Mobile Robot Cooperation in Simple Environments

Adam Borkowski, Michał Gnatowski and Jacek Malec

Abstract— **The paper presents the problem of organizing cooperation among heterogeneous mobile robots. It is assumed that cooperation of a number of robots is necessary to achieve the goal. Another constraint is introduced by simplicity of the control system of each robot. A simple model of cooperation is introduced and verified experimentally using Khepera robots with different sets of resources.**

Keywords— **mobile robots, cooperation, topological map structure investigation**

I. Introduction

Investigations on autonomous mobile robots are at least as old as Artificial Intelligence. Since Shakey, robotics has made great steps forward, albeit most of the successes, including important applications, can be attributed to the area of individual autonomous robots, while multi-robot systems research is lagging behind, mostly due to the complexity of the problems involved.

Multi-robot systems are interesting because of several reasons. The most important one is the possibility of using a team of simple and cheap robots instead of a single complex one. The classical application is space exploration - the failure of one of the robots will probably not jeopardize the whole mission assigned to a team, while a failure of a single (and not replaceable) robot might do that.

Another potential application of a multi-robot system might be in a task requiring diverse sensori-motor capabilities from the robotic system: it might be very expensive, hard, or even impossible to realize a robot fulfilling all the specifications. E.g., in a rescue mission there might occur a need to use a robot with non-standard morphology (snake-like or elephant-trunk-like robots), with non-standard sensors (like sensitive smelling devices recognizing gas leakages, sensitive IR cameras looking for survivors, etc.), or non-standard effectors (transport system allowing to negotiate narrow passages and stairs, or allowing the robot to move on electricity wires or inside sewage pipes).

There is a multitude of interesting questions addressed by the researchers in the multi-robot systems area. A recent survey of the domain can be found in [1]. Murphy [2] quotes the following problems as fundamental:

1. Multi-robot system design is inherently harder than design of single robots;
2. Multiple robots may distract activities of each other, in the extreme precluding the team from achieving the goal of the mission;
3. A team may have problems with recognizing the case when one or more team members, or the team as a whole, become unproductive;
4. The communication among the robots is a nontrivial issue (what, to whom and when to communicate?);
5. The "appropriate" level of individualism and cooperation within a team is problem-dependent.

In the experiments described in this paper we have focused on the fourth problem from the list above. We have considered the interesting case of heterogeneous robots forming a team. A natural description of such case might be done by introducing resources (in our case it is the morphology of the individual robots and, thus, their physical capabilities). Then we have asked the question about communication needs in such heterogeneous team.

The work has been presented as follows. In Section II we discuss the need of introducing the model of cooperation among the robots. Section III present the assumptions, the introduced model, the communication needs and, finally, the experimental setup. In Section IV we present the related work. The paper ends with some conclusions.

II. Models of robot cooperation

The cooperation of autonomous robots or, more generally, autonomous agents, is a vivid area of research within distributed artificial intelligence. A not so fresh, but still informative, introduction to the area may be found in [3].

There are numerous textbooks introducing the area of multi-agent systems. E.g., [4] and [5] describe the field thoroughly, although from different viewpoints. An interesting discussion of agent cooperation has been presented in [6].

The necessity of introducing a cooperation model may be shortly motivated as follows:

- Without a model each particular problem requiring robot cooperation has to be analyzed from scratch, without the possibility of re-using earlier experience expressed in a model of cooperation situation. It leads to inefficient design process and to more errors in the implementation phase.
- A model allows (in some cases) to predict, or sometimes even guarantee, that a cooperation among the team members will indeed occur, that the team will reach its goal, or even that the goal will be achieved within a given time.
- A model allows to introduce and formally analyze a communication protocol among the agents. Communication, although is not necessary, appears very useful for guaranteeing successful cooperation, especially in case of very simple interacting robots. Obtaining a guarantee without a model seems impossible.
- In order to establish communication protocol for a team one needs a model for all involved robot control systems (where the possible levels of analysis are e.g, specification, architecture, or simulation). The control system imposes

Adam Borkowski and Michał Gnatowski are with IPPT, Polish Academy of Sciences, ul. Świetokrzyska 21, 00 049 Warsaw, Poland, email: {abork,mignat}@ippt.gov.pl

Jacek Malec is with the Department of Computer Science, Lund University, Box 118, 221 00 Lund, Sweden, email: jacek@cs.lth.se

constraints on possible expressive power of the messages defined in the communication protocol.

