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The State of the Art in Distributed Mobile Robotics

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This thesis is submitted to the Department of Software Engineering and Computer Science at Blekinge Institute of Technology in partial fulfilment of the requirements for the degree of Master of Science in Software Engineering. The thesis is equivalent to ten weeks of full time studies.

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Abstract

Distributed Mobile Robotics (DMR) is a multidisciplinary research area with many open research questions. This is a survey of the state of the art in Distributed Mobile Robotics research. DMR is sometimes referred to as cooperative robotics or multi-robotic systems.

DMR is about how multiple robots can cooperate to achieve goals and complete tasks better than single robot systems. It covers architectures, communication, learning, exploration and many other areas presented in this master thesis.

Keywords: Robotics, Distributed, Mobile, state of the art survey, multirobot systems, distributed artificial intelligence (DAI), multi-agent systems, cooperative robotics

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1. Introduction

Distributed Mobile Robotics (DMR) is a multidisciplinary research area that includes elements of e.g. electronics, computer science, artificial intelligence, mechatronics, nanotechnology, human-robot interaction and bioengineering. The Department of Software Engineering and Computer Science (IPD) at Blekinge Institute of Technology (BIT) needs to know the state of the art in DMR prior to a decision whether to start research projects in this area or not.

1.1 Purpose and goals

This thesis is a state-of-the-art survey of the field of DMR focusing on the following questions:

?? What research problems are currently studied within DMR?

?? Which research labs (both academic and industrial) are doing DMR research?

?? What are the current and future applications of DMR?

1.2 Scope

This master thesis will comprise of a survey of the state of the art in DMR and discuss how it could be used to bring different engineering disciplines together in a joint effort. The work effort for this thesis is equivalent to ten weeks of fulltime studies (ten academic points).

1.3 Method

The method used in this thesis was to search for DMR articles on the Internet. I also borrowed two books from InfoCenter, “Introduction to AI Robotics” and “Mobile Robots, Inspiration to Implementation”. I used the references lists of the books and articles I found to find more interesting articles on the DMR area. I also searched for DMR laboratories and tried to locate the bibliographies of prominent DMR researchers to get to know what their latest research was about.

1.4 Thesis outline

In chapter 2 I define what DMR is in this thesis as well as defining other relevant keywords within DMR research as well as showing the history of robotics. Chapter 3 presents why one should use DMR systems instead of single robot systems and what applications are suitable for DMR systems. Chapter 4 presents some of the current applications of DMR systems that exist today and some applications that researches have proposed as future applications. Chapter 5 is about the state of the art in DMR. It is divided into different areas like communication, learning etc. In chapter some conclusions and guidelines for DMR research at BIT are presented. There is also a list of open research questions and some directions for future work and the summary of the thesis. Chapter 7 shows the references used throughout the thesis.

Appendix I lists different research facilities (both academic and governmental).

Appendix II is a list of companies involved in creating DMR applications.

Appendix III shows different organizations that have interest in DMR research.

Appendix IV is a list of conferences and journals related to DMR.

Appendix V contains terms and abbreviations used in this thesis and in other DMR research papers.

2. Background

To be able to do a survey on the state of the art in Distributed Mobile Robotics one must have a definition of what DMR really is. This chapter shows how other people have defined each of the words. Related definitions are also included in this chapter. Then a definition of DMR, as it will be used in the rest of this thesis, is presented. The chapter is concluded with the history of robotics.

2.1 Definition of distributed, mobile and robotics

2.1.1 Definition of "distributed"

Common motives for distributing a system is that there are many geographically spread users or that some processing task could be divided onto many units to increase the systems performance or fault tolerance. A task that can be distributed can be described with a distributed algorithm. Communication is very important in distributed systems and it takes care of transferring messages (data) or synchronizing different subsystems so that the operation that is performed in them is carried out in the correct order. The procedure that is used in the communication is called protocol *[1]*.

2.1.2 Definition of "mobile"

Is able to move freely or be easily moved *[W1]*.

Capable of being moved; not fixed in place or condition *[W2]*.

2.1.3 Definition of "robotics"

The science or study of the technology associated with the design, fabrication, theory, and application of robots *[W2]*.

The area of AI (Artificial Intelligence) concerned with the practical use of robots *[W2]*.

Robotics is a branch of engineering that involves the conception, design, manufacturing operation of robots.

2.2 Related definitions

2.2.1 Intelligent robot

A mechanical creature, which can function autonomously *[2]*.

2.2.2 Definition of "self-contained"

When its body contains everything, such as sensors, information processing units, locomotion units, and power supply, needed for its behaviours. Autonomy and self-containedness are necessary conditions for the intelligent robot *[3]*.

2.2.3 Classification of intelligent robotic systems

1) Nonmobile, nonmanipulative systems such as monitoring and control systems.

2) Nonmobile, manipulative systems such as robot arms fixed in place at the shoulder.

3) Mobile nonmanipulative systems such as inspection robots.

4) Mobile manipulative systems such as mobile robots with arms and end-effectors *[4]*.

2.2.4 Definition of an agent

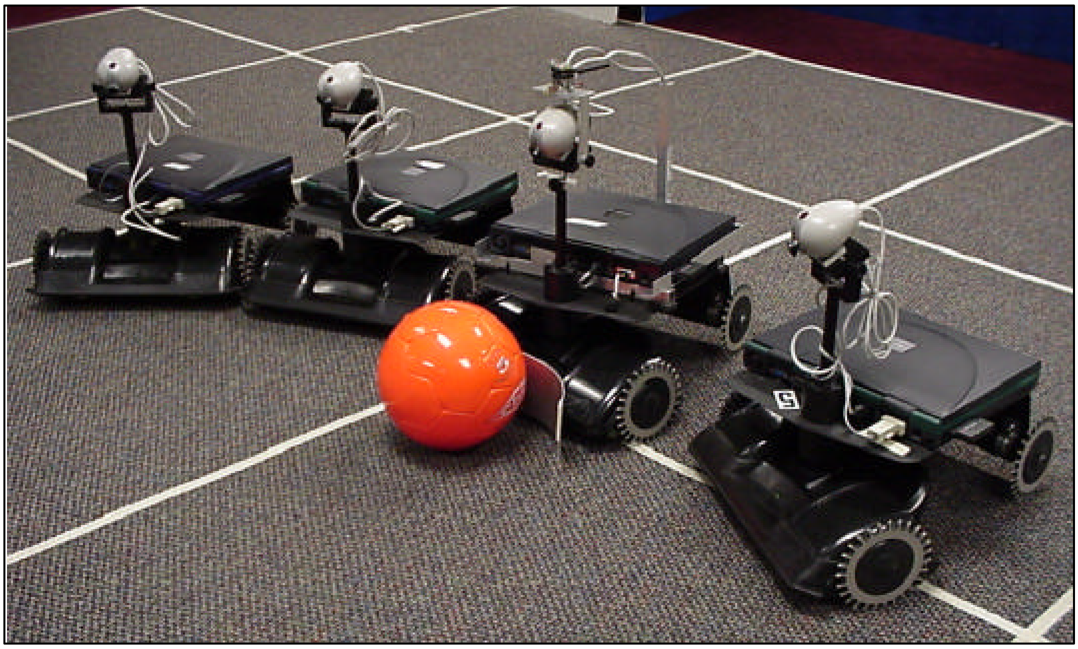
An agent perceives the world in which it is situated *[5]*. It has the capability of interacting with other agents. It is pro-active in the sense that it may take the initiative and persistently pursue its own goals. Atomic agents are parameterised instances of primitive behaviours *[6]*. Assemblages are coordinated societies of agents, which function as a new cohesive agent.

2.3 My definition of DMR

In the thesis I define DMR as the research area studying multiple moving robots that are self-contained and act somewhat autonomic, that cooperate to perform one or more tasks more efficient than any one single robot could do. What is meant by efficient depends on the performance metric chosen for the application of interest (could be completion time, fault tolerance etc.).

Many researchers use the terms multi-robot systems or cooperative robotics when addressing DMR. These terms will be used interchangeably within this thesis, and to me, they all mean the same.

This thesis will only cover mobile manipulative and mobile nonmanipulative systems as described in *[4]* (segments 3 and 4 in chapter 2.2.3). A DMR system can be seen as a physical multi-agent system.



Photograph of Tucker Balch's robots at http://www.cs.cmu.edu/~trb/robotphotos.html where they cooperate to push an orange ball.

2.4 History

"One must know the past in order to analyze the present"

Gustavus Myers

To be able to discuss the state of the art in DMR and to predict the future one must know the past. Here the highlights of the history of robotics and DMR will be presented.

1941. Science fiction writer Isaac Asimov used the word "robotics" to describe the technology of robots and predicted the rise of a powerful robot industry *[W3]*.

1950. The technical development of robotics started *[1]*.

1961. The first prototype of an industry robot was installed *[1]*.

1967-1990. The Hierarchial paradigm is state of the art *[5]*. In the hierarchical paradigm the robot get information about the environment through its sensors system, and then a processing system extracts the necessary information from the data sensors. Then the planning system can compute the necessary motion to achieve the goal and then the execution system will produce the right motion commands to the actuators system.

1980. The industrial usage of robots was modest. This was dependent on the cost and the performance of the robots. During this decade computers got cheaper and better and allowed the robotic industry to boom *[1]*.

1980. Many robotics researchers realised that the AI approach to robotics wasn't living up to expectations *[23]*.

1986. Behaviour-based approach, Brooks propose the subsumption architecture *[23]*. In the behaviour-based approach there is a direct functional connection between sensors and actuators

1988-1992. The reactive paradigm is state of the art. Researchers wanted to investigate biology, cognitive psychology and behaviours. The computer hardware got cheaper *[5]*.

1988 (about). The research field distributed robotics emerged *[24]*.

1990-now. The hybrid deliberative / reactive paradigm is state of the art *[5]*. See Appendix V for more details.

1994. The key areas of robotics were to develop regulators, sensors, computer guidance, artificial intelligence and to model robotic structure and robotic tasks *[1]*.

1997. NASA pathfinder mission landed on Mars and the first autonomous robotics system, Sojourner, was deployed *[W5]*.

1997. The computer Deep Blue wins a chess game over the reigning chess grand master Garry Kasparov *[15]*.

1997. The first official RoboCup games were held *[W6]*.

1998. The company Cybermotion has placed more than 80 androids working with security *[16]*.

1999. Stiga introduces robotic lawn mowers *[W7]*.

1999. Sony introduces the robotic dog, Aibo *[W8]*.

2000. In industry, material-handling applications emerged as the leading use for robots, followed by spot welding, arc welding, assembly, material removal, coating, dispensing and inspection. RIA estimated the U.S. robot population to approximately 98000 *[25]*.

3. Why use a DMR system?

3.1 Advantages

There are many advantages of using DMR systems described in the literature.

Economically

Constructing a single multi-purpose robot costs more in time and money than creating multiple single-purpose robots *[7]*.

Robustness & Reliability

A distributed solution with multiple robots compared to a single robot system is immune to the single point of failure that may occur in the latter systems. The distributed solution is inherently redundant *[8]*.

Distributed action

Multiple robots can be in many places at the same time and they can work on different tasks *[9]*.

