TOWARDS PRACTICAL APPLICATION OF SWARM ROBOTICS: OVERVIEW OF SWARM TASKS

Aleksis Liekna, Janis Grundspenkis
Riga Technical University, Latvia
aleksis.liekna@rtu.lv, janis.grundspenkis@rtu.lv

Abstract. Swarm robotics is