- A model allows meta-reasoning about the knowledge that needs or may be transferred among agents, when should it be transferred and why. Such analysis may (and should) be independent of the concrete cooperation model and on the assumed protocol.

The cooperation models may be roughly classified into one of the following four groups [7]:

- *distributed, unconscious*: the cooperation is emergent, the agents are not aware of it;
- *distributed, conscious*: robots are equal partners, the cooperation is initiated and accepted or rejected by group members, without any coordinator or mediator;
- *intermediate, hierarchical*: some robots are able to initiate or negotiate cooperation while others have to obey the will of those from the first group;
- *centralized*: the leader decides about the cooperation, others execute its orders. A more advanced case would be a purely hierarchical model (of a military kind).

For an alternative, although much similar, classification, see [1].

The assumed cooperation model or, more exactly, the type of negotiations leading to cooperation, will obviously affect the communication among the agents. The more complex negotiation, the higher requirements on the protocol, both semantical and throughput-wise, have to be imposed. Therefore the limitations of the robots constituting a team, their complexity (or simplicity) and throughput of their information channels will restrict the space of possible communication models. A simple case of such considerations is presented below.

III. Cooperation in a team of simple mobile robots

A. The problem

The starting point for our discussion is a minimalistic cooperation in the centralized case. We consider it to be the opposite of a distributed, unconscious cooperation, when simple robots have been shown to engage in emergent cooperative activities [8]. Although such cooperation might be achieved with minimal computational resources, guaranteeing that it will actually occur is much more problematic and often requires unnatural assumptions and problem simplification. Centralization seems to be the solution in such cases.

In our experiments we have assumed that cooperation should be enforced and asked ourselves how much information needs to be transferred among the engaged robots. The chosen task is the classical object search and collection in an initially unknown environment. It may be considered as a drastically simplified model of a rescue mission.

Additionally we assume that the robots in the team possess different resources. In our experiments we have used Kheperas equipped with different turrets: one kind of robots (carriers) had the gripper, while the other kind of robots (investigators) had its vision turret active, but possessed no gripper. Besides that, both kinds of robots had the radio modem turrets allowing direct communication. The robots are shown on Figure 1. Although extremely

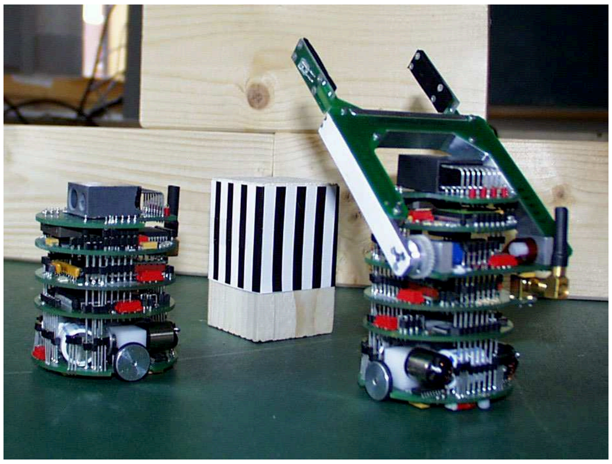

Fig. 1. The investigator (left) and the carrier (right).

simple, we consider this case as interesting due to following reasons:

- In may situations the computational or communicational resources available might be very limited. It is especially important when we want to limit the cost of the robots, e.g, when deployment of many simple agents is preferable to a few more complex ones, or when the number of robots is expected to increase the reliability or chances of success of the whole team (e.g., in de-mining applications). Consequently, we have limited ourselves to Kheperas with extremely simple control systems;
- In many tasks there is a need to guarantee goal achievement rather than just to maximize its chances. The simpler the system, the more plausible is such guarantee;
- In some tasks we may assume that some type of robots is disposable (and therefore should be kept as simple as possible) while other kinds are more expensive and should be saved for the future use.

