffield TM 2005-241; Defence R&D Canada – Suffield;
December 2005.

Introduction

The future battlespace will see an increased number of semi-autonomous and fully-autonomous systems. By 2030 it is expected that fully autonomous systems will be sufficiently robust to permit them to vastly outnumber humans on the battlefield. To advance to the lofty goals of 2030 we are currently researching multirobot systems and collective robotics. The purpose of this paper is to provide a comprehensive, though not exhaustive, review of the works that have been done in multirobot systems. In order to get a sense of what multirobot systems are and how they can effect the future battlespace, it is necessary to complete a review of what has been done. In the preliminary sections we will provide both a brief introduction of the robotic inspirations and of the biological influences to multirobot research. This will lead us to our most important section which will answer the question - what is a multirobot system? To answer this question, we will sort many of the various works according to a high-level taxonomic structure.

Taxonomy

A multirobot system is a team of robots, either heterogeneous or homogeneous, having the following characteristics: cooperation, awareness, communication and coordination. Each of these terms, as it pertains to the qualification of multirobot systems, is defined below:

Cooperation is defined as joint operation or action amongst a group of individuals.

Awareness is defined as the knowledge of the existence of other individuals in a system.

Communication is defined as the act of relaying information from one individual, either directly or indirectly, to another individual.

Coordination is defined as cooperation in which the actions of the group are performed as a reaction to the previous actions of the group. Coordination can be either centralized or decentralized.

Rather than grouping the various research articles in multirobot systems into a specific taxonomy, we have organized this research into categories that have received the highest amount of attention. Therefore, the rest of this paper will concentrate on the following seven areas of multirobot systems:

- Architectures - centralized/decentralized systems, homo/heterogeneous systems;

- Communication - indirect vs direct communications;
- Cooperation - eusocial vs cooperative behaviours;
- Object transport - foraging/sorting, collective building;
- Localization - mapping, exploration;
- Resource Conflicts; and
- Applications.

Significance

This paper includes a brief introduction to both traditional and behaviour-based robotics, and to multirobot systems. Next, we the biological inspirations and taxonomic categorization of a multirobot system are discussed. Finally, we provide a comprehensive survey of architectures, communication, cooperation, object transport, localization, and resource conflicts with respect to multirobot systems. The purpose of this research is to inform the reader about the current research that has been performed in multirobot systems and provide the reader with insight into what may be the future of multirobot systems. The main goals of this research are to both answer the question - what is a multirobot system? - and provide a survey that will enlighten the reader about multirobot systems.

Sommaire

Current State of the Art in Multirobot Systems

S. Verret; DRDC Suffield TM 2005-241; R & D pour la défense Canada – Suffield; décembre 2005.

Introduction

Les espaces de combats du futur seront les témoins d'une augmentation des systèmes semi-autonomes et complètement autonomes. On prévoit que d'ici 2030, les systèmes complètement autonomes seront suffisamment robustes et seront plus nombreux que les humains sur les champs de bataille. Pour être en mesure d'atteindre cet objectif audacieux, nous examinons actuellement les systèmes multirobots ainsi que la robotique collective. Le but de cet article est de fournir une étude extensive, bien que non exhaustive, des travaux effectués sur les systèmes multirobots. Pour être en mesure de mieux comprendre les systèmes multirobots et comment ces derniers pourront affecter les futurs espaces de combat, il faut examiner ce qui a déjà été accompli dans ce domaine. Les sections préliminaires fournissent à la fois une brève introduction au sujet des sources d'inspiration en robotique ainsi que des influences biologiques sur la recherche multirobot. Ceci amènera à la section la plus importante qui répondra à la question : qu'est-ce qu'un système multirobot ? Pour répondre à cette question, nous classifierons une variété de travaux selon une structure taxonomique de haut niveau.

Taxonomie

Un système multirobot est une équipe de robots, soit hétérogène soit homogène, qui possède les caractéristiques suivantes : coopération, reconnaissance, communication et coordination. Chacun de ces termes, relatifs à la qualification des systèmes multirobots, est défini ci-dessous :

Coopération est définie comme une opération conjointe ou une action parmi un groupe d'individus.

Reconnaissance est définie comme la connaissance de l'existence d'autres individus dans un système.

Communication est définie comme l'acte de relayer, soit directement soit indirectement à un autre individu, l'information qui provient d'un individu.

Coordination est définie comme un état de coopération dans lequel les actions d'un groupe sont effectuées en réaction aux actions précédentes d'un groupe. La coordination peut être soit centralisée soit décentralisée.

Au lieu de grouper les articles provenant d’une variété de recherches sur les systèmes multirobot dans une taxonomie spécifique, on a organisé cette recherche selon les catégories qui ont reçu le plus d’attention. La fin de cet article se concentre donc sur sept domaines des systèmes multirobots suivants :

- Architectures – systèmes centralisés / décentralisés ; systèmes homogènes / hétérogènes ;
- Communication – communication indirecte par rapport à communication directe ;
- Coopération – comportement asocial par rapport à comportement coopératif ;
- Transport d’objets – collecte et tri, édifice commun;
- Localisation - cartographie, exploration ;
- Conflits quant aux ressources et
- Applications.

La portée des résultats

Cet article introduit brièvement les comportements traditionnels et ceux basés sur la robotique ainsi que sur les systèmes multirobots. Ensuite, on y discute les sources d’inspiration biologiques et la catégorisation taxonomique d’un système multirobot. On termine avec un sondage compréhensif des architectures, de la communication, de la coopération, du transport des objets, de la localisation et des conflits quant aux ressources concernant les systèmes multirobots. Le but de cette recherche est d’informer le lecteur au sujet de la recherche actuelle qui a été effectuée sur les systèmes multirobots et de procurer au lecteur un aperçu de l’avenir de ces système. Les buts principaux de cette recherche sont à la fois de répondre à la question : qu’est-ce qu’un système multirobot ? Et de procurer un sondage qui donnera un aperçu au lecteur des systèmes multirobots.

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1 Introduction

The purpose of this paper is to provide a comprehensive, though not exhaustive, review of the works that have been done in multirobot systems. In order to get a sense of what multirobot systems are, it is necessary to complete a review of what has been done. For instance we try to answer the question - what is a multirobot system? To answer this question we we will sort many of the various works according to a high-level taxonomic structure (section 5). This categorization will then be explained in detail in section 4. First, however, we will detail the robotic inspirations (section 2) and biological influences (section 3) of multirobot systems.