Parallelism

Many robots can work simultaneously and cooperatively to accomplish a task *[7]*.

Complexity

Complexity affects the cost of the system and the complexity can be reduced since designing and constructing multiple simpler robots compared to designing and constructing a single robot system is easier. Many environments or missions may require a mixture of robotic capabilities that is too extensive to implement into one single robot *[7]*. Often each agent in a team of robots can be simpler than a more comprehensive single robot solution *[9]*.

Performance

Team members can exchange sensor information, help each other to scale obstacles and collaborate to manipulate heavy objects. A single robot system does not have these capabilities *[10]*.

Potential metrics on performance in distributed robotic systems are *[11]*:

Cost – Build a system to accomplish the task for the minimum cost.

Time – Build a system to accomplish the task in minimum time.

Energy – Build a system that will complete the task using the smallest amount of energy.

Reliability/Survivability – Build a system that will have the greatest probability to complete the task even at the expense of time or cost.

Divide and Conquer

A large number of human solutions to real world problems use multiple humans supporting and complementing each other. These tasks are inherently distributed in space, time or functionality and require a distributed solution *[7]*. Certain problems are well suited for decomposition and allocation among many robots *[9]*.

Task completion time

Many robots can accomplish the mission faster than a single robot can (this can only be applied to tasks that can be divided into subtasks that can be executed in parallel.

Human lives

Using a DMR system instead of humans removes humans from danger. Many of the target applications of DMR systems are potentially hazardous to humans. Introducing robots correctly can improve the quality of life by freeing workers from dirty, boring, dangerous and heavy labour *[W3],[12]*.

3.2 Disadvantages

Coordination and cooperation can be hard to achieve. Single robot systems don't have these problems.

Having multiple robots in a limited area introduces the problem of interference and collisions.

Controlling multi-robot systems are harder than controlling single robot systems.

Testing multi-robot systems ought to be harder than single robot systems because in single robot systems the robot only needs to be tested with its surrounding environment but in multi-robot systems the robots needs to be tested in the environment in the presence of the other robots.

4. Current and future DMR applications

The literature used in this survey shows many application areas for DMR systems. Some of these are presented here. These applications are well suited for team-based approaches. Some of these application areas are potentially dangerous tasks for humans. These applications areas represent extreme environments (except industrial and household applications) where the environment might change any time during the mission affecting the robots sensors and ability to function. It is not easy to make one almost flawless robot that would function in these environments and if it breaks the mission would fail. Sending many robots increases the chance of mission success. Robots are suited for applications that involve one of the three D's (dirty, dull or dangerous).

4.1 Current DMR applications

These are some of the current DMR applications that exist in research and industry today. Researchers have certain domains they use to experiment their theories on:

4.1.1 Test domains

Test domains are applications that researchers use to test their algorithms, architectures and robots on. The test domains used are box pushing, trash can collecting, cleaning, keeping formation, hazardous waste cleanup, cooperative observation of multiple moving targets and robot soccer.

4.1.2 Robot soccer

Robot soccer is played in different ways. Balch *[13]* utilizes the following rules. Teams are composed of four players. The sidelines are walls (no out-of-bounds). The goal spans the width of the field's boundary. The gameplay is continuous. In RoboCup there are different classes with partly different rules.

4.1.3 Cleaning

Robots are used for decontamination and decommissioning of legacy manufacturing facilities and hazardous waste cleanup. They can also be part of a nuclear accident response. In a real world application today robots are used for surveillance and characterization prior to and during clean up activities of radiologically contaminated areas instead of exposing a radiation control technician. In Anderson's *[14]* report we can see how MACS (Mobile Automated Characterization System), RACS (Reduced Access Characterization Subsystem) and TRACS (Transmitter for Reduced Access Characterization Subsystem) cooperate to accomplish the cleaning task. MACS deploys RACS for areas that is non accessible by a large floor characterization system. TRACS works as a repeater to improve the radio communication between RACS and MACS.

There exist robotic vacuum cleaners but these are single robot systems.

4.1.4 Robot wars

Robots are used in various military operations, either as weapons, as surveillance equipment where multiple robots cooperate and perform tasks such as target recognition, dynamic target tracking, terrain recognition, and autoconfiguration to maximize field coverage. There is also a TV-show called "Robot Wars" where robots are put into a battle zone to destroy each other. These robots, however, are teleoperated and not autonomous.

4.1.5 Medical and personal care

Robots can perform surgery and they could be created so that they don't suffer from communication misunderstandings between the actors in the surgery. Robots can also be designed and manufactured so that they are more accurate and precise than humans *[15]*. It is uncertain if the surgery application is a DMR application or not. If modelling it to resemblance human action there certainly will be more than one robot helping to make the surgery as efficient as possible.

4.1.6 Security

The company Cybermotion has placed more than 80 guard robots (1998) to its customers where they monitor facilities for fire *[16]*. The guard robots can be fitted with a camera, optical flame detector, microwave intrusion radar, smoke, humidity, gas and temperature sensor. It is uncertain if their security robots cooperate in their tasks but surely they can be fitted and programmed to do so. Related areas to security are surveillance and reconnaissance.

4.1.7 Household and industrial maintenance

There exist both auto lawn mowers and vacuum cleaners that do these duties for you. Other areas are painting, assembling, pressing, welding, handling, sorting, finishing and gluing. It is uncertain if it exists DMR applications in these areas today.

4.1.8 Entertainment

Entertainment is also an area suited for DMR systems. One example is the advanced Sony AIBO robot dog that is programmable. Another not so advanced example is the annoying toy Furby that can chat with its Furby friends.

4.2 Future DMR applications

"What is considered fiction today might be the facts of tomorrow."

Victor Adolfsson

Apicella *[17]* believes that it is not necessity that is the mother of invention. Instead it is laziness, to reduce manual or intellectual work or to extend human ability. Today's robots are well suited to repetitive or remotely controlled tasks in manufacturing, medicine, industrial research, and other areas, but autonomous and freely mobile robots will require 10 to 20 more years of technology advances.

Future technologies that are believed to impact robotics are pattern recognition, speech recognition, natural language processing and synthetic characters *[17]*.

Hans Moravec at Carnegie Mellon University presents this timeline for robot intelligence.

Year: 2010,Processing power: 3,000 MIPS, Intelligence equivalent: lizard

Year: 2020, Processing power: 100,000 MIPS, Intelligence equivalent: mouse

Year: 2030, Processing power: 3,000,000 MIPS, Intelligence equivalent: monkey

Year:2040, Processing power: 100,000,000 MIPS, Intelligence equivalent: human

According to his timeline it takes 40 years until we can create robots with the intelligence equivalent to humans. It is not only processing power (the hardware) that will make robots smarter. I believe that the software of the robots must be better than today for his timeline to be true. Within twenty, thirty years, household robots will be sold to a price about the same as for cars. These robots aren't specialized; instead they learn how to do a job (this according to the Daily News (Dagens Nyheter)) *[15]*.

4.2.1 The Borg from Star Trek.

"The Borg is an immensely powerful race of humanoids from the Delta Quadrant. Strengthened with cybernetic implants, Borg awareness is as a collective. Individual thought is considered primal and should be "assimilated" into the collective. All Borg are equipped with cybernetic hardware. Different devices are given to different Borg to assist in the specific task they work at. Each Borg is part of a giant subspace communications network, called the Borg Collective." From http://www.ucip.org/divisions/borg/

Although fiction, it does raise several interesting DMR topics. The Borg collective is the way they communicate and it is used for sharing information. Each Borg is a distributed sensor, as well as an actuator that can affect the environment. They assimilate the behaviours of the one they come in contact with and hence learn from them. They are modular (can attach different devices to them) and they are specialized for a certain tasks hence they are heteregenous team.

In the future, robots will probably have and use polymorphic capabilities and shift shapes in order to complete missions like Transformers *[18]*. This requires good building blocks and a proper design when creating the robots in the first place. The ability to shift shape will allow the robot system to scale obstacles and move over unstructured terrain according to Ünsual *[19]*.

4.2.2 Save human lives

Robots will take care of those jobs that are dangerous for humans. There exist both military and civilian applications where robots can take care of dangerous jobs. Robot teams can be created that have higher performance than its human counterpart according to Ericksson *[4]*.

Robots are ideal for fire fighting because they can be designed to withstand heat and be of low weight and hence can help to locate survivors in a burning building without jeopardizing the human fire fighters.

Arkin *[9]* describes robotic scout teams that will be able to perform better than a human scout team thus removing humans from possible danger. These could be operated in sea, on ground, in air and also in space.

Robots can also be used for security and monitoring presence and communications infrastructure according to Thayer *[12]*.

"Over 200 miners is believed to have died in a flooding accident in a tin mine in China" (from Aftonbladet 31 July 2001). Mining is a dangerous job for humans and it is suggested that robots do this job in the future *[15]*.

Small robots are well suited for mine sweeping, nuclear power plant maintenance work and military applications, where the environment is unsafe for humans, and the risk factor is too high to utilize expensive, highly specialized robots. This is according to Evans *[20]*.

Robots could be dispersed in an area that suffers from some sort of environmental disaster or fire and find survivors faster than ordinary search and rescue teams containing humans, dogs and heat cameras *[W4]*.

DMR systems could be used in war situations to gain information advantages over an enemy allowing its weapons to be deployed more efficient.

Many (or all) researchers believe that DMR systems will do these dangerous tasks for us.

4.2.3 Site preparation on Mars

Robot systems are expected to be used in different space applications. Robots operating in space really need to be autonomous since it is hard to teleoperate over vast distances because of the time delay. Ericksson *[4]* writes that supervised intelligent systems (supervised autonomous robotic systems) will enable space exploration.

One of the applications suitable for robots is site preparation task on Mars (and other planets). There they will prepare the infrastructure. This kind of application requires path planning and control of mobile robots in rough terrain environments. Teams of robots are required to work together to physically alter outdoor terrains, levelling the soil and transporting and deploying PV (photovoltaic) tent arrays. The site preparation task is described by Guo *[21]*.

On other planets there is still the need to control the robot team to ensure that they cooperate efficient in highly unpredictable and uncertain environments.

To build robot teams that survive in these harsh environments, the architecture must allow robots to opportunistically select actions based upon the variety of dynamic changes they may experience. Some of those actions could be cooperative clearing and to recruit help when needed.

Teleoperation is necessary in order for the human controller to select certain tasks that need to be prioritised by the robots or to prohibit them from executing a particular task. Robot team members should also be constructed so that they will suggest new activities based on information that they have gathered and the human controller might have missed.

After the site has been prepared and when humans have arrived at the site the robots are needed for maintenance work on the site.

4.2.4 Exploration

Exploration is an area that is suited for DMR systems. Both on land, in air, in sea, in space and on other planets. Brooks *[22]* favours swarms of totally autonomous microrovers (1 to 2 kg per rover) because of the minimized mass delivered to the area and the fact that multiple copies of the rovers increase the chance of mission success. He reports numerous advantages using swarm technology, cost savings due to mass production and lower payload, long delay teleoperation is avoided and simplicity increases reliability. The reduced complexity of the overall mission will allow complete programs to be conceived, researched, developed and launched on shorter time scales than those of today.