Previously [7] we have presented a very simple model of robot cooperation and illustrated it with an example of two robots initiating cooperation in a very simple environment. Additionally, the carrier was assumed to lack the capability of investigating the environment, what left us with a very natural division of labour between the team members. This paper presents an extension of this model to a more complex case of joint investigation of an office-like environment in search of an object. The previous model may be scaled up to this case as well. We expect to have the experiments performed within the incoming weeks, but in this paper the experimental set-up still describes the original case with two robots in a rectangular scene.

This paper does not consider the map creation as an issue by itself - there is vast literature discussing it (see e.g. [9]) - but rather the analysis of conditions under which the cooperation in this task might be ensured. In particular, we focus on a distributed topological map creation where the ultimate result of the teamwork might be represented as a graph of locations that the team has collectively inves-

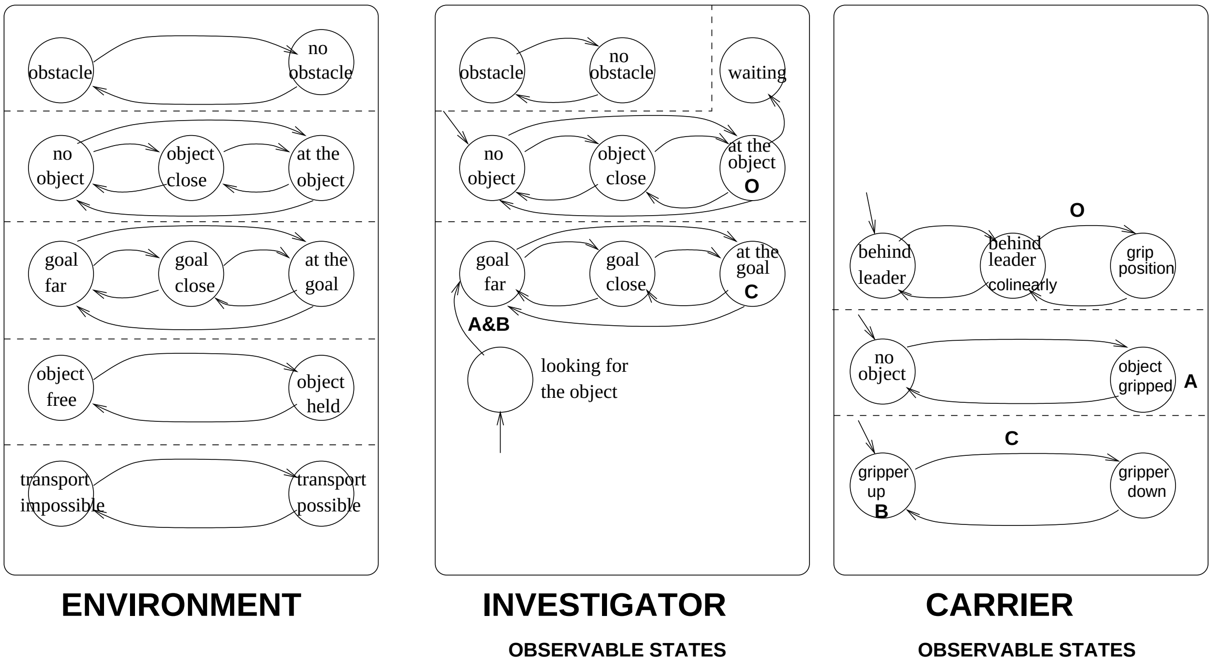

Fig. 2. The automaton model.

tigated, but where the explicit global map is never created. The process of map creation ends when localizing the object in one of the existing map nodes succeeds.