2 Robotic Inspirations

The word “robot” was first introduced by the acclaimed Czech playwright Karel Capek (1890-1938). Derived from the Czech word “robota” for forced labor or serf, the word “robot” was introduced into his play R.U.R. (Rossum’s Universal Robots) which opened in Prague in January 25, 1921 [1]. Since then, “robot” has been defined in several different contexts and the definition will undoubtedly continue to evolve. The purpose of this section is to give the reader some brief background on collective robotics. Several examples of collective robotics are given and emphasis is put on experiments specifically dealing with collective sorting and the communication challenges involved in collective robotics. First, a very brief summary of the robotics world before collective robotics was explored will be given.

2.1 Traditional Robotics

The first actual use of a robot was in 1942, when the United States government undertook a project, called the Manhattan Project, to build a nuclear bomb [1]. The telemanipulator was first developed when the scientists involved came across problems with the handling and processing of radioactive materials. The telemanipulator was handled by the scientist who would move it around and watch a display of what the end of the manipulator was doing. This is very similar to what is now being done in the field of medicine as robotic telemanipulators are helping surgeons perform key maneuvers without taking drastic measures on the patient. It was the partial automation of this first manipulator that paved the way towards automated manipulators for other applications.

It is widely agreed that the first programmable robot was designed by George Devol, who developed Unimation. Unimation [1] was bought by General Motors in the early 1960’s and was the first robot of its kind to be used in industry. Since then the two most common types of robot technology that have evolved for industrial use are robot arms (industrial manipulators) and mobile carts (automated guided vehicles) [1]. Eventually, robots that acted semi-autonomously or under supervisory control were being developed. Finally, current research is developing teleoperated robots equipped with sensors that acquire information and communication links that send sensory data to the operator.

In 1967, Shakey, the first Artificially Intelligent (AI) robot was created at the Stanford Research Institute. Shakey operated using a strictly hierarchical pattern of intelligence as shown in Figure 1. A hierarchical pattern of intelligence operates sequentially and in an ordered fashion. A step cannot be initiated until the step before has finished. Until the late 80's, the hierarchical approach, was "the" method used by researchers.

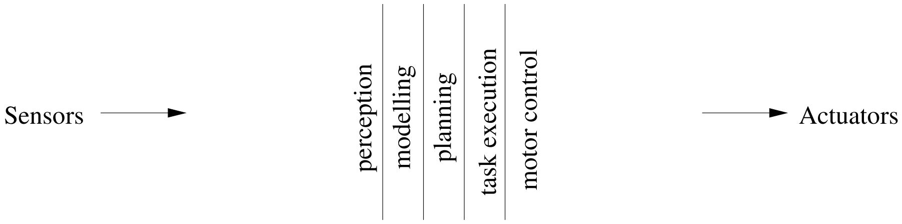

Figure 1: *A traditional or hierarchal decomposition of a mobile robot control system into functional modules [2].*

It is important to understand, however, that even today, the majority of robots reside in highly structured worlds and very closely monitored environments that are amenable to traditional AI approaches.

2.2 Behaviour Based Robotics

In 1984 Valentino Braitenberg wrote a book [3] that described a set of experiments in which increasingly complex vehicles are built from simple mechanical and electrical components. Each of these imaginary vehicles in some way mimics intelligent behaviour and each was labeled with a name corresponding to the behaviour it imitates (e.g. Fear, Aggression, Logic, Values). Braitenberg's vehicles progress and the reader sees very intricate behaviours emerging from the interaction of simple component parts. Essentially, by the end of the book Braitenberg builds intelligent behaviour.

Until 1986, intelligence was implemented using the hierarchical approach mentioned in Section 2.1. At about the same time as Braitenberg was developing his hypothetical experiments, Rodney A. Brooks wrote his paper titled, "A Robust Layered Control System for a Mobile Robot" [2]. The entire mobile robotics scene was revolutionized. Brooks outlined a layered, behaviour based approach (see Figure 2) that acted in a nearly orthogonal fashion to the hierarchical approach and very similarly to the approach described by Braitenberg's experiments [3]. Brooks outlined a system that was designed solely for the purpose of mobile robotics. He outlined the requirements of a control system for an intelligent autonomous mobile robot that could possibly include: multiple goals, multiple sensors, robustness, and additivity [2]. These requirements put constraints on any possible future control system. Brooks came up with a method, labeled the "behaviour based approach", that simplified the control system needed for autonomous mobile robots. This system paved the way for mobile robots that could be created, maintained and improved upon in a more efficient manner. The reason being that if a new sensor was added or needed repairs, or if more capabilities were needed, a new behaviour could be added or dropped with ease.

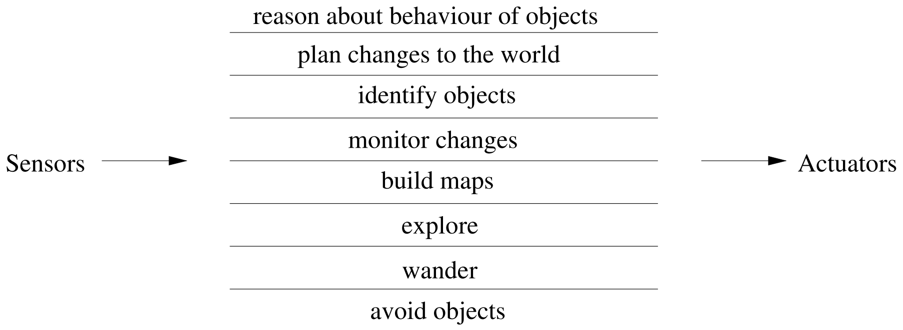

Figure 2: *A decomposition of a mobile robot control that is based on task achieving behaviours [2].*

Around the same time, Reynolds [4] was examining flocks of birds and the aggregate motion associated with a flying flock. Reynolds developed a distributed behavioural model for a bird in a flock. His approach assumed that a flock is simply the result of the interaction between the behaviours of the individual birds. Reynolds created simple behaviours like collision avoidance, velocity matching, and flock centering into his simulated birds. The approach developed by Reynolds was very similar to Brooks' methods mentioned above.