5. State of the art

“One must analyze the present in order to predict the future.”

Victor Adolfsson

In this chapter different research areas pursued within DMR will be presented. The DMR research area is still new so no topic area is considered mature *[24]*. Some topics have been studied more thoroughly and experimented with while some topics have only been simulated on computers.

5.1 Characterization of a DMR system

A DMR system can be designed in many different ways. The designer of a DMR system must evaluate these attributes prior to designing the system. This list will help to characterize and divide different research approaches.

Arkin *[9]* presents this list of attributes.

Team size: Single robot systems; 1, Multi robot systems; 2, size-limited, size-infinite

Communication range: None, near, infinite

Communication topology: Broadcast, addressed, tree, graph

Communication bandwidth: High, motion-related, low, zero

Team reconfigurability: Static, coordinated, dynamic

Team unit processing ability: Non-linear summation, finite state automata, push-down automata, Turing machine equivalent

Team composition: Homogeneous, heterogeneous

Jung *[23]* differentiates among various communication structures and control:

Communication structures: Interaction via environment, via sensing, via communication.

Control: Centralized, decentralized. (Centralized means that one robot is leader and plans the actions of the other robots while in decentralized all robots have planning capabilities)

There are at least three paradigms for organizing intelligence in robots according to Murphy *[2]* where the hybrid deliberative/reactive paradigm is the paradigm that is most extensively studied presently:

Paradigm: Hierarchical, reactive, hybrid deliberative / reactive (behavioural)

Parker *[26]* makes the following differentiation:

Communication type: Implicit, explicit

I think that this list could be extended to cover the different types of autonomicity:

Autonomicity: Direct control (teleoperated), supervised autonomy, fully autonomous

This is since some of the research involves the way a human operator can control a team of robots or not. When considering swarm robots, they should probably be completely autonomous and no teleoperation should be conducted, at least not on the level of the individual robot.

In this chapter many different areas of DMR research are presented to show the scope of DMR research. These problems and areas have been addressed and are currently being addressed within DMR research. They are quite challenging problems and they involve both designing and implementing multi-robot systems.

5.2 Communication

The communication aspects in DMR has been studied since the DMR research field appeared. The taxonomy showed that there are many variants of communication. The range can be: None, near or infinite. The communication topology can be broadcasted, addressed, by tree or by graph. The bandwidth can be high, motion-related, low or zero. The communication structures can be via environment, via sensing or via communication. The types of communication can be no direct communication between robots, transmission of state information between agents and goal communication. The communication can be explicit or implicit (implicit does not require a deliberate act of transmission, for example, vision to determine the behavioural state of another robot) *[23]*. Explicit communication is an activity designed solely to transmit information to other robots on the team *[24]*.

Why should robots communicate?

Communication between robots can multiply their capabilities and increase the efficiency. This has been shown in simulation and on real robots. The amount of communication has also been studied. Sometimes even little communication will enhance the performance of the system.

What information needs to be communicated?

In a DMR system the robots need to message other robots and get to know each other's state, what resources they need, what activities they are about to perform and what these tasks are, what the environment looks like, their payload and their imposed deadlines. Looking at the robot soccer domain it would be beneficiary if a robot sees the ball can communicate this to his team members and also to tell his team-mates that he's about to pass the ball to a certain player.

Communication is needed so that robots can cooperate efficient. When designing the robot team one must determine what type, speed, complexity and structure the communication should have according to Arkin *[11]*.

Research results

These are the research results found during the literature survey regarding communication aspects in DMR systems.

Task and environment affect the communication payoffs according to Arkin *[11]*. Communication improves performance significantly in tasks with little implicit or environmental communication (activities like forage and consume). Communication appears unnecessary in tasks for which implicit communication exists. More complex communication strategies (goal) offer little benefit over basic (state) communication for these tasks.

Fault tolerance in multi-robot communication, such as setting up and maintaining distributed communications networks and ensuring reliability in multi-robot communications has had some progress according to Parker *[24]*.

Distributed sensing can be used as a means of communication among robots, one robot obtains and integrates the sensing information about environment states sensed by other robots and distributed in time, space and function. This is used in CEBOT described by Cai *[27]*. Multisource data analysis requires sound mathematic theories like evidential reasoning to be able to integrate the multiple sources.

Avoiding explicit message passing is crucial in multi-robot systems according to Evans *[20]* since it can cause a communication bottleneck. In his work in the Army Ant swarm project the robots broadcasts heartbeats. Only indirect communication, in the form of broadcast or cues, offers a practical solution to the swarm coordination problem. The ability of the Army Ant swarm to accomplish complex goals relies upon implicit cooperation between individual agents. Different scenarios where explicit communications are combined with heartbeats approach can also be considered to obtain more precise swarm coordination at the expense of cost and complexity.

Gerkey *[28]* concurs with Evans about never addressing a robot by name. Instead, robots should communicate anonymously through broadcast means. In his work each robot tracks both its own and its team-mates' fitness and progress, incorporating this performance information into local measures of impatience and acquiescence.

One way of utilizing broadcasting is to use subject-based addressing. It can be used to divide the network into a loosely coupled association of anonymous data producers and data consumers. A data producer simply tags a message with a subject describing its content, and "publishes" it onto the network; any data consumers who have registered interest in that subject by "subscribing" will automatically receive the message. This way all every robot doesn't have to process each broadcasted message.

Researchers seems to agree that it is not appropriate to communicate using names as addresses. Instead broadcasts should be used or addressing should be directed to resources or the message tagged with a subject for everyone to read.

Parker *[24]* writes that recent work in multi-robot communication has focused on representations of languages and the grounding of these representations in the physical world.

A signal-processing student at BIT currently undertakes a master thesis in signal processing focusing on communication between Sony AIBO robot dogs for the RoboCup domain. Communication between moving objects, especially when the head of the robot is constantly moving left to right, is harder than ordinary mobile communication and requires some signal processing solutions. The amplitude differs when the ears move relative to the sender of the message hence adaptive algorithms might be needed to sort out the interference (Doppler effect). So far the robot dogs are able to send 10-12 different messages to each other using sound as a mean for communication *[29]*.

I do not think that communication is a prerequisite for DMR systems; it all depends on the task and the robot systems complexity. I would favour a DMR solution that involves communication because this would enable the robots to cooperate in more complex ways and the DMR system would be more efficient.

5.3 Architecture

A great deal of research in distributed robotics has focused on the development of architectures, task planning capabilities, and control. This research area addresses the issues of action selection, delegation of authority and control, the communication structure, heterogeneity versus homogeneity of robots, achieving coherence amidst local actions, resolution of conflicts, and other related issues. All architectures that have been developed for multi-robot teams tend to focus on providing a specific type of capability to the distributed robot team. Capabilities that have been of particular emphasis include task planning, fault tolerance, swarm control, human design of mission plans etc *[24]*.

There are some important aspects regarding architecture of DMR systems.

Evaluation

Oliviera *[5]* proposes these criteria for robot architecture evaluation

1. Support for modularity
2. Nice targetability
3. Ease of portability to other domains
4. Robustness

I think that research teams that want to develop architectures for DMR systems should know these criteria.

In the following sections some of the architectures that exist today are presented.

Free market architecture

Thayer *[12]* describes how the robot system can be an economic system where the robots exchange services and enter contracts at will. Hence economical models can be used for modelling the system and making the robots conduct the tasks presented at the most cost-efficient way. This should be very interesting for researchers in economics to build robotic economical eco-systems.

Alliance

Parker *[7]* has developed Alliance. It is an architecture for fault tolerant multi-robot cooperation. Cooperative robotic teams usually work in dynamic and unpredictable environments. This software architecture allows the robot team members to respond robustly, reliably, flexibly, and coherently to unexpected environmental changes and modifications in the robot team that may occur due to mechanical failure, the learning of new skills, or the addition or removal of robots from the team by human intervention.

Experience with physical mobile robots has shown that robot failure is very common, not only due to the complexity of the robots themselves, but also due to the complexity of the environment in which these robots must be able to operate. Two types of internal motivations are modelled in ALLIANCE - robot impatience and robot acquiescence. Gerkey *[28]* also uses impatience and acquiescence in his work.

Control architecture

Cai *[27]* describes information sharing in hierarchical control architectures. The information sharing has three aspects (task descriptions, acquiring of robot states and acquiring of environment states). This is proposed to enhance the efficiency of reasoning and planning for cooperative actions. These layers are proposed; Task acquiring layer, reasoning and planning layer, sensing and executing layer. Hence this is a hierarchical architecture.

Collaboration framework

At Carnegie Mellon University they have built CyberRave. It is built to support a robot collaboration framework. With CyberRave, each robot can easily communicate with each other. Humans can input commands from a remote terminal, then the appointed robot performs the task and returns the result back to the human. Related problems currently studied are:

1.Task Decomposition - How can we divide a task and assign the parts to each robot?

2.Resource Management - How can the robots share the limited resources?

3.Synchronization - How can we make the robot do things at the right time?

There are many other architectures for DMR systems and other aspects of interest to DMR architectures and even more architectures for single robot system but these four areas were chosen because they cover four different aspects.

5.4 Centralized or decentralized approach

This area is somewhat related to homogenous (decentralized) and heterogeneous (centralized) robots. Research is conducted on both the central and the decentralized approach. Having a centralized system means that some robot is specialized as an overall control or leader robot. A decentralized system however can consist of homogeneous robots with the same abilities and hence there are no leader selected in priori.

Evans *[20]* suggests that homogenous swarms, which are composed of similar robots, have many advantages over heterogeneous systems. The Army Ant project is immune to the single point failures that plague heterogeneous systems.

Centralized approach

According to Murphy *[2]* a robot team can be seen as a single robot entity with many degrees of freedom. A central computer coordinates the team and gives it instructions according to an optimal plan. Optimal coordination is however exponential in complexity. It assumes that information can be sent freely between the robots and that the environment does not change prior the plan has been created. These assumptions are unrealistic and it makes it a highly vulnerable system. If the leader malfunctions, a new leader must be elected or the team is disabled. Hence the potential single point of failure is a disadvantage of the centralized approach.

In order to get an optimal solution of the task, important things to be considered are as follows according to Premvuti *[3]:*

1) Planning of jobs to be done, deciding roles of each robot

2) Synchronization of those jobs

That means, when the whole system has a common objective, the decision making mechanism should not be distributed to each robot but rather be done at the center. Although a system is distributed, it does not mean that each sub-element of the system is autonomous.

Vaughan *[30]* presents a robot device server for distributed control. There are three main motivations for providing a socket based robot server:

1. Distribution
2. Independence
3. Convenience

Distributed approach

Mataric *[31]* applied a distributed control approach both on the level of the individual robot and on the level of the colony.

When each robot has a separate objective in a multi-robot system, Premvuti *[3]* proposes a distributed approach because it is complicated to integrate all controls and management into one place.

Distributed robotic systems have traditionally been very difficult to coordinate and control due to the absence of a central supervisor or a hierarchy of command. Agents in a distributed system must be capable of collectively accomplishing tasks using only locally sensed information and little or no direct communication. Toward this goal Evans *[20]* paper has introduced a broadcast based coordination scheme that provides global group dynamic that can control individual agents, is influenced by all the agents, but does not reside in any agent. Sensor driven behaviour is consistent with a distributed control approach. Sensor driven behaviours offer greater flexibility to cope with changing environments.