B. The assumed model

In the extreme case the task realization does not require any communication among the team members. Behavioral control may realize cooperation based solely on the information passed via the environment. But in order to ensure it one has either to put into the robots quite a lot of knowledge about the environment or to adapt the environments for the robots.

In our work we assume slightly more complex set of scenarios where the robots might communicate using the radio link. However, as the number of states necessary to be distinguished is very small, the robots may restrict the communication to simple signals sent to denote achievement of some of the states.

Let us begin with repeating the assumptions from [7]: we consider two heterogeneous robots looking for an object in a possibly cluttered area. In order to describe the cooperation among the robots we have used finite state automata. Every state in the environment automaton (see Figure 2) corresponds to a specific situation in the world that might be of interest for the task execution. We use the statechart [10] syntax and semantics[1] to express parallel composition of automata and information passing between the sub-automata of the system. Some of those states might be recognized by the robots, what is illustrated in the rest of the figure. The interesting case occurs when a state important for one of the robots needs to be recognized, but the robot lacks the resources (sensors or processing power) to recognize it. Then it has to be informed by some other team member(s), possessing appropriate recognition capabilities, about the current situation. In our case there are a few such situations: the object has been found, the object has been lifted, the goal position has been found. Only these states are marked by capital letters on the figure, not to clutter it unnecessarily.

Note that there are states about which the investigator has to inform the carrier, as well as states about which the carrier has to notify the investigator. The automaton model reveals them and imposes a natural communication protocol.

One can easily extend this description to the case of n robots, where only a selected subgroup of robots can together recognize a specific state of the environment. Let us consider a statechart S being a parallel composition of k finite-state automata, describing the system consisting of all n robots and the environment.

$$S = A_1 || A_2 || \dots || A_k \tag{1}$$

Each of the robots R_i can be described by its individual statechart S_i, $i = 1, \dots, n$ reflecting this robot's sensory and actuatory capabilities. The statechart S_i will consist of a composition of some of the original automata.

$$S_i = A_1^{b_1} || A_2^{b_2} || \dots || A_k^{b_k} \tag{2}$$

where $\forall i \; b_i \in \{0, 1\}$ and A_j^1 means that the automaton A_j is present in the parallel composition while A_j^0 means that it is absent.

[1] We do not consider the issue of competing semantics for statecharts as relevant here, as all of them allow passing signals between different parts of a complex system - this is the only feature of statecharts we are interested in in this paper, besides their capability of illustrating parallel composition of finite state automata.

This definition introduces a mapping from the set of automata constituting the global statechart S to sets of robots capable of recognizing states of a particular automaton.

$$r : \{A_1, A_2, \ldots, A_k\} \rightarrow \mathcal{P}(\bigcup_{i=1}^{n}\{R_i\}) \tag{3}$$

where $\mathcal{P}$ denotes the power set operation.

For each automaton A_i in the statechart S there is a set of robots $r(A_i)$ capable to recognize its states. If a task requires that some of the robots not belonging to the set $r(A_i)$ acts upon the knowledge of being in one of the states of A_i then it requires that the communication includes a signal from one of the robots recognizing this automaton to the robot not recognizing it. This way we have a clear specification of the communication needs of the team.

Of course, the formal model presented above describes only the simplest case where each robot's state space contains complete automata A_i constituting the global statechart S. The next step consists of extending it to the situation where automata in the statechart S are compositions of the corresponding automata of the recognizing robots. An example of such case is presented in Figure 3. The function r needs to be extended in such case to take