These three very separate sources eventually formed what is now known as behaviour based robotics. Brooks has also provided additional work [5] into behaviour based systems as have others [6, 7, 8].

2.2.1 Why Behaviour Based Robots

Why did behaviour based robots appear? Why are behaviour based robots "simpler" and what is the impact of these simpler robots?

There are several reasons why behaviour based robotics has emerged in the field of mobile robots:

- Robots need to execute behaviours quickly, and a tighter coupling with the sensors and the actuators allow the robots to “react” and operate in near “real-time.” The overall simplicity of the behaviour based system means that such systems have excellent real-time performance, even with modest resources [9].
- Behaviours can be implemented in either software or hardware with very low complexity and thus can be executed quickly regardless of computational power.
- Behaviours are controlled by the environment; in the sense that they operate reactively, rather than by storing previous states in memory and then acting accordingly.
- As Brooks subsumption architecture demonstrates, behaviour based robots can be layered with incremental bits of circuitry. Circuitry is used here loosely, meaning either direct physical circuitry or firmware organized in a manner analogous to circuitry. By leaving old circuitry (layers) in place, there is an ability to continue to operate even if the new circuitry fails [5].
- Behaviours are inherently modular and easy to test in isolation from the system [1].

However the use of behaviour-based robotics also has its drawbacks:

- Robots aren’t necessarily robust. For instance, if an upper layer fails there are usually no mechanisms to indicate that a degradation has occurred [1].
- Finite state mechanisms are only as good as the level of situations that can be anticipated or incorporated into the state machine [1]. For example, hardwired behaviours result in the robot not being able to adapt to unforeseen situations
- As with humans, reactive robots will react according to the environment, but won’t necessarily do the correct thing [1].
- Most behaviour based robots lack a planning/reasoning component – they cannot predict consequences of actions. However, there is work being done so that new behaviours can be learned using techniques such as neural networks, Bayesian nets and reinforcement learning. Also, researchers are inserting global knowledge and planning abilities on higher level deliberative systems, which typically rely on behaviour based processes.

As mobile robots became easier to create, researchers then started incorporating the research that was going on in the biological sciences (see section 3) into the control of groups or teams of robots.

2.3 Collective Robotics

Collective robotics is quickly becoming a vast research area and includes several different topics and ideas, as shown in the various surveys [10, 11, 12, 13, 14, 15, 16].

In this paper we will define a multirobot system as a team of robots, either heterogeneous or homogeneous, having the following characteristics: cooperation, awareness, communication and coordination. The exact categorization that we are using for this survey along with each of these characteristics will be defined further in section 4. It is important to mention that a multirobot system is a system that exhibits cooperative behaviour. Cao *et al.* define cooperative behaviour as a system that, due to some underlying mechanism of cooperation, increases the total utility of the system [12].

Now that we've come up with an idea of what collective robotics is, we need to understand why collective robotics is an important area to study.

2.3.1 Why Collective Robotics

Dudek *et al.*, explained that collectives offer the possibility of enhanced task performance, increased task reliability and decreased cost over more traditional robotic systems [11].

Cao *et al.* [12] says that systems of multiple robots are interesting because while the overall task may be overly complex, building and using several simple robots to address the problem can be easier, cheaper, more flexible and more fault tolerant. Cao *et al.* [12] also discusses how a single robot is spatially limited when "multiple robot systems can accomplish tasks that no single robot can accomplish, since ultimately a single robot, no matter how capable, is spatially limited."

Arkin and Balch [17] argued that two (or more) robots can be better than one for several reasons:

- Many robots can be in many places at the same time (distributed action).
- Many robots can do many, perhaps different things at the same time (inherent parallelism).
- Often each agent in a team of robots can be simpler than a more comprehensive single robot solution (simpler is better).

These examples all describe useful examples of multirobot systems and why the research is important. It is also interesting to understand where the ideas for solutions to these problems have come from. The next section describes the biological influence on multirobot systems.

3 Biological Influence

Many AI roboticists often turn to the biological sciences for inspiration because animals and man provide existence proofs of different aspects of intelligence [1]. The proof that intelligence exists has driven these roboticists to attempt to mimic this intelligence in machines. Insects are considered to be very “simple” organisms but yet they are still able to accomplish intelligent tasks despite the fact that they have basically no sophisticated intelligence. Thus, nature has provided the robotics community with an abundance of different “behaviours” that designers have attempted to incorporate into their robotic system designs.

The biological influence that definitely appears in collective robotics is not seen as a proof of collective robotics but rather as an inspiration for collective robotics. One of the most important biological species that has influenced the collective robotics research is that of insects such as ants [18, 19, 20], bees, wasps, and termites [21].

One of the more comprehensive references on insects is the book by Holldobler and Wilson [22], which serves as an excellent reference on the communication and social organization between ants. They also discuss how the communication between ants is typically of the chemical (pheromones) variety. Others, like Deneubourg [23] and Franks [24, 25] have written publications about foraging and sorting behaviours amongst ants.

There are also other notable works that have discussed biologically inspired experiments in robotics [26, 20, 19].

These researchers and others have laid out simple behaviour-based models that can accomplish complex tasks such as foraging and cooperative transport. Researchers [27, 28, 9, 29, 30] have then gone on to implement these models with real robots and have been able to prove experimentally that the use of basic behaviours inspired by the biological world can reproduce similar larger scale collective behaviours in the robotic world.

The biological world has indeed inspired the collective robotics community to ask important questions about how emergent behaviours and emergent intelligence actually occur, especially amongst “simple” organisms.

4 Categorization

4.1 Introduction

Before we begin our survey we first must describe the method we used to group the various works in multirobot systems. As mentioned previously in Section 2.3 a multirobot system is a team of robots, either heterogeneous or homogeneous, having the following characteristics: cooperation, awareness, communication and coordination. Each of these terms as it pertains to the qualification of multirobot systems is defined below:

Cooperation is defined as joint operation or action amongst a group of individuals.

Awareness is defined as the knowledge of the existence of other individuals in a system.

Communication is defined as the act of relaying information from one individual, either directly or indirectly, to another individual.

Coordination is defined as cooperation in which the actions of the group are performed as a reaction to the previous actions of the group. Coordination can be either centralized or decentralized.