5.5 Deadlock

If a deadlock occurs it must be fixed quickly since deadlocks degrades the performance of the system. Premvuti *[3]* suggests the following shunting algorithm for solving the problem of deadlocks.

1. Each robot must recognize any deadlock and broadcast the recognition to other robots.
2. By discussing through the communication network, the concerned robots and resources will be fixed and reserved.
3. A solution of deadlock problem can be considered as a common objective among concerned robots and should be resolved by a robot that is assigned to a leader position.
4. All other robots move as instructed by the leader to go out of deadlock.
5. Then, each robot returns back to its original objective.

This is a centralized approach since one robot is assigned the leader position. Can deadlocks occur using the modest cooperation schema proposed by Premvuti *[3]?* (see the next section about cooperation).

5.6 Cooperation

Communication allows robots to cooperate and cooperation will make the robot system more efficient in solving its tasks.

Cooperation can be either explicit or implicit. Balch *[8]* describes implicit cooperation where cooperation is implemented using inter-robot repulsion only (no explicit communication). When a robot is located in the camera field of view then the motor schema generates a repulsive force away from the detected robot.

There are different types of cooperation according to Premvuti *[3]*:

1. The robot actively helps other robots that are doing their work.
2. The robot helps other robots when asked to do so. (Rather, the leader is decided and the cooperation is done through a centralized decision making method).
3. The robot behaves so that not to disturb others.

Jung *[23]* classifies the different types of cooperation as: emergent cooperation, cooperation with observation, cooperation by communication and cooperation by planning.

Implicit or explicit cooperation?

Some tasks require explicit cooperation according to Mataric *[31]*, like joint object transportation or moving in formation. McKenzie *[6]* states that cooperation can occur between robots without explicit coordination strategies for some tasks. Hence robots should use implicit cooperation where appropriate, based on the performance metric chosen. I ponder that the cost in time and processing power is different for explicit and implicit cooperation and the choice of cooperation must depend on the task at hand and the characteristics of the cooperating robots.

Modest cooperation

In the paper by Premvuti, *[3]*, he describes an approach to cooperation of multiple autonomous mobile robots from a standpoint of a robot, which uses environmental resources while working toward its goal. A meaningful cooperation of such robots is nothing but an avoidance of collisions while accessing the resources. The key behaviour is not to interfere with others (hence called modest cooperation).

A robot will be said to be cooperative if it decides its actions by considering not only its own objective but also the intentions of other robots or the community to which the robot belongs. For a robot, Premvuti argues that cooperation is contrary to autonomy in principle. I do not agree with this statement. I do not believe that cooperation is contrary to autonomy since autonomous robots can cooperate accomplishing a task in their own way, performing autonomously in their subtask.

In order to make cooperation among robots possible, each robot has to be able to examine what the objectives of the other robots' task are, or, what they are going to do. Thus recognition of types, positions and motions of robots near by are necessary things in autonomous decision-making. Hence robots should share their roles mutually to cooperate synchronously.

Modest cooperation falls under the third type of cooperation listed in the previous page. Disturbances could be:

1. Standing in the road of others
2. Interfering in operations of other robots by using active sensors that emit something like light that causes the sensors of the other robots not to function properly.
3. Occupying some tools, that the other robot is going to use

The actions should be achieved without any discussion among robots; rather, a robot should let the others use the resource autonomously, when the former recognizes that a collision may occur if it tries to access the resource. This would also decrease the risk of deadlocks.

Strong cooperation

Gerkey describes strong cooperation in his paper *[28]*. He argues that robots should, whenever possible, cooperate strongly in order to maximize their overall task performance. Modern robots can be equipped with high-bandwidth communications and a diverse array of sensors and actuators; these resources can and should be exploited in order to achieve cooperative behaviour at the group level. By sharing information and leveraging each others' skills, a group of robots can truly be more than the sum of its parts.

Social cooperation

Simple social cooperation according to Arkin *[11]* involves sympathetic induction (doing the same thing as others), reciprocal behaviour (feeding activity), and antagonistic behaviour; mating behaviours involving persuasion, appeasement, and orientation; family and group life behaviours involving flocking, communal attack (mobs), herding behaviours, and infectious behaviours (alarm, sleep, eating); and fight related behaviours involving reproductive fighting (spacing rivals), mutual hostility (spacing group individuals) and peck order (reducing fighting). Social cooperation is the way many animals use to increase their chance of surviving.

Jung *[23]* states the following "truths" regarding cooperation in his thesis:

1. The ability of robots to identify each other is integral to cooperation.
2. Intelligent navigation requires planning-ahead.
3. Sophisticated cooperation involves real-time construction and adaption of joint-plans.
4. Conversation is a sophisticated instance of joint-planning.
5. The sophistication of communication scales with that of cooperation.

Policy for interaction

According to Oliviera *[5]* task decomposition and distribution should be done using these criteria:

1. To avoid overloading of critical resources
2. To assign tasks according to appropriate robots competencies
3. To enable possible sub-decomposition by some important robots
4. To minimize communications through appropriate clustering of robots

The solution is:

1. Use of the contract net protocol, which proposes episodic rounds of inter-communication acts (announcements, bids, award messages). The contract net protocol is mainly applicable to well-defined coarse-grained task decomposition
2. Multi-robot planning implies that all robots have planning capabilities.
3. Computational market-based mechanisms can be designed to enhance the adaptivity, robustness and flexibility of multi-agent systems.

Much more research is needed so that robots will evolve to cooperate with each other and with humans.

5.7 Learning

The robot team should be able to learn from its previous actions and their result so that it will evolve and get better at doing its job. Learning allows the robot team to adapt to new situations that the designer of the robots couldn't anticipate and design them into the robot team. This way the team will be better prepared for demanding and changing environments.

Some applications where multi-robot learning has been studied are predator/prey, box pushing, foraging, multi-robot soccer, and cooperative target observation. These applications vary in their characteristics.

Balch *[32]* proposes a new measure of robot team behavioural diversity called social entropy.

Reinforcement learning

Each robot has a common set of skills (motor schema-based behavioural assemblages) from which it builds a task achieving strategy using reinforcement learning. Balch *[13]* states that robots learn individually to activate particular behavioural assemblages given their current situation and a reward signal. He has simulated this in robot soccer simulations to evaluate the agents in terms of performance, policy convergence and behavioural diversity. When the entire team is jointly rewarded or penalized (global reinforcement), teams tend towards heterogeneous behaviour. When agents are provided feedback individually (local reinforcement), they converge to identical policies. Reinforcement learning can shift the burden of behaviour refinement from the designer to the robots operating autonomously in their environment. Q-learning is a type of reinforcement learning in which the value of taking each possible action in each situation is represented as a utility function. If the function is properly computed, an agent can act optimally simply by looking up the best valued action for any situation. This is also called the minmax algorithm, which is a heuristic function.

Conclusions in Balch's report are that individual learning robots will, in many cases, automatically diversify to fill different roles on a team, teams of learning robots can outperform human-designed teams, global reinforcement leads to better performance and greater diversity, but slow policy convergence for robot teams and local reinforcement leads to poorer performance and fully homogeneous behaviour, but fast policy convergence.

Inherently cooperative tasks

Particularly challenging domains for multi-robot learning are those tasks that are inherently cooperative, tasks in which the utility of the action of one robot is dependent upon the current actions of the other team members. Inherently cooperative tasks cannot be decomposed into independent subtasks to be solved by a distributed robot team. Instead, the success of the team throughout its execution is measured by the combined actions of the robot team, rather than the individual robot actions. This type of task is particularly challenging in multi-robot learning, due to the difficulty of assigning credit for the individual actions of the robot team members. Multi-robot learning in general, and inherently cooperative task learning in particular are areas in which significant research for multi-robot systems remains according to Parker *[24]*.

Genetic, evolutionary programming

Lawrence Fogel, John Holland and Hans-Paul Schwefel invented genetic programming in the 1960'ies. It is a computational process, which evolves solutions on complex problems by creating populations of possible solutions, and then crossbreeds these solutions and iterates this. The solution, which is strongest, is the best one. Perhaps this technique can be used for robots to learn behaviours *[15]*.

5.8 Reconfiguration

Reconfiguration is about how robots can change shape and assemble and disassemble their selves in order to gain advantages of their new shape. Arkin *[9]* describes Fukuda's cellular robot system (CEBOT), which is a collection of heterogeneous robots that are capable of assembling and disassembling themselves. Their ability to allow complex structures to be constructed on-site and the additional capability of reconfiguring the combined units is of potentially great value for a wide range of applications in space-constrained environments.

This is somewhat coupled to the learning ability of robots. If they cannot complete a task using their current behaviour and shape they must adapt to the situation and alter either their behaviour or shape to serve the needed function. Put to the extreme we will eventually create Transformers, with the ability to change form for different situations and in some situations merge into bigger robots for special tasks *[18]*. Giving the robots the ability to reconfigure "on the fly" (that is, allowing them to connect into any shape and size) is probably very complex and it might be risky put in a doomsday perspective where robots replicate themselves to take over the world *[33]*.

Reconfigurable systems have the theoretical capability of showing great robustness, versatility, and even self-repair. So far reconfigurable robots have been demonstrated to form into various navigation configurations like a rolling track motion, an earthworm or snake motion, and a spider or hexapod motion. Research in this area is still very young, and most of the systems developed are not yet able to perform beyond simple laboratory experiments *[24]*. Even more research needs to be done to solve the problems of making robots able to replicate themselves although some progress have been made in this area at e.g. Brandeis University.

5.9 Navigation / Exploration / Reconnaissance

Parker *[24]* reports that researchers have studied navigation, exploration and reconnaissance extensively but only in single robot systems. This has only recently been applied to the DMR domain as well. This topic covers sensing, acting, planning, communicating, architectures, hardware, computational efficiencies and problem solving to get to a particular location. Most researchers tries to use an existing single robot algorithm for exploration and extends it to multi-robot systems instead of developing new distributed algorithms from scratch. There is however one exception in the area of multi-robot localization, which takes advantage of multiple robots to improve positioning accuracy beyond that which is possible with single robots.

Line of sight communication

Sgorbissa *[34]* shows how a team of robots navigating within an unknown environment with local communication capabilities (only line-of sight communication is allowed) can cooperate by helping each other to achieve their own goals. All the local navigation algorithms that previously have been proposed in literature offer poor performance (or even fail) whenever the geometry of the free space in which the robot is requested to operate increases its complexity. Artificial potential field based approaches have the tendency to lead the robot into local minima, search algorithms may require a long time for the robot to find a path to its goal and are therefore inefficient whenever the time spent in exploring the environment is a factor that needs to be minimized. The method has these two characteristics:

Goal-sharing: a robot is attracted by teammates that can see or have seen its goal.

State-sharing: a robot in trouble is attracted by teammates that are not in trouble.

Reconnaissance and mapping

Thayer *[12]* describes a distributed robotic system that enables autonomous reconnaissance and mapping in urban structures using teams of robots. Robot teams (MOUT (Military Operations in Urban Terrain)) scout remote sites, maintain operational tempos, and successfully execute tasks, principally the construction of 3-d maps, despite multiple robot failures.