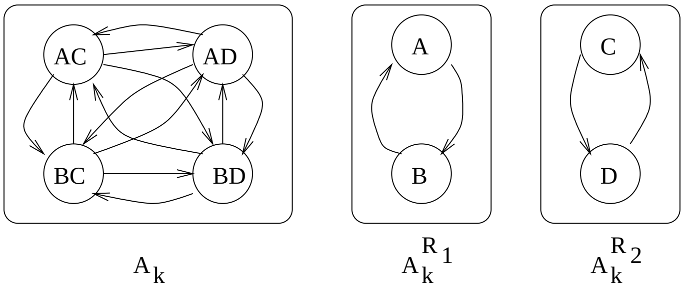

Fig. 3. The case when an automaton A_k in the global statechart is a composition of two automata $A_k^{R_1}$ and $A_k^{R_2}$ of two different robots R_1 and R_2.

all the single states of the statechart S as its domain. Each state s of S has its corresponding set $r(s)$ of robots and the communication protocol specification would need to take into account the fact that some of the states need to be signaled by more than one robot in order to get the information about the system being in some global state. But for the sake of simplicity we do not introduce the formal definitions here.

C. Simple topological maps

The case we are interested in investigating is the following: We consider a team of heterogeneous robots, with two kinds of team members - investigators and carriers. The carriers are also investigators, that is, they can map the environment and search for the object, but moreover they can carry the object out of a building. However, the object requires at least k carriers to transport it out. The building consists of a number of rooms and corridors connected by doors. A natural map for such an environment is a topological map forming a graph, where nodes correspond to rooms and corridors and edges correspond to existing navigable connections between them. There are many existing methods for creating such maps (e.g., [9], [11]). In general, such graphs will include one or more cycles, although a "real" office environment would contain only few of them.

The investigators explore the environment departing from a common place - a particular initial node in the map, possibly representing the outside of a building - and create successively more and more accurate map of the building. Simplifying further we may assume that the environment is orthogonal, what means that all the walls in the building are oriented in one of the two directions: NS and EW, and that each robot needs to move only in either of the four directions: N, E, S and W. Then, forgetting the distances that might be associated with edges of the graph, the path of each robot might be represented as a string over the alphabet $\Sigma = \{N, S, W, E\}$ where each symbol corresponds to the direction chosen by the robot at each possible choice or turning point.

Let us now assume that the investigators have spent some time in the building, mapping some parts of it. Such investigations need not to be coordinated, although some amount of coordination would increase the efficiency of search. Each robot has a topological map of that part of the building it has traveled through, possibly in from of a string or tree over Σ. One of the investigators finds the object of search. What does it need to communicate to other robots?

If we assume no previous synchronization of individual maps, then obviously the entire map string or map tree has to be communicated to the carriers, while other investigators need only to know that the search is finished. When a carrier receives a map from the successful investigator, it matches it with its own map in order to find out the shortest possible path to the object. Such a string matching or, if the map is stored in some other format, then tree or graph matching, is a non-trivial problem in general case, with many interesting applications outside robotics, but lies outside the scope of the work presented here.

Some complexity might be added by requiring that only exactly k carriers proceed towards the object while others move towards the exit from the building. An interesting question then is how to decide which k carriers should stay and carry out the object? This might be done via negotiation (carriers inform each other about the distance they have to the object and those k with the shortest paths stay in the building) or reactively - all proceed towards the object, but when k carriers have already got there, then a signal is sent to everybody else about no more necessity of help.

An interesting observation is that the communication between the robots might be described as a language over Σ, with all the advantages of such approach. One may describe the problems of map synchronization and coordination in terms of language manipulation.

D. Robot control systems

As the experiments we have performed so far were limited to the simple two-robot case, what follows is a summary of the experiments reported in [7].

The control systems of both robots have hybrid, layered architecture, where the upper level, discrete, corresponds to one of the automata presented in Figure 2 and consists of a number of discrete states describing different control modes of each robot, while the lower layer, continuous, implements modes, or individual behaviors. There are many existing architectures for implementing hybrid robot controllers (see, e.g., [12] or [2]), but as the systems here are very simple, they have been implemented directly, without employing any advanced software tools.

E. Implementation of the two-robot case

Below we present briefly the functionality of the software used to implement the control systems for the robots used during our experiments. The software structure mirrors the respective automaton from Figure 2.