Previous works by Iocchi *et al.* [14], Dudek *et al.* [11] and Cao *et al.* [12] have all attempted to understand multirobot systems by categorizing or classifying multirobot systems according to specific groups. For instance, Cao *et al.* provided a taxonomic organization of the literature based on the problems and solutions that have arisen in the field and came up with five research axes. They are group architecture, resource conflicts, origins of cooperation, learning and geometric problems, Second, Dudek *et al.* presented a taxonomy that classified multiagent efforts according to communication, computational and other abilities. Finally, Iocchi *et al.* proposed six different classification dimensions including, a cooperation level, a knowledge level, a coordination level, an organization level, communication and team composition.

Rather than grouping the various research articles in multirobot systems into a specific taxonomy such as Dudek, Cao and Iocchi we have organized this research into categories that have received the highest amount of attention. Therefore the rest of this paper will concentrate on the following seven areas of multirobot systems:

- Architectures, centralized/decentralized systems, homo/heterogeneous systems;
- Communication, indirect vs direct communications;
- Cooperation, eusocial vs cooperative behaviours;
- Object transport, foraging/sorting, collective building;
- Localization, mapping, exploration;
- Resource Conflicts; and
- Applications.

5 Survey

5.1 Introduction

The field of collective robotics emerged in the late 1980s. However, in the early 1950s Walter's robots Elsie and Elmer [31, 32] demonstrated cooperative behaviours. Although not widely publicized, perhaps because Walter did not call them robots, they are indeed the first example of robots that could coordinate and coexist. Since Elsie and Elmer, there have been several different task domains that researchers have used to demonstrate collective robotics. The task domain survey below, which is by no means exhaustive, includes: architectures, communication, cooperation, object transport, localization, resource conflicts, and other examples.

5.2 Architectures

In robotic systems there are three basic system architectures. Deliberative systems follow the sense-model-plan-act method and are based mainly on planning; reactive systems follow the behaviour-based approach and have a tight coupling between the system's sensors and actuators; hybrid systems are a mixture of the two.

From the three basic architectures, researchers have started to develop more complex architectures that, under a wide range of environmental conditions, have the ability to negotiate the issues of synchronization, cooperation, coordination, task allocation, communication. At a very low level, robots must be able to react quickly to dynamic changes in the environment and perform reactive routines in order to accomplish tasks such as obstacle avoidance. These robots must be able to do this while at an intermediate level accomplishing longer term missions, such as route planning and world mapping. Finally, at higher levels, robots must be able to coordinate with each other, performing asynchronous tasks such as cooperative search or highly synchronized tasks such as cooperative transportation. Any system architecture that has multirobot systems in mind must allow flexibility between the various levels of the architecture as well as provide for arbitration amongst the various control strategies.

In multirobot systems there are two different high-level control strategies: centralized and decentralized. Centralized systems have one machine, agent or process that is in control of the entire system. This agent controls all of the other agents in the system. Decentralized systems [33, 9, 34, 35] do not have a central agent that monitors all the agents. There also exists hybrid strategies [36, 37, 38, 39] in which there is a centralized planning system that overlooks the decentralized agents. One can also imagine a centralized control system consisting of centralized teams comprised of decentralized agents.

There are several examples of different multirobot specific architectures, employing different control strategies. Below we briefly describe four prominent architectures:

ALLIANCE: The ALLIANCE architecture by Parker [40] facilitates the fault tolerant cooperative control of teams of heterogeneous mobile robots performing missions composed of loosely coupled subtasks that may have ordering dependencies. ALLIANCE is a fully distributed, behaviour-based architecture that incorporates the use of mathematically-modeled motivations [40]. The ALLIANCE architecture, implemented on each robot in the cooperative team, delineates several behavior sets, each of which correspond to some high-level task-achieving function. The primary mechanism enabling a robot to select a high-level function to activate is the motivational behavior [40]. A complete description can be found in [40]. Figure 3 shows a graphical representation of the ALLIANCE architecture.

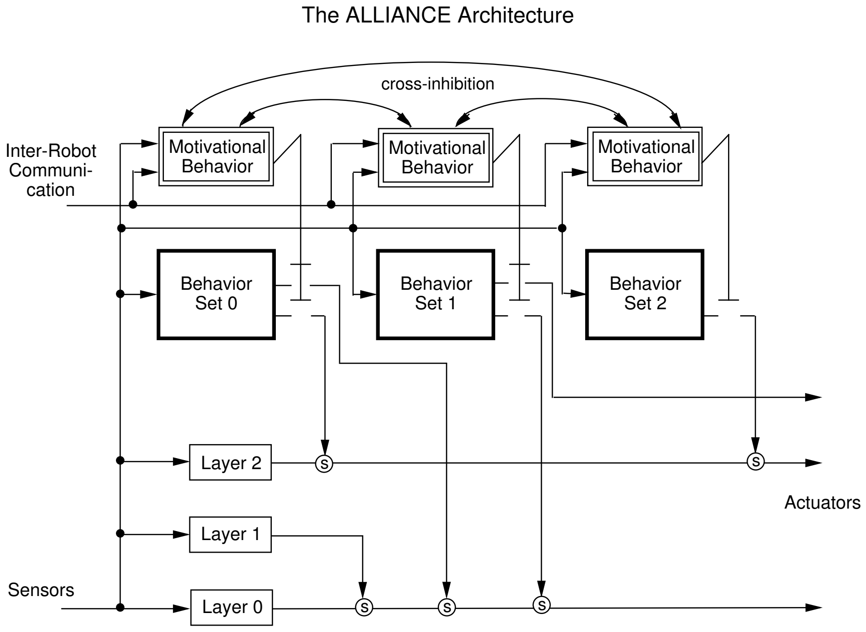

Figure 3: *The ALLIANCE Architecture [40]. Implemented on each robot in the cooperative team, delineates several behavior sets, each of which correspond to some high-level task-achieving function. The primary mechanism enabling a robot to select a high-level function to activate is the motivational behavior. The symbols that connect the output of each motivational behavior with the output of its corresponding behavior set (vertical lines with short horizontal bars) indicate that a motivational behavior either allows all or none of the outputs of its behavior set to pass through to the robot's actuators. The non-bold, single-bordered rectangles correspond to individual layers of competence that are always active.*

LAYERED ARCHITECTURE: The Layered Architecture for coordination of mobile robots by Simmons *et al.* [41] is an architecture that enables multiple robots to explicitly coordinate actions at multiple levels of abstraction. Their layered architecture has three layers than enables robots to interact directly at the behavioural level, the executive level and the planning level.