Navigation types

Murphy *[2]* divides navigation into Topological navigation (Qualitative) or Metric navigation (Quantitative). In his book he sets up four questions for single robot systems but I believe they are very interesting to answer for multi robot systems as well.

Where are we going?

What is our best way there?

Where have we been?

Where are we?

The question themselves get more complex since they are put in the we-perspective but they might be easier to answer because many robots help each other to evaluate the situation based on their history and sensor readings and merges everything into the answers. Merging the information, multi source data analysis is however another topic within DMR.

Frontier-based Exploration

The central question in exploration according to Yamauchi *[W9]* is: Given what you know about the world, where should you move to gain as much new information as possible? The key idea behind frontier-based exploration is to gain the most new information, move to the boundary between open space and uncharted territory.

Localization

A robot team must know where it is to be able to complete its task efficiently. They can use GPS, ultrasound-based localization system without fixed beacons, landmark based localization and dead reckoning. There exist few algorithms that benefits from using multi robot teams. Trilateration is used by the Millibots presented by Navarro *[10]* where the position is determined based on distance measurements to known landmarks or beacons, which could be stationary robots with known position.

Distributed sensing

Navarro *[10]* reports that they use ATVs with a range of up to 100 miles that transports a user with multiple smaller robots to the area of interest. By building the robots inexpensively, they can be deployed in large numbers to achieve dense sensing coverage, adaptability at the team level, and fault tolerance. In this case these robots act as distributed sensor platforms remotely controlled by a team leader who performs the high level planning. Hence this is a central controlled approach.

There has been much research in this area and there exist many technologies and algorithms that can be used in future DMR research ventures.

5.10 Formations

Formations can benefit the robot team since it allows the individual robot team members to concentrate their sensors across a section of the environment while their partners cover the rest. This is beneficiary in search and rescue, agricultural coverage tasks and security patrols and other applications. Formation behaviours exist in nature among flocking animals. By becoming a group the animals combines their sensors to maximize the chance of detecting predators or prey.

Formations are a way to avoid collisions, matching velocity and centering the flock. When inter-robot communication is required, the robots transmit their current position in world coordinates with updates as rapidly as required for the given formation, speed and environmental conditions. Errors and latency in the transmission of positional information can negatively impact the performance according to Balch *[35]*.

Related research areas besides formation generation and formation keeping are multi-robot path planning and traffic control. These issues are now fairly well understood, according to Parker *[24]* although demonstration of these techniques in physical multi-robot teams (rather than in simulation) has been limited. One of the most limiting characteristics of much of the existing path planning work is the computational complexity of the approaches. Perhaps as computing processor speed increases, the computational time will take care of itself. In the meantime, this characteristic is a limiting factor to the applicability of much of the path planning research in dynamic, real-time robot teams.

5.11 Multi-target observation

Multi-target observation is needed in many security, surveillance and reconnaissance tasks. Parker *[36]* presents a distributed approximate approach to solving the problem (called A-CMOMMT) that combines low-level multi-robot control with higher-level control. The low level control is described with force fields emanating from the targets and the robots. The higher-level control is presented with the ALLIANCE formalism (see chapter 5.2 to learn more about Alliance), which provides mechanisms for fault tolerant cooperative control, and allows robot team members to adjust their low-level actions based upon the actions of their teammates. According to Parker this problem requires a strongly cooperative solution to achieve the goal, meaning intuitively that the robots must act in concert to achieve the goal, and that the task is not trivially serializable.

Parker *[24]* reports that more recent issues studied within the motion coordination context are target tracking, target search, and multi-robot docking behaviours. Nearly all of the previous work has been aimed at 2D domains, although some work has been aimed at 3D environments.

5.12 Task allocation

One of the greatest challenges in DMR research is how to formulate, describe, decompose, and allocate tasks to the robot team.

Thayer *[12]* reports that a robot team can accomplish a given task more quickly than a single robot can by dividing the task into sub-tasks and executing them concurrently. This is one of the biggest advantages to DMR systems compared to single robot systems.

Task allocation based on explicit negotiation

Gerkey *[28]* states that task allocation based on explicit negotiation can be an effective and fault tolerant method for controlling multi-robot systems. In his approach to task allocation, he strive to minimize three aspects of the system:

1. Resource usage
2. Task completion time
3. Communication overhead

There exist other ways to allocate tasks to the robot team.

5.13 Transportation

In some applications the robot team has to transport items cooperatively. They also need to be transported to an area before operation. The team can go there single handed or they can piggyback on another robot (preferably bigger, specialized in transporting over longer distances).

Cooperative Object Transport

Enabling multiple robots to cooperatively carry, push, or manipulate common objects has been a long-standing, yet difficult, goal of multi-robot systems. Many research projects have dealt with this topic area; fewer of these projects have been demonstrated on physical robot systems. This research area has a number of practical applications that make it of particular interest to study. Numerous variations on this task area have been studied, including constrained and unconstrained motions, two-robot teams versus “swarm"-type teams, compliant versus non-compliant grasping mechanisms, cluttered versus uncluttered environments, global system models versus distributed models, and so forth. The most demonstrated task involving cooperative transport is the pushing of objects by multi-robot teams.

The pushing task seems inherently easier than the carry task, in which multiple robots must grip common objects and navigate to a destination in a coordinated fashion. A novel form of multi-robot transportation that has been demonstrated is the use of ropes wrapped around objects to move them along desired trajectories. Nearly all of the previous work in this area work involves robots moving across a flat surface. A challenging open issue in this area is cooperative transport over uneven outdoor terrains according to Parker *[24]*.

5.14 Biology

Much research emanates partly from biology, how animals solves task and how they behave. They make robotic models out of biological systems.

Nearly all of the work in cooperative mobile robotics began after the introduction of behaviour-based control paradigm. Because the behaviour-based paradigm for mobile robotics is rooted in biological inspirations, many cooperative robotics researchers have also found it instructive to examine the social characteristics of insects and animals, and to apply these findings to the design of multi-robot systems according to Parker *[24]*.

The most common application of this knowledge is in the use of the simple local control rules of various biological societies - particularly ants, bees, and birds - to the development of similar behaviours in cooperative robot systems.

Animal behaviours

Murphy *[2]* describes reflexive behaviour (stimulus-response), reactive behaviour (are learned) and conscious behaviour. Behaviours take sensory inputs and produces motor actions as an output. It can be represented as a schema, which is about the same as an object-oriented programming construct. A schema is activated by releasers. The transformation of sensory inputs into motor action outputs can be divided into two subprocesses: a perceptual schema and a motor schema.

There are four ways to acquire behaviours;

1. Innate (is born with it)
2. Sequence of innate behaviours
3. Innate with memory
4. Learn

Jung *[23]* makes a comparison between classical/hybrid and behaviour-based approaches and one advantage with behaviour-based approaches is that complexity is reduced since many unexpected situations are handled naturally – only resulting in lost performance.

Application

Research have shown the abilities of robot teams to flock, disperse, aggregate, forage, and follow trails. To some extent, cooperation in higher animals, such as wolf packs, has also generated advances in cooperative control. Significant study in predator-prey systems has occurred, although primarily in simulation. Competition in multi-robot systems, such found in higher animals including humans, is beginning to be studied in domains like multi-robot soccer. These areas of biological inspiration and their applicability to multi-robot teams seem to be fairly well understood. More recently identified, less well understood according to Parker *[24]*, biological topics of relevance include the use of imitation in higher animals to learn new behaviours, and the physical interconnectivity demonstrated by insects such as ants to enable collective navigation over challenging terrains.

5.15 Synthesis of robot teams

McKenzie *[6]* describes how to create a multi-agent robot configuration involves three steps:

1. Determining an appropriate set of skills for each of the agents.

2. Translating those mission-oriented skills into sets of suitable behaviours (assemblages).

3. Construction/selection of suitable coordination mechanisms to ensure that the correct skill assemblages are deployed over the duration of the mission.

Parker *[26]* has also researched in this vein and she states that the objective of their research is to reduce the complexity of cooperative robotic systems through the development of a methodology that enables the automated synthesis of cooperative robot teams. A methodology is needed to determine the proper robot team composition for a given mission. Given a pool of heterogeneous robots and a mission to be accomplished, what is the optimal composition of robots for the team to optimise the issues of cost, fault tolerance, efficiency, interference, individual robot complexity, team size and what strategy of cooperation and interaction should they use? The optimality will vary depending on the mission and the optimality criteria, which should be a part of the mission specifications. The proposed approach is:

1. Determine the mission's information invariants.

2. Map the information invariants to equivalence classes of robot teams that can solve the mission.

3. Select the minimal set of robot team components based on costs.

4. Use the mission metrics as optimisation criteria to distribute the collective set of team components across individual robots that will compose the team.

5.16 Traffic telematics

Brings together two ideas: physical entities (normally vehicles, but in some cases even humans) and IT infrastructure to form a new class of applications. Three basic technologies form the basis for traffic telematics applications: Intelligent agents and multi-agent systems, Satellite and mobile phone communication and Global positioning systems.

The applications within traffic telematics could be fleet management, handling of an emergency situation, theft protection of vehicles, road pricing and mobile office applications. Perhaps in the boundary of DMR but it is still of interest to a DMR venture at BIT since the Intelligent Transportation Systems research venture in Karlshamn has competency that could be useful. I believe results from any of the ventures can be used by the other venture.

6. Conclusion

There are many areas of DMR that could be interesting to BIT. Most DMR areas presented in this thesis are still in need for more research.

There are perhaps too many paths to research and there is really no unified image on what the aim and goals of DMR research are. Perhaps a killer application that everyone could work towards would help in this effort, like in the RoboCup challenge which's goal is to;

> *"By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer champions" [W6]*

I believe it will take some years before we have truly autonomous DMR systems operating in the field. Looking at some of the intended applications for DMR systems I think that Asimov's robot rules are outdated because DMR systems will be involved in warfare and thus will harm humans.

6.1 Guidelines

Some guidelines I have deducted from reading these reports for this thesis.

Architecture

It would be good to have a general architecture that could be ported to any physical robot (a.k.a. Product Line Architecture) with only minor adjustments since this would cut down development time, make reuse easier and eliminate the problem with different communication protocols since they all use the same. The evaluation criteria presented by Oliviera *[5]* can probably be extended.

Biology

Most researchers agree that conclusions can be drawn from studying biological systems since they have evolved to survive for hundreds of years and thus have experience that could be used. I also think that heterogeneous teams of robots are preferable since each robot then can specialize and learn to do a specialized task very well.

Communication

The DMR system should be able to communicate in many different ways (via sensing, environment and direct communication) since this makes the DMR system less vulnerable to failures and noisy environments. The drawback is that the complexity in the robot increases and the requirements on computational power increases but this should not be a problem since computer hardware gets smaller and cheaper.

Cooperation

The DMR system should be built so that the robots will help each other when it is beneficiary for the whole system to do so. To achieve this cooperation might require priorities in the different subtasks so that the robots know which activity they should help accomplish although they have a subtask of their own that they are working on.