The investigator might be executing one of the following behaviors:

1. Looking for the object;
2. Approaching the object;
3. Giving way to the carrier to lift the object;
4. Waiting for the object to be lifted by the carrier;
5. Looking for the goal position;
6. Getting to the goal position.

The carrier executes the following behaviors, depending on the current mode:

1. Following the investigator;
2. Lifting the object;
3. Putting the object down.

The communication needs have been extremely minimal in this task. The investigator sends two different messages while the carrier needs to send only one. Therefore we have used very simple, inherently binary, signals that were passed between the robots via radio modems.

We have performed a number of test runs of the scenario. Although one may criticize the robustness or efficiency of individual behaviors, the cooperation has occured successfully every time. The robots had no problems whatsoever with getting to the goal position with the found object.

IV. Related work

During recent years one of the most important achievements on robot cooperation is the ALLIANCE architecture proposed by Parker [13]. The main assumption there is use of simple homogeneous robots for tasks requiring cooperation. The robots used are controlled behaviorally and the cooperation emerges out of (or is enforced by) use of so called *motivational behaviors*. ALLIANCE proposes designing the control systems for the robots as hierarchical behaviors, where the topmost level, motivational behaviors, are turned on and off on the basis of communication with other robots.

ALLIANCE is a completely distributed system: there is no central mediator for the coordination and all the team members have the same rights to initiate or engage in communication with other robots.

Definitely ALLIANCE would be more than sufficient to implement a multi-robot system for our task. The only objection might be that it is too elaborate and complex for this purpose and that a straightforward implementation is easier and faster to achieve. Moreover, ALLIANCE does not explicitly address heterogeneous multi-robot systems, what is our primary concern, although it can obviously accommodate them as well.

Slightly different approach has been presented in the work [14]. The point of departure is the same as ours: a team of heterogeneous robots cooperating on equal basis while executing a task. However, the assumptions made about each robot are much more advanced: besides a usual behavioral control system each robot creates and maintains a relatively detailed world model called *map*, much more complex than our topological map, and then, on the basis of the map contents, derives actions that would enforce the cooperation and, ultimately, the task completion.

This approach may be considered inconsequent, because behavioral control on the basis of a faithful world model seems to be an oversimplification, while the control architecture itself, although multi-threaded, resembles too much the classical sense-think-act architecture to allow scaling up. Unavoidably there will occur bottlenecks in map information processing. However, the idea of *map focusing* is very interesting and definitely worth further investigation.

Dudek [11] describes research on collective map creation and maintenance. Without doubt it is one of the most important applications for multi-robot systems, useful in many areas. In our case we have chosen to use simple topological maps in order to simplify the communication problem, therefore a direct comparison would not be fair.

The research closest to ours has been reported in [15], where authors investigate the information exchange needs among cooperating robots. But the work has been limited to the robots based on CEBOT architecture, while our aim was to introduce a more general cooperation model that is architecture-independent.

In a recent paper Xuan, Lesser and Zilberstein [16] introduce a more advanced model of communication among individuals in a multi-agent system. The model is more realistic by taking into account the cost of the communication itself. On the other hand, it is based on Markov decision processes, thus introducing uncertainty, and assumes a common goal of all individuals, which need not to be the case in realistic situations. In our opinion, one should first investigate the limits of deterministic models before resorting to probabilistic ones, at least for such simple cases as ours.

The problems related to string, tree and graph matching are studied very intensively nowadays as it is one of the basic problems within the field of computational biology. For an overview of this research the reader might consult [17]. As in our case we deal with short, simple strings, straightforward brute-force matching is sufficient. But more complex environments might require use of more advanced methods. This type of problems is central in computer science since its beginning. A classical summary of related results may be found in [18].

V. Conclusions

Robot cooperation in multi-robot systems is an interesting area of research. In this paper we have looked at the problem of modeling cooperation, motivated use of models for the purpose of developing communication protocols and focused on a simple case of a system describable using hybrid automata (although the paper presented only the discrete, statechart part of the model). We have discussed the observability function determining the communication needs in our simple case. We can conclude that in cases where automata-based models are applicable, e.g., when only behavioral control is used, the communication protocol can be safely derived without complex tools.