This architecture ensures that at all levels the robots utilize coordinated behaviours, coordinated task execution and coordinated planning. Each robot essentially has these three layers and on an individual robot the layers can exchange information while on a robot-to-robot basis the synonymous layers (e.g. the executive layer) talk to each other.

Figure 4 shows a graphical representation of this layered architecture.

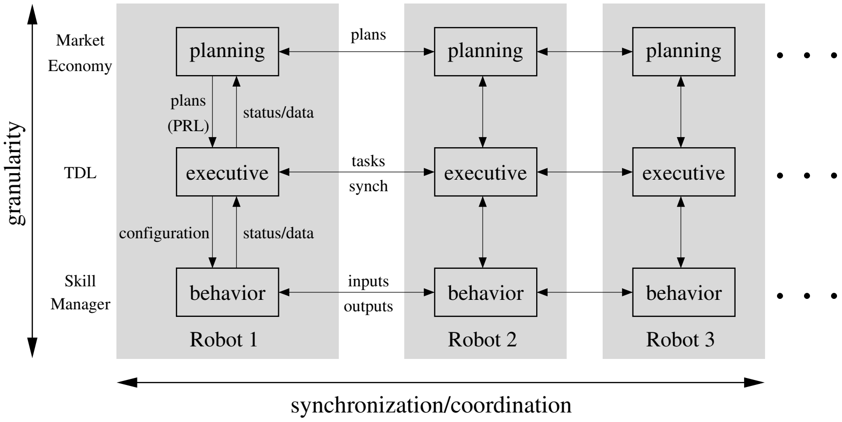

Figure 4: *The LAYERED multirobot architecture [41]*

CHARON: The CHARON high-level language describes multi-agent systems [42]. CHARON is a language for modular specification of interacting hybrid systems based on the notions of agents and modes. “For the hierarchical description of the system architecture, CHARON provides the operations of instantiation, hiding, and parallel composition on agents, which can be used to build a complex agent from other agents. For the hierarchical description of the behaviour of an agent, CHARON supports the operations of instantiation and nesting of modes” [42]. Figure 5 gives four graphical representations of the CHARON system.

CAMPOUT: The CAMPOUT architecture, designed by Huntsberger *et al.* [43], is an architecture that is able to autonomously adapt to the uncertainties of a dynamic environment. “CAMPOUT is a distributed control architecture based on a multi-agent behaviour-based methodology, wherein higher-level functionality is composed by coordination of more basic behaviours under the downward task decomposition of a multi-agent planner. Basically CAMPOUT provides the infrastructure, tools and guidelines that consolidate a number of diverse techniques to allow the efficient use

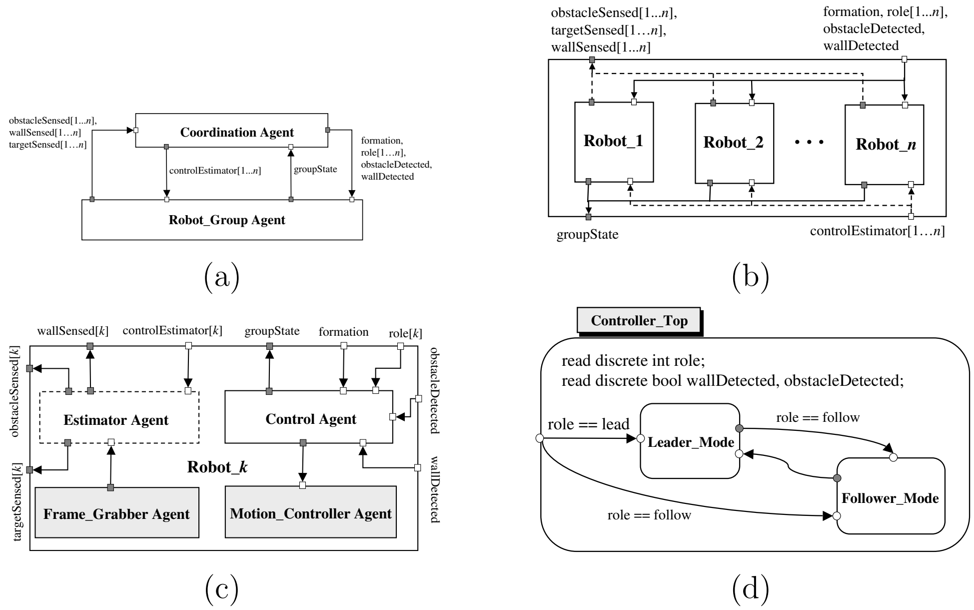

Figure 5: *The CHARON architecture [42]. a) Agent hierarchy diagram. b) Robot-group agent. c) A robot agent consists of estimator, control and hardware interface agents. d) Robot modes within the Controller Top mode.*

and integration of these components for meaningful interaction and operation" [43]. CAMPOUT is comprised of five different architectural mechanisms including, behaviour representation, behaviour composition, behaviour coordination, group coordination and communication behaviours. A schematic overview is shown in Figure 6.

OTHER:The above architectures are but a few of the complex architectures that have been developed strictly for multirobot systems. However there are many other architectures like CLARAty [44], AuRA [45], CEBOT [46] and others [47, 48, 39, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80] that were not explicitly reviewed (for the sake of time and document length) for this document.

5.2.1 Task Allocation

The problem of task allocation in multirobot systems has received significant interest since the 1990s. In 2003 Gerkey *et al.* provided an analysis of the complexity and optimality of key architectures with respect to multirobot task allocation (MRTA) [15]. In their work Gerkey analyzed the computational requirements and the communication requirements of the following six architectures: ALLIANCE [40], Broadcast of Local Eligibility(BLE) [81], M+ [82], MURDOCH [83], First-price auctions [84, 85] and Dynamic role assignment [86]. Gerkey *et al.* reduced the MRTA problem to an instance of the Optimal Assignment Problem [87].