Size

The smaller the robot the cheaper it is to manufacture and transport. The performance is also affected since the strength to weight ratio increases dramatically as mass goes down by a cube law, while cross sections go down only by a square law.

Some researchers propose GNAT robots (entire robot on a chip using silicon micro-machining). These are cheap and reliable because they don't have to be controlled from a mission organisation and hence are completely autonomous. Robots can also be equipped with nanomuscles instead of using electrical motors, which allows the robots to be even smaller *[W10]*.

Decentralized versus centralized

Some high-level planning should be done by a central robot to decrease the computational load on each robot and to make sure that all robots have the same mission plan and that they won't work against each other. The robots control should be autonomous so that they may conduct their appointed task in the way they seem fit.

6.2 BIT resources for DMR research

This section will be a brief discussion on which resources BIT holds today that could be used for DMR research. These opinions are completely my own and can of course be somewhat wrong in cases where I have misunderstood the research areas of the different institutions. The different institutions mentioned here is described in the terms and abbreviations appendix.

IAM is probably best suited to study the behaviours of robots and the animals they will mimic if that direction of research is chosen. They will also prove valuable on how the robots will learn to accomplish new tasks and how to change and adapt their behaviours. Another area is how teleoperation of robots is best conducted.

IPD will take care of the software engineering aspects of DMR systems. This includes creating an architecture, looking at the AI aspects of robotic systems, agent technology and much more.

ITS is best suited to take care of areas such as creating fault tolerant mobile communication, using different communication spectra, bluetooth, radio, image analysis, sound and other signal processing and telecommunication aspects.

IEM could create a model for a free market architecture where the robots are part of an economical society where they exchange services and enter contracts. This might help them in achieving their tasks at the lowest possible cost and utilizing the robots full potential. The department could also make use of its knowledge in organizational and management theory and apply these skills to robot teams.

IHN will be the experts in the mathematical aspects of DMR such as evidential reasoning for multi source data analysis. They might also provide interesting applications in the health care domain.

IMA will be the experts on actually designing own robots and making simulation runs of many robots in a simulated virtual environment. This will allow algorithms and designs to be tested prior to constructing them. Teleoperation from virtual reality environments would also be an area of interest.

IHU will help in designing a possible philosophy layer to make sure that the robots never will harm anybody during their lifetime. Other interesting areas are the ethics of robotic systems if we create robots with emotions and what rights these robots should have.

BIT must also choose which organizations that they should be involved in concerning DMR research. The most important thing BIT must discuss is what their goals of conducting DMR research are. BIT must also get funding for this venture and this could be from Vinnova and the Knowledge Foundation.

6.3 Open research questions

There are numerous open research questions in the DMR area according to researchers in the DMR research community. The open questions appear in many different research areas;

6.3.1 Communication

Communication is a very broad topic and it involves hardware, software and other aspects, such as protocols and which symbols to choose. These are some of the questions researchers have presented;

What are the most suitable protocols and languages enabling a possibly sophisticated and meaningful interaction between robots in a DMR system?

How can we ensure robust inter-robot communication that is both task and environment sensitive? *[9]*

How do we make multi-robot teams to operate reliably amidst faulty communication environments? *[24]*

How do we enable robots (agents) to communicate and interact? *[31]*

6.3.2 Learning

How can we introduce adaptation and learning to make multi-robot systems more flexible within a changing environment? *[9]*

How do we achieve multi-robot learning in inherently cooperative tasks? *[24]*

6.3.3 Architecture

Architectures is a topic that several researchers have presented many open questions.

Is there a need for specialized architectures for each type of robot team and application domain or can a more general architecture be developed that can be tailored easily to fit a wider range of multi-robot systems? *[24]*

The question above is somewhat related to Product Line Architecture research that IPD do research on at BIT.

How can biological systems inform us to ensure we are providing a sound ecological fit of the robot to its environment, producing long-term survivable systems? *[9]*

How can we allow agents to recognize and reconcile conflicts? *[31]*

How can a multi-robot system recognize livelocks?

Are there other ways to fix deadlocks?

What techniques and tools are needed to support multi-agent systems design and implementation in a safe, easy, and productive way?

How can multi robot systems be verified? Sending multi million dollar unverified systems into space might be a waste of time and money. How do we verify systems that must work in extreme conditions and in changing environments?

What formal and practical approaches will allow us to verify, diagnose and easily correct multi-robot systems applications?

The two previous questions are directly related to software engineering and verification and validation. It may be coupled to the software quality research venture at IPD supported by the Knowledge Foundation (http://www.kks.se).

6.3.4 Team size

Some research ventures within DMR aim to study the effect the number of robots in the system will have on the performance. Some open questions reported are;

How well will the ideas of DMR systems scale to large swarms of robots on the order of perhaps ten thousand or more? *[9]*

What is the difference in effectiveness between single robot systems and DMR systems when it comes to localization, mapping and exploration? How many robots could be added to increase performance? *[24]*

Can we scale up to demonstrations involving more than a dozen or so robots? *[24]*

How do we identify and quantify the fundamental advantages and characteristics of multi-robot systems? *[24]*

Does the best policy for a robot depend on how many are on the team? *[13]*

6.3.5 Control

How do we easily enable humans to control multi-robot teams? *[24]*

Other interesting questions would be which interfaces to use when controlling large number of robots and how this information should be presented. Could Virtual Reality environments be a way to control and command a robot team?

6.3.6 Reconfiguration

Reconfiguration abilities need to be demonstrated and developed since little progress has been made in this area. *[24]*

Little work has been done here but the possibilities should be vast. Imagine robots that can disassemble themselves and put the pieces together to form new robots with new capabilities. If this is coupled to learning then a robot could adapt its shape until it has a desired form to optimally conduct a task. Such capabilities is complex and puts high requirements on the software of the robot to evaluate if the form is good or not and on the hardware design so that it will be able to transform itself.

6.3.7 Performance

How do you design cooperative mobile robot teams for specific missions to optimise the issues of cost, fault tolerance, efficiency, interference, individual robot complexity, cooperative control and team size? *[26]*

How can we enable physical multi-robot systems to work under hard real-time constraints? *[24]*

When is a heterogeneous team better? *[13]*

Can we design and implement a system in a way that avoids computational overload by means of load balancing strategies?

How can we enforce the necessary teamwork, leading to coherent and effective results according to the overall system's goals and preventing agents from being "autistic" by giving them the possibility to reason about other agents plans, strategies, beliefs, and actions?

How do we ensure that agents act coherently in their actions? *[31]*

Hence, there are many different aspects of performance in DMR systems. Some relate to cooperation, while some are about the structure of the team. Much work remains to create DMR systems with high performance, and different performance metrics should be chosen for different applications.

6.3.8 Other

Is passive action recognition in multi-robot teams possible? *[24]*

How does the complexity of the task and of the environment affect the design of multi-robot systems? *[24]*

How can we formulate in a non-ambiguous way the problem at hand? Is it possible to adapt existing software and knowledge engineering methodologies, like object-oriented approaches, to be applied to agent-based systems?

Is it possibly and beneficiary to add a philosophical principles layer on top of the architecture to ensure that the robot only do right things and act in the interest of humans and ensure that they will be useful their whole operational time span? *[37]*

How and when do robot behavioural castes arise? *[13]*

Will robots ever get human rights as in Asimov's book "The bi-centennial man"?

The last three questions in this section are philosophical questions that must be dealt with so that we can have a sound use for robots that will live next to us our whole lives and maybe even outlive us.

6.4 Future work

Future DMR researchers at BIT should read the special issues on cooperative and multi-robot systems that will be published in the near future. These journals are the International Journal of Robotics and Automation, Special issue on Computational Intelligence Techniques in Co-operative Robotics. Edited by H. Hagras. Deadline: Dec 15, 2000 and IEEE Transactions on Robotics & Automation, Special issue on Multi-Robot Systems. Edited by T. Arai, E. Pagello, and L. Parker. Deadline: Mar 15, 2001. To be published in August 2002.

The appendixes should also be updated with other research facilities of interest and other relevant material that will help in building up competence in the DMR area.

The BIT resources section should be re-written by one responsible from each institution that will take part in the DMR research venture so that all stakeholders have the same view, and can act in concert to achieve the goals that they set up.

6.5 Summary

This thesis presents the state of the art in distributed mobile robotics. Many research topics within DMR have been described. The thesis also presents a number of open research questions that has been proposed by the DMR research community. A list of relevant DMR facilities, both from academia and governmental as well as important companies and organizations is also provided in the thesis (see appendix.I, II and III). A number of different application areas have been presented, both those applications that exist today in some form and also the future applications where DMR systems might be used.

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Appendix I. DMR Research laboratories

This list presents research organisations that have stated to have research in cooperative, distributed and multi robotics of some sort. Of course there are other research facilities around the world doing DMR research but these labs have brought my attention. The chapter is divided into academia and government laboratories.

Academia

North America

Massachusetts Institute of Technology (MIT)

http://www.mit.edu, http://www.ai.mit.edu/ (did not work 7 August 2001)

MIT researchers tries to make it easier for humans to program robots by using reinforcement learning and supplying a very high-level task description instead of explicit control instructions. They are also doing research about robust visual navigation of mobile autonomous agents. They also have a humanoid robotics group. The company Real World Interface is a spin off company from MIT.

University of Southern California (USC)

http://www-robotics.usc.edu/

At the Interaction Lab at USC they do research in the control and learning in distributed multi-robot systems. At the Robotic Embedded Systems Laboratory they study how to control and coordinate large numbers of distributed embedded systems (could be mobile robots).

Draper laboratory

http://www.draper.com/

Draper laboratory study cooperative robotic systems emphasizing on man-portable micro-rovers for standoff operations. They focus on advanced guidance, navigation, control, and sensing technology.

VirginiaTech

http://www.vt.edu

VirginiaTech study distributed artificial intelligence in mobile robotics, genetic algorithms, group decision-making.

Carnegie Mellon University (CMU)

http://www.ri.cmu.edu/

CMU has many interesting laboratories related to DMR research. Some of these are the multirobot lab (1), the Advanced Mechatronics Lab (2), the Medical Robotics and Computer Assisted Surgery (MRCAS) (3), the Mobile Robot Programming Lab (4), the Robot Learning Lab (5), Distributed Robotics Systems (6), Collaborative Agents (7).

These labs do research in many areas, such as:

1. Building and studying teams of robots that operate in dynamic and uncertain environments,

2. Rapidly deployable intelligent systems focusing on composition, collaboration, task management, and adaptation.

3. Medical robotics that spans the broad areas of science and engineering to realize intelligent machineries that can be applied to clinical practice.

4. How to design autonomous, deliberate systems that achieve real-world goals. This includes formal representations of perception and action; learning and planning with incomplete information; interleaving planning and execution; mobile robot architectures; real-time visual obstacle avoidance and navigation; robot team communication and cooperation; robotics for the handicapped.

5. Robot learning and human robot interaction.

6. Collaborative surveillance among a team of semi-autonomous all-terrain vehicles.

7. How many robots can be arranged to perform tasks cooperatively to gain in efficiency.

Georgia Institute of Technology,

http://www.cc.gatech.edu/

This institute has two laboratories of interest to DMR. It is the Mobile Robot Laboratory and the Intelligent Systems and Robotics.