We intend to continue this line of research by looking at communication needs in more advanced cases, e.g., when another kind of map, possibly distributed or shared, is necessary for task execution. We expect that the automata-based models may scale up to that level as well and thus provide a simple but powerful tool for designing multi-robot cooperation.

We intend to report during the Workshop about the results of our practical experiments with map communication and synchronization.

Acknowledgments

This research has been done in cooperation between the Polish Academy of Sciences, Institute of Fundamental Technological Research (IPPT) and the Department of Computer Science, Lund University. This work has been partially supported by the grants from the Polish Academy of Sciences and The Royal Swedish Academy of Sciences.

References

[1] Luca Iocchi, Daniele Nardi, and Massimiliano Salerno, "Reactivity and deliberation: A survey on multi robot systems," In Hannebauer et al. [19], pp. 9–32.

[2] Robin R. Murphy, *Introduction to AI Robotics*, MIT Press, 2000.

[3] A. Bond and L. Gasser, Eds., *Readings in Distributed Artificial Intelligence*, Morgan Kaufman, 1988.

[4] Jacques Ferber, *Multi Agent Systems*, Addison-Wesley, 1995.

[5] Gerhard Weiss, Ed., *Multiagent System*, The MIT Press, 1999.

[6] Sascha Ossowski, *Co-ordination in Artificial Agent Societies*, vol. 1535 of *LNAI*, Springer, 1999.

[7] Michał Gnatowski and Jacek Malec, "A minimalistic model of mobile robot cooperation," Accepted to the 7th National Conference on Robotics, September 2001.

[8] Maja J. Matarić, "Minimizing complexity in controlling mobile robot population," *IEEE Trans. Robotics and Automation*, pp. 830–835, 1992.

[9] Ulrich Nehmzow, *Mobile robotics: a practical introduction*, Applied Computing. Springer, 2000.

[10] David Harel, "Statecharts: A visual formalism for complex systems," *Science of Computer Programming*, vol. 8, pp. 231–274, 1987.

[11] Gregory Dudek and Michael Jenkin, *Computational Principles of Mobile Robotics*, Cambridge University Press, 1999.

[12] Man Lin, *Analysis and Synthesis of Reactive Systems: A Generic Layered Architecture Perspective*, Ph.D. thesis, Department of Computer Science, Linköping University, 1999, Linköping Studies in Science and Technology, Dissertation No 613.

[13] Lynne E. Parker, "ALLIANCE: An architecture for fault tolerant multirobot cooperation," *IEEE Transactions on Robotics and Automation*, vol. 14, no. 2, pp. 220–240, April 1998.

[14] Stefano Carpin, Carlo Ferrari, Enrico Pagello, and Pierluigi Patuelli, "Bridging deliberation and reactivity in cooperative multi-robot systems through map focus," In Hannebauer et al. [19], pp. 35–52.

[15] Anhui Cai, Toshio Fukuda, and Fumihito Arai, "Information sharing among multiple robots for cooperation in cellular robotic system," in *Proc. IROS 97*, 1997, pp. 1768–1773.

[16] Ping Xuan, Victor Lesser, and Shlomo Zilberstein, "Communication decisions in multi-agent cooperation: Model and experiments," in *Proc. AGENTS'01*, Montreal, Canada, 2001.

[17] P. A. Pevzner, *Computational Molecular Biology: An Algorithmic Approach*, The MIT Press, 2000.

[18] Donald E. Knuth, *The Art of Computer Programming, Sorting and Searching*, vol. 3, Addison-Wesley, 3 edition, 1998.

[19] Markus Hannebauer, Jan Wendler, and Enrico Pagello, Eds., *Balancing Reactivity and Social Deliberation in Multi-Agent Systems*, vol. 2103 of *LNAI*, Springer, 2001.