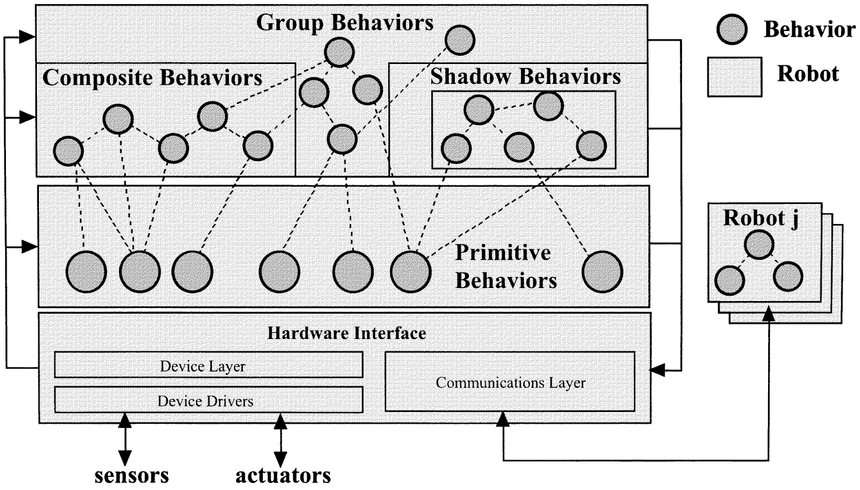

Figure 6: *The CAMPOUT architecture [43].*

Other task allocation work has been done, especially in market-based systems. Market-based approaches often use the auction process to distribute planning for task allocation. For example, each robot locally computes its costs and bids on tasks. TraderBots [88] is an example. Dias *et al.* provide an excellent survey on the market-based methods in [16].

5.3 Communications

Communication in multirobot systems has several meanings. We ask the question, how are robots going to communicate with each other? Other communication issues are concerned with how different processes "talk" to each other or how different modules on a robot share information with each other. These important issues are not discussed in this survey but are discussed in [89].

Centralized coordination, capable of optimal or near-optimal distribution of unmanned forces, requires reliable and frequent feedback and control to ensure predictable performance. Unfortunately, neither the rate nor quality of communications can guarantee this performance on the battlefield or even in urban settings. Autonomy can compensate for this deficit by inserting greater intelligence into each unmanned system. This reduces the communication bandwidth and monitoring requirements but at the cost of optimality and predictability. Research must seek out the minimum necessary level of communication that achieves the maximum optimality or, perhaps more realistically, predictability.

In multirobot systems inter-robot communication can be either implicit (stigmergic), i.e. the robots infer what each other is doing based on other robots actions or how the environment has been changed, or explicit (direct), i.e. the robots can explicitly communicate with each other. When considering explicit communications, the major concern of the system is what data should be sent and how should it be sent. In a bandwidth-rich simulation environment living on a high-power CPU, sending large data packets of information might be acceptable, but in an outdoor wireless environment this luxury may not be available. Instead, care must be taken in data transmissions such that only useful information is sent and that the information will be easily interpreted by its receivers. Robots in an explicit-communication-poor environment need the ability to interpret the dynamics of the environment and behaviours of the robots in the environment in order to gain intelligence and make smart decisions. Therefore a need for both stigmergic and explicit communications exist. Stigmergic communications [90, 9, 33, 91, 92, 93, 94, 74] are warranted so that all information about the world (even when it is available) need not be communicated to each robot. Also we do not want a multirobot system to come to a halt if there is a temporary or even permanent loss in explicit communications. Finally, there will always be a need for explicit communications for higher level communications such as task allocation, task planning etc.

The problem of direct inter-robot communication is an important subject of research in collective robotics. There is a general consensus among the researchers who have examined this problem with regard to the role of communication in multirobot systems cooperative tasks. Balch and Arkin [95] ran experiments with LED indicators on top of the robots signifying what state they were in. They concluded that communication significantly improves performance in tasks with little environmental communication, and that complex communication strategies offer little or no benefit over low-level communication. Dahl *et al.* [96] ran experiments with robots attached with GPS modules that enabled communication between robots that were within $2m$ of each other and observed that individual controllers using communication are significantly more effective than those using a communication-free controller. Easton and Martinoli [97], using infrared signaling on their Khepera robots, found that communication schemes heavily influence the rate of success of the system. Matarić [98] used communication to share sensory data to overcome a hidden state and share reinforcement to overcome the credit assignment problem between the agents. She concluded that communication may compensate for the limitations of more direct sensory modalities, thus enabling efficient learning in multi-robot systems. Verret [99] examined the benefits of communicating information about the perceived world between robots that were in “view” of each other. He concluded that the communication of perceived information can benefit the system up to a certain extent. Each robot in this system was aware of each other as in [34]. Finally, research in vision-based communications [100, 101, 102] , representative communication languages [103, 104], communication reliability [105], network maintenance [106], and other explicit communication methods [107, 108, 109, 110, 111, 112, 113, 114, 115] have been implemented.

Researchers in this field generally agree [116] that adding communication to the system leads to an improvement in performance (as measured by many different task-dependent performance metrics).

5.4 Cooperation

Cooperation, similar to communication, can be either implicit or explicit. McFarland [117] identified two significant types of group behaviours found in nature: eusocial behaviour and cooperative behaviour. Eusocial societies are incapable as individuals but collective interactions can yield intelligent behaviours. For example, it is impossible for one ant to pick up a large bread crumb, but several ants working together can handle this problem with ease. Examples include [117, 35, 94, 92, 9, 77, 118]. Kube [119] took cooperation even further by modeling multirobot tasks in an explicit communicationless environment. Other research in multirobot models can be found in [120, 121, 78, 122]. Similarly belief-desire-intention frameworks have been developed [123, 124, 125] and provide prescriptions for agent coordination.

Cao [12] defined cooperation as the result of interaction, not motivated by innate behaviour, but by an "intentional" desire to cooperate in order to maximize efficiency. Many RoboCup[126, 127] examples [128, 129, 130, 131] include explicit communication while others [132] do not.

Some examples of explicit cooperation are contained in [133, 134]

Robot Formation: As mentioned above, Balch [135] has studied military-based formation strategies. Reynolds [4], however, may have been one of the first to study flocks and their formations with his distributed behaviour model back in 1987. Since then Tang and Zhang [136], as well as Fredslund and Matarić [137], have also performed separate studies of robot formation in a decentralized environment. Formation has been studied on several different platforms and in simulation. Some of the latest works include [64, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 34].