Their aim is to discover and develop fundamental scientific principles and practices that are applicable to intelligent mobile robot systems and to transfer its research results to yield solutions to real world problems. Other goals are to understand and design systems, which use intelligence to interact with the world, making computer-controlled systems more autonomous and ubiquitous. Intelligent systems perceive, reason and plan, act, and learn from previous experience.

Europe

The GMD Institute for Autonomous intelligent Systems

http://ais.gmd.de

Their scientific goal is to explain how autonomy can be achieved or enhanced, and use this distinctive feature to build technical information systems. These systems should be able to modify and adapt themselves depending on the requirements of their actual operating environment. They think that autonomous systems cannot be specified completely during their design or construction phase. They focus their research on fast moving robots in soccer matches (primarily Robocup). They use biologically inspired approaches to cognitive robotics.

Distributed Artificial Intelligence & Robotics Group, Oporto, Portugal

http://www.fe.up.pt/~eol/Welcome.html

They research about architectures and have developed ARCoS - Autonomous Mobile Robot Control System. The proposed ARCoS architecture is a hybrid architecture integrating both the reactive and deliberative paradigms. It is heavy influenced from the behaviour-based approach.

Team Sweden, Swedish Robot Soccer

http://aass.oru.se/Agora/RoboCup/

Team Sweden is a national effort to produce a team of soccer playing physical robots to enter the RoboCup international competition. The members of the team reside in Umeå University, Örebro University and Blekinge Institute of Technology.

Center for Applied Autonomous Sensor Systems (AASS), Örebro university

http://www.oru.se/forsk/forskstrategi/fstrategi7.html#sensorsystem

AASS is a multi-disciplinary research center where ideas from Systems and Control, Measurement Science, Computer Science, Artificial Intelligence, and Operations Research are combined to create autonomous sensor systems.

These autonomous sensor systems are mobile and immobile platforms that employ a vast array of sensors in order to analyse and/or influence highly dynamic environments. Examples of these systems include: autonomous robotic systems; complex process control systems; flexible manufacturing and inspection systems; automotive systems; and unmanned vehicles moving on land, water, air, or space

Some focus areas are coordination of a team of robots in dynamic and uncertain environments, planning and strategy evaluation on mobile robots and unmanned rescue vehicles. The focus is also on artificial minds and they study the interplay between human sensing and technical innovative solutions in the form of autonomous sensor systems.

Politecnico di Milano, Dipartimento di Elettronica e Informazione

http://www.elet.polimi.it/section/compeng/air/robotics/mobile/index.html

This department researches about agency of robots, optimal sensor explorations, self-localization, robot's environment modelling, obstacle avoidance, motion planning, control architectures for autonomous robots, legged robots and soccer robots.

Agency of Robots means to design the architecture of a new abstract machine, the agency, considered as an integrated system of navigation, manipulation, and perception robots (agents). Methodologies and techniques devoted to programming and planning of agencies, and to person-agency interaction are investigated. The particular application of a fleet of two navigation agents exploring and modelling unknown environments is being investigated.

Soccer robots: They are involved in the middle-size league of RoboCup soccer-playing robots, participating to the Italian National Team (Azzurra Robocup Team). They have developed a general-purpose platform and specialized it to play soccer. It is designed and implemented as a low-level fuzzy control system, a high-level behavioural system and a dedicated vision system.

Asia

Electrotechnical laboratory (ETL), Japan

http://www.etl.go.jp/welcome.html

Their Intelligent Systems Division covers robotics and related areas. It consists of the following sections; Intelligent Machine Behaviour, Autonomous Systems, Computer Vision, Interactive Interface Systems, and Communicating Intelligence.

The robotics group in the division focuses on intelligent robots and system integration. Its current research topics include: Multiple-robot cooperation, Dextrous manipulation, Motion planning, Active vision, Multi-sensor fusion, Multi-fingered hands, Hand-eye systems, Mobile robot navigation, Intelligent teleoperation, Learning, and Architecture. ETL is said to have continuously been at the frontier of intelligent robotics research

Those interested in learning about other laboratories doing robotics research can check this URL: http://robotics.stanford.edu/other-labs.html

Government

These are some government organizations that has or may have interest in DMR research, either to participate in actual research or by providing funding for it.

Swedish Defence Research Institute (FOI)

http://www.foi.se

FOI has a thesis project proposal involving multiple cooperating missiles targetting an area with several targets and how they can optimise their behaviour to improve the scanning of the area. Hence FOI might be interested to support DMR research.

DARPA

http://www.darpa.mil/MTO/DRobotics/index.html

DARPA is interested in robotics since they can perform military actions at greater stand-off distances, allow dangerous missions to be performed with minimal risk to people, can be forward deployed, and permit certain missions to be performed that would otherwise be impossible. In addition, numerous robots collaborating in parallel can perform certain tasks in much less time and at lower cost than single, more complex robots. Micro and miniature robots are the primary thrust of this solicitation because

(1) the confluence of various technologies such as microelectronics, micro-electro-mechanical systems (MEMS), smart materials, advanced packaging, energy storage, biologically inspired systems, etc. enable micro and miniature robots to be fabricated at relatively low unit cost, and

(2) micro and miniature robots offer a range of unique mission advantages. Because of their small size and potentially low cost, micro and miniature robots can be carried and deployed by individuals and small teams to augment human capability, perform hazardous missions, or perform missions presently unimaginable

Potential applications for such robots or systems of robots include surveillance, reconnaissance, pathfinding, deception, weapon delivery, transporting artifacts, and small scale actuation. Applications might include minefield detection wherein small sensors are mounted on hopping robots or robots with multi-task capabilities, intelligence gathering in city pipelines, robots used in large numbers for decoy applications, or extremely small robots that might be injected and pick a door lock.

NASA Jet Propulsion Laboratory (JPL)

http://robotics.jpl.nasa.gov/

JPL is NASA's lead center for creating robotic spacecraft and rovers, they build smart machines that can perform very complicated tasks millions of miles from home. Robots can literally go where no person has gone before, to other planets where the environments are not suitable for humans until we have studied them in much greater detail. The robots and spacecraft they build are the eyes and ears on these distant planets.

JPL Robotics researchers perform development, integration, and demonstration of innovative robotics and automation technologies, supporting NASA missions and addressing other problems of national importance. Researchers work toward enabling more efficient, lower cost missions dedicated to planetary surface and solar system exploration, Earth observations from space, astrophysical experiments in space and on the Moon, and the extension of human capabilities in space.

Center for Engineering Systems Advanced Research, Oak Ridge National Laboratory (ORNL)

http://www.ornl.gov/

ORNL do research in mobile and manipulator robotics, including redundant and multiple manipulators, cooperating mobile robots, parallel vision systems, sensor fusion, laser range finder research, real-time quantitative reasoning and behaviour based control, and machine learning. Current applications include robots for nuclear power stations, environmental restoration and waste management, material handling, and automated manufacturing.

Appendix II. DMR companies

There exist many companies that manufactures robots or parts that can be used to build robotic systems. There exist simulators for robot systems so that algorithms and software can be tested in a simulated environment before putting it into the actual hardware thus saving time when developing the programs. These companies are also research laboratories but they have economic goals instead of pure research goals that academically research facilities have.

Sony

http://www.sony.com

Sony manufactures the AIBO robot dog. It is the robot used in Robocup's Sony Four Legged Robot League. It can communicate directly using ears and speakers and indirectly using a camera to observe the behaviors of other robot dogs to learn their state.

Irobot corporation

http://www.irobot.com

They develop advanced mobility systems, intuitive user interfaces, multiple robot collaboration algorithms, embedded intelligence, dynamic programming environments, and machine learning algorithms. This company was previously named RWI (Real World Interface).

Activmedia robots

http://www.activrobots.com/

Sells robots, among those Pioneer robots mentioned in some research reports.

Cybermotion

http://www.cybermotion.com/

Designs, manufactures, sell and supports mobile robot systems since 1984. The company is widely recognized as a leading manufacturer of mobile robotic systems and as a developer of advanced sensor fusion systems.

Denning

http://www.southcom.com.au/~robot/

Denning is one of the world's oldest and most experienced mobile robotics company with intelligent, autonomous, mobile robots in several market sectors such as security, research, navigation and guidance.

K-Team

http://www.k-team.com/

Develops, manufactures and markets a family of mobile robotic platforms to academic and commercial research laboratories.

Lego Mindstorm

http://mindstorms.lego.com/

Lego Mindstorms are advanced sets of Lego pieces that are programmable. Hence you can build your own robots and program them for the task at hand. Lego robots can communicate with each other and hence it should be possible to make distributed robotic systems using Lego Mindstorms.

Honda

http://world.honda.com/robot/

Honda's humanoid robot project tries to give the robot mobility and intelligence and the ability for the robot to cooperate with humans.

Electrolux

http://www.electrolux.se

Has manufactured a robotic vacuum cleaner that is listed in the Guinness Book of World Records as "the world´s most advanced domestic robot." It uses an electronic brain and a radar system to prevent it from bumping into obstacles.

Husqvarna

http://www.husqvarna.se

Husqvarna manufacture and sells an automatic lawn mower called Automower that works independently mowing the lawn.

ABB Robotics

http://www.abb.se/global/seabb/seabb360.nsf?OpenDatabase&db=/global/seabb/seabb361.nsf&v=d&e=se&c=942A94E707B6B749C1256801002BD47E

Although a manufacturer of industrial manipulators they are still of interest for DMR research at BIT because of their experience and successes in designing, manufacturing and selling robotics. The Swedish company ABB, together with Adept, Fanuc, Motoman, Seiko, Panasonic, Kawasaki, Reis, Sony, and Nachi are the biggest international manufacturers of robots: All of these companies are Japanese except for ABB (Swedish) and Adept which is the largest US based robot manufacturer.

SAAB

http://www.saab.se

SAAB has many business divisions and some of them develops robot in the form of missiles. These could be created to cooperate and share sensor data. They can in turn turn their radar on and off and share this information with each other to decrease the chance for counter measures finding and locking onto them. Hence DMR research could be of benefit to SAAB.

Nomadic

http://www.robots.com

Many research reports refer to Nomadic robots and their multi-robot simulator. The simulator could be used to test and debug algorithms written in C in simulation prior to executing them on actual robots. The code could be ported directly to the robots for experimentation in a real environment *[36]*.

It seems like Nomadic have seized their activities as of October 3, 2000.

Here is a bigger list of companies that manufactures robots. It is from the robotics FAQ. http://www.frc.ri.cmu.edu/robotics-faq/8.html

Appendix III. DMR Organisations

International Federation of Robotics (IFR)

http://www.ifr.org

The purpose of the International Federation of Robotics is to promote research, development, use and international co-operation in the entire field of robotics and to act as a focal point for organisations and governmental representatives in activities related to robotics.

National Science Foundation (NSF), Robotic council

http://www.interact.nsf.gov/cise/descriptions.nsf/30ff6e7ea7d05a0d85256659004c0237/5e8661fa698fe674852565d9005985ef?OpenDocument

This council serves as the NSF Robotics and Human Augmentation Program counselling body. The council is constituted of the most distinguished and well-known scientists. Its functions include: reviewing current directions in research, recommending changes in priorities, and advising on the distribution of resources; proposing workshops for initiating new areas; publicizing the program; reviewing regular proposals submitted to the program.

Swedish Industrial Robot Association (SWIRA),

http://www.vibab.se/swira

Many large universities are members of SWIRA. I guess it is to become a member of IFR. The overall goal of SWIRA is to support the development and the use of flexible automation.

RoboCup Federation

http://www.robocup.org

RoboCup is an international research and education initiative. It is an attempt to foster AI and intelligent robotics research by providing a standard problem where a wide range of technologies can be integrated and examined, as well as being used for integrated project-oriented education. Current activities comprises of technical conferences, the Robot World Cup, RoboCup challenge programs, education programs and infrastructure development

International Federation of Automatic Control (IFAC)

http://www.ifac-control.org/

The purpose of the Federation is to promote the science and technology of control in the broadest sense in all systems, whether, for example, engineering, physical, biological, social or economic, in both theory and application. IFAC is also concerned with the impact of control technology on society.

It is uncertain íf IFAC is involved with DMR research.

European Robotics Research Network (EURON)

http://www.euron.org

EURON is a network of excellence in robotics, that is aimed at coordinating and promoting robotics research in Europe. The network is sponsored by the European Commission through the Future and Emerging Technologies Programme under DG-INFSOC. The network is organised around a set of key areas: Research Planning and Coordination, Education and Training, Publication and Conferences, Industrial links, International Links, Interest Groups and List of Members. The most interesting topics for DMR are cooperative robotics and field robotics. These topics include technology such as formation analysis and control, cooperative perception, multi-robot self-localization, multi-robot task coordination, role assignment, and inter-agent communication, perception in natural environments, navigation and manipulation in unknown or partially unknown and uncertain environments, safety and reliability, large and heavy robots, telecommunications for robotics, implementation of robotic functions in existing machinery, application of new components (innovative sensors, MEMS and mechatronic technologies), cost oriented issues, and others.

Key application domains include: collaborative manipulation, space and underwater exploration, entertainment, surveillance, rescue operations.

The activity on the mailing list for this organization has been low. Only one message has been sent during the last month.

IEEE Robotics and Automation Society

http://www.ncsu.edu/IEEE-RAS/

The Society is interested in both applied and theoretical issues in robotics and automation. Robotics is here defined to include intelligent machines and systems used, for example, in space exploration, human services, or manufacturing; whereas automation includes the use of automated methods in various applications, for example, factory, office, home, or transportation systems to improve performance and productivity.

Appendix IV. DMR Journals and conferences

Journals

These journals publish articles about DMR research. They are interesting for anyone that wishes to be up to date with robotics research.

IEEE/ASME Transactions on Mechatronics

http://www.ieee.org/organizations/pubs/transactions/tmech.htm

http://www.ieee-asme-mechatronics.org/

The International Journal of Robotics Research

http://www.sagepub.co.uk/frame.html?http://www.sagepub.co.uk/journals/details/j0237.html

IEEE Transactions on Robotics and Automation

http://www.ncsu.edu/IEEE-RAS/TRA/TRA.html

International Journal of Robotics and Automation

http://www.actapress.com/journals/journals.htm#Robotics

Presence: Teleoperators and Virtual Environments

http://mitpress.mit.edu/journal-home.tcl?issn=10547460

Conferences

These are important conferences that a future research team in DMR should be aware of. The relevance of these conferences to DMR research has not been studied.

International Symposium on Distributed Autonomous Robotic Systems, (DARS2002), 2002 June 25-27

IEEE **International Conference on Robotics and Automation** (ICRA2001) 2002, May 11-15, http://www.icra-iros.com/icra2002

IEEE/RSJ **International Conference on Intelligent Robots and Systems** (IROS2001) 2001, October 29-November 3, http://www.icra-iros.com/iros2001

IEEE **International Symposium on Computational Intelligence in Robotics and Automation** (CIRA2003), 2003, http://www.icra-iros.com/cira2003 (probable URL, does not exist yet)

International Symposium of Robotics Research (ISSR), 2001, November 9-12,

IASTED **International Conference Robotics and Applications** (RA2001), 2001, November 19-22 http://www.iasted.org/conferences/2001/tampa/ra.htm

Autonomous Minirobots for Research and Edutainment (AMIRE2001) 2001 October 22-25 http://www.amire.org

AAAI Fall Symposium on Anchoring Symbols to Sensor Data in Single and Multiple Robot Systems, 2001, November 2-4, http://www.aaai.org/Symposia/Fall/2001/fss-01.html

IEEE International Conference on Advanced Robotics, 2001, August 22-25, http://www.banki.hu/icar2001/index_c.html

RoboCup 2002, http://www.robocup2002.org/index.html

Mobile Robot Contest & Exhibition (AAAI-sponsored), probably collocated with RoboCup

International Symposium on Artificial Intelligence, (ISAI2001) 2001 December 18-20, http://geocities.com/tmrfkop/conf.htm#agents

National Conference on Artificial Intelligence, 2002, July 28 – August 1, http://aaai.org/Conferences/National/2002/aaai02.html

International Conference on Evolvable Systems: From Biology To Hardware (ICES2001). 2001, October 3-5, http://www.islab.is.tsukuba.ac.jp/~ices2001/

International ICSC Congress on **Autonomous Intelligent Systems** 2002, February 12 - 15, http://www.icsc-naiso.org/conferences/icais2002/index.html

International Conference on Development and Learning (ICDL02), 2002, June 12-15. http://www.egr.msu.edu/icdl02/

Appendix V. Terms and abbreviations

Adaptivity	The ability of the robot team to change its behaviour over time in response to a dynamic environment, changes in the team mission, or changes in the team capabilities or composition, to either improve performance or to prevent unnecessary degradation in performance.
Agent	Software agents can be seen as virtual robots that are specialized for different tasks: We-bots (web), know-bots (databases).
AI	Artificial Intelligence.
AI point of view	Percepts world, integrate perception into internal world model, reasons about this internal world model to find out which action it should perform next, execute the selected action. *[5]*
Asimov, Isaac	Science fiction writer. Formulated the four laws of robotics: 0) Robots must never harm humanity 1) Robots must never harm human beings. 2) Robots must follow instructions from humans without violating rule 1. 3) Robots must protect themselves without violating the other rules.
ATV	All Terrain Vehicle.
Autonomy	In a robot it means that it is self-governing.
Behaviour	A functional connection between sensors and actuators (possibly complex). In robots, it is usually a programmatic connection, also called a schema. The observed or expressed actions of a robot or organism (in total).
BHDL	Behaviour and Hardware Description Language *[8]*
BIT	Blekinge Institute of Technology.
Broadcast	Information is transmitted indiscriminately, so all robots receives the information sent.
CEBOT	Cellular Robotic System *[27]*
Closed world assumption	The world model contains everything the robot needs to know (no surprises).
CMOMMT	Observation of multiple moving targets *[36]*.
Coherence	The absence of wasted effort and progress toward a chosen goal *[37]*.
Cooperate	To work towards a common goal *[20]*.
Cooperation	1: The act or process of cooperating. 2: Association of persons for common benefit. 3: A dynamic ecological state of organisms living in aggregation characterized by sufficient mutual benefit to outweigh disadvantages associated with crowding. *[W2] , [23]*
Coordinate	To perform a common action or movement in a harmonized manner *[20]*.
Cue	A prompt that a robot perceives from its environment.

DARS	Distributed Autonomous Robotic Systems *[27]*.
DBI	Desires Beliefs Intentions.
Deadlock	A deadlock is a situation in which two computer programs sharing the same resource are efficiently preventing each other from accessing the resource, resulting in both programs ceasing to function *[W11]*.
DMR	Distributed Mobile Robotics.
Doppler effect	The frequency and wavelength of an electromagnetic field are affected by relative motion. Only the radial (approaching or receding) component of motion produces this phenomenon. The Doppler effect also occurs with acoustic waves *[W11]*.
Explicit communication	A specific act designed solely to convey information to other robots on the team.
Explicit cooperation	A set of interactions between agents which involve exchanging information or performing actions in order to help other agents achieve their goals *[20]*.
FAQ	Frequently Asked Questions.
Fault tolerance	The ability of the robot team to respond to individual robot failures or failures in communication that may occur at any time during the mission.
Frame problem	The problem of representing a real-world situation in a way that is computationally tractable.
FSA	Finite State Acceptor *[11]*.
GNAT robot	Self-contained completely autonomous chip robot.
GUT	Grand Unifying Theory *[23]*.
Hierarchical paradigm	Using this architecture, the robot first get information of the environment through its sensors system, then a processing system extracts the necessary information from the data sensors, then the planning system can compute the necessary motion to achieve the goal, afterwards the execution system will produce the right motion commands to the actuators system, then the environment has been modified and the loop has been closed by the sensors system
Hybrid / Deliberative Reactive paradigm	Involves task decomposition (mission planning), mapping behaviours to subtasks. Executes according to the reactive paradigm.
IAM	Department of Work Science and Media
IEM	Department of Economics and Management
IFP	Department of Spatial Planning
IFR	International Federation of Robotics.
IHN	Department of Science and Health
IHU	Department of Humanities
IMA	Department of Machine Technology
Implicit communcation	It occurs as a side-effect of other actions, or “through the world".
Industrial manipu-	Reprogrammable and multi-functional mechanism that is designed to move

lator	materials, parts, tools or specialized devices *[2]*.
Interference	Something that disturbs the operation of a robot. It could be confusion of a received radio signal due to the presence of noise (as atmospherics) or signals from two or more transmitters on a single frequency *[W12]*.
IPD	Department of Software Engineering and Computer Science
ITS	Department of Telecommunications and Signal Processing
Livelock	It is when a process has no enabled transition during a sequence of more than a given number of "successive states in the state space". It differs form deadlock in that the process is not blocked or waiting for anything, but has virtually infinite amount of work to do and can never catch up.
MEMS	Micro-Electro-Mechanical Systems.
MIPS	Million instructions per second. MIPS is a general measure of computing performance *[W11]*.
Motor schema	Low-level behaviours such as "avoid obstacle" and "move to the goal".
MOUT	Military Operations in Urban Terrain
PV	Photovoltaic. Uses the sun to generate electric power.
Reactive paradigm	Paradigm that emerged in the mid-1980's for controlling robots. In this paradigm, multiple parallel behaviours are constructed in a modular fashion. The design of the systems is in a bottom-up manner incrementally adding more and more competence to the robot. Perception and action are tightly coupled. Reliance on explicit world models and representational knowledge is avoided during execution. They are particularly well suited for dynamic and unstructured domains *[11]*.
RIA	Robotics Industries Association.
Robotics	The science or study of the technology associated with the design, fabrication, theory, and application of robots *[W2]*.
SCS	Sensori-computational systems *[26]*.
SDR	Software for Distributed Robotics, DARPA program *[W13]*.
Subsumption architecture	The robots behaviour is directly triggered by the sensor data it perceives from the outside environment *[22]*.
Swarm intelligence	The interplay of computation and dynamics *[31]*.
SWIRA	Swedish Industrial Robot Association.
Teleoperation	Human controlling a robot society remotely.