5.5 Object Transport

Many of the original works in multirobot research started out with various object transport problems. Cooperative transport of objects larger than one robot could transport was an interesting problem because more than one robot was needed to accomplish the task. Most of the cooperative transport problem was solved with methods that were biologically inspired. Also stemming from a biological inspiration was the foraging/sorting problem. The foraging/sorting problem examined searching, clustering, and grouping of objects and like objects together. The latest work in object transport involves collective building and some inspirations stem from the goal of sending autonomous teams of robots to Mars. Below, all three object transport problems are examined.

Cooperative Transport: As mentioned above, cooperative transport of large objects (especially objects that are much bigger than the robots) is particularly interesting because a single robot is unable to accomplish this task. Kube's experiments [27, 28] provided the first formalized model of cooperative transport in ants with his wheeled robots. Matarić [151] went on to do similar work with her 6-legged box-pushing robots. The cooperative transport problem was again examined by Trebi-Ollennu *et al.* [152] when they discussed a Mars Rover pair cooperatively transporting a long payload. Other research in cooperative transport includes [18, 153, 154, 155, 156, 157, 119, 158, 159, 138, 160, 161, 162].

Foraging/Sorting: Clustering of objects into piles by homogeneous and heterogeneous groups of robots has been examined in many different ways by several different researchers. Initially, simply clustering objects into a pile, as demonstrated by [9, 163, 164], was a problem that was overcome. Similarly, the trash-collecting robots [165] of Georgia Tech and the artificial toxic waste cleanup mission [166], described by Parker, both looked into the cleaning up of specific areas.

Much of this research was most likely inspired by the writing of Deneubourg *et al.* [23] in their paper "The Dynamics of Collective Sorting Robot-like Ants and Ant-like Robots." Deneubourg *et al.* describe a simple behaviour algorithm that is used by each worker and generates a sorting process.

Melhuish *et al.* [29] and Verret *et al.* [167] built physical systems using minimalist agents that were able to sort colored objects. Melhuish *et al.*was able to sort objects into annular rings, while Verret *et al.* accomplished segregated sorting.

The four different of sorting as defined by Melhuish [29] are:

1. Clustering: grouping a class of objects within a contiguous area that is a small fraction of the area of the available environment. See Figure 7.
2. Segregation: grouping two or more classes of objects so that each occupies a continuous area of the environment that is not occupied by members of any other class. See Figure 8.
3. Patch sorting: grouping two or more classes of objects so that each is both clustered and segregated, and each lies outside the boundary of each other. See Figure 9.

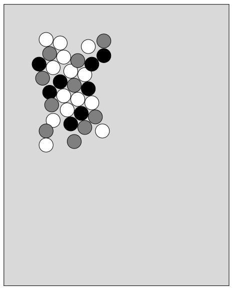

Figure 7: *Clustered objects.*

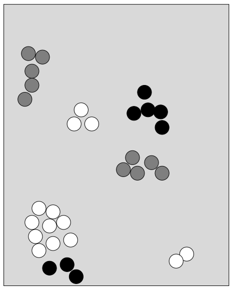

Figure 8: *Segregated objects.*

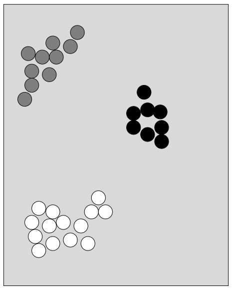

Figure 9: *Patch sorted objects.*

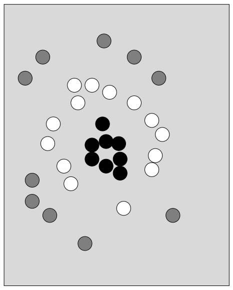

Figure 10: *Annular sorted objects.*

4. Annular sorting: forming a cluster of one class of objects, and surrounding it with annular bands of the other classes, each band containing objects of only one type. See Figure 10.

The foraging/sorting problem has also been tackled by [168, 33, 169, 114, 90, 111, 34, 91].

Collective Building: Collective building or collective construction is a rather new area of exploration in the collective robotics realm with the exception of [168]. Most research that has been done has been biologically inspired by ant and termite collectives. These researchers have also attempted to complete their construction tasks using robots with minimalist behaviours. Wawerla *et al.* [170] may have been the first to demonstrate collective construction abilities in robots. They also demonstrated the ability of robots to construct simple 2D structures. In similar work, Parker [171, 30] designed a group of minimalist robots that could perform blind bulldozing techniques for the clearance of an area mimicking a specific species of ant, the Leptothorax tubero-interruptus.

5.6 Localization

Precise localization is one of the main requirements for mobile robot autonomy [172]. In both the indoor and the outdoor environment robots also need to know their exact pose (position and orientation) information in order to perform any "useful" tasks. In the single robot domain localization is determined by a combination of measurements from proprioceptive sensors that monitor vehicle motion and information collected by exteroceptive sensors that provide world representation.

Navigation between places of interest can be achieved with sensors like GPS and INS, but it can also be achieved through landmark recognition, cooperative positioning and other visual methods. However, none of these methods have any validity if a robot is not able to localize itself with respect to the places of interest. Some of the latest work by Roumeliotis *et al.* [173, 174] combines individual robot motion data via direct communication. A single estimator (a Kalman Filter) processes the latest positioning information from all of the members and generates a pose for each robot. Other research in localization has been done with respect to landmarks [175, 176], scan matching [61], cooperative positioning [177], in the outdoors [178] and graphs [179]. Finally, Schmitt *et al.* provided a vision-based localization method for a multirobot system using cooperative probabilistic state estimation [180].

The localization problem also has two more specific research areas: exploration and mapping.

Collective Exploration: The problem of exploring an environment is also one of the fundamental problems in mobile robotics. In order to construct a model of their environment mobile robots need the ability to efficiently explore it. The NP-hard question then is, where should the robot move in order to minimize the time needed to completely explore an environment? In this case it directly corresponds to the problem of finding the shortest round trip through all nodes of the graph, which is the well-known traveling salesman problem. Arkin and Diaz [181] discussed a line-of-sight constrained exploration algorithm for reactive multi-agent robotic teams. This algorithm allowed a team of robots to explore an area as long as the vehicles stayed within sight of each other. Maio and Rizzi developed an unsupervised exploration algorithm in which several agents cooperate to acquire knowledge of the environment. All agents are structurally equal and pursue the same local exploration strategy; nevertheless, the existence of multiple levels of abstraction in the representation of the environment allows for the agents' behaviours to differentiate [72]. Finally, Burgard and Fox examined collaborative multi-robot exploration [61, 182] by choosing appropriate target points for the individual robots so that they simultaneously explore different regions of their environment. They presented a probabilistic approach for the coordination of multiple robots which simultaneously takes into account the costs of reaching a target point and the utility of target points. Finally, Hughes [183] has also done some collective exploration work.

Mapping: The final aspect of localization is map making or map generation. Combining maps from various robots is a difficult problem especially if the localization information is slightly inaccurate. Several different researchers including Singh [184], Thurn [185], Howard [186] and Fregene [187] have tackled the specific task of mapping the environment based on local sensory information from teams of robots.

5.7 Resources Conflicts

In a multirobot system a resource conflict occurs if a resource is required at any time by more than one robot. There are several different resources including, space or bandwidth, that at one time or another may be needed by more than one robot. This section introduces the traffic control problem, discusses the effects of interference in a multirobot system and provides specific examples of sharing bandwidth techniques.

Traffic Control: Cao *et al.* [12] describe the traffic-control task domain or collision avoidance domain as a problem of resource conflict, which may be resolved by introducing traffic rules. These traffic rules are commonly used to reduce planning cost for avoiding collisions and deadlock in real-world environments, for example, a network of roads. Traffic congestion is one of the leading causes of lost productivity and decreased standard of living in urban areas. Just as human driven vehicles need to deal with traffic problems, nearly all multirobot systems also have to deal with obstacle avoidance, path planning etc. However, Cao *et al.* [12] state that in the experiments that use the behaviour-based approach, robots are never restricted to road networks. Some of the work done in the field of traffic control includes [188, 189, 190, 191, 192, 193].

Interference: As more and more robots are introduced into a system, the probability of robots interfering with each other grows. Lerman [194] studied the effects of interference in a group of foraging robots and examined the overall effectiveness of a group of robots as their numbers increased in a similar-sized environment. Some of the latest work on task interference was done by Ortiz *et al.* [195] with their Centibots system. The Centibots system is a very large scale distributed robot system consisting of more than 100 robots and has been deployed successfully in large unknown environments. One of the key differences between the Centibots system and others is that the set of tasks about which teams must collaborate is not given *a priori*. Finally, other research that has discussed interference, space sharing and path planning problems include [196, 57, 197, 198, 160, 77, 199, 200, 201, 202, 203, 204, 162, 205].

Bandwidth Sharing: In multirobot systems with explicit communication, bandwidth can become an issue. There are several systems that attempt to perform tasks like map merging [206] or multirobot mapping [186] in which explicit communications of large arrays of data is necessary. In a multirobot system similar to the Centibots system [195] high-bandwidth communication between 100s of robots is not necessarily going to be possible. There has been some specific research in methods of sharing bandwidth in situations just like this and they include [207, 208, 209].

5.8 Applications

Multirobot research is an ever growing field and there is still many field applications that are starting to solve their problems with multirobot systems. Some of these applications include landmine detection, various military/space applications and mining. First, however, we will briefly touch on the impact the field of learning is having and will have in multirobot systems.

Learning: Learning in multirobot systems can include, but is not limited to, techniques like Markov models, Q-learning, reinforcement learning, fuzzy logic, neural/neural nets, Bayesian nets, and game theory. Yang *et al.* [210] have compiled a survey of multiagent reinforcement learning for multirobot systems and concluded that even though reinforcement learning seems to be a good option for learning in multiagent systems, the continuous state and action space often hamper its ability in multirobot systems. There has been much work done on learning techniques and two of the best resources for this work include [12, 210].

Landmine Detection: Landmine detection has been studied for many years. Many times the problem has been solved by very sophisticated machines with a wide array of sensors available to the machine. Franklin *et al.* [211] were some of the first researchers to tackle this problem with distributed sensing and multiple search agents. Gage's [212] research outlined how the evolution of today's sensors will soon make it possible for inexpensive yet highly effective autonomous agents to accomplish such tasks as landmine detection.

Military/Space Applications: Huntsberger and his colleagues have written several different papers on the robotic challenges of developing multiple planetary rovers for different types of missions [213, 214, 215]. Balch [135] has also written about different military based applications in which behaviour-based formation control of multi-robot teams would be useful. Other military based multirobot experiments include [216] and [217].

Collective Mining: Dunbar and Klein [218] wrote a technical note in 2002 that considered using mini- or micro-machines to improve control and efficiency of fragmentation, heap leaching and other mining and mineral processing operations.

5.9 Summary

There are several areas of research currently being explored in the field of collective robotics. We focused largely on architectures, communication, cooperation, object transport, localization, resource conflicts, and included some other examples to a lesser extent. However there are still topics like reconfigurable robots and multirobot learning that have barely been mentioned let alone reviewed in this survey. We have not claimed that section is an exhaustive survey, however we feel it is comprehensive in many of the major areas of multirobot systems.

6 Conclusion

This paper included a brief introduction to both traditional and behaviour-based robotics, and to multirobot systems. Next we discussed the biological inspirations behind multirobot systems and attempted to define the key characteristics and taxonomic categorization of a multirobot system. Finally we provided a comprehensive survey of architectures, communication, cooperation, object transport, localization, and resource conflicts with respect to multirobot systems. The main goal was to both answer the question - what is a multirobot system? - and provide a survey that will enlighten the reader about multirobot systems.

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Since the late 1980s, researchers have been working with teams of robots, both homogeneous and heterogeneous in composition. All have shown different levels of cooperation, coordination, awareness and communication. During that time, research in multirobot systems has progressed along many fronts including architectures, communication methods, coordination efforts, and several more. This paper will give a brief history of robotics and detail some of the inspirations and influences in multirobot systems. Finally, it will conclude with a non-exhaustive but expansive survey of the various research that has been performed in the past two decades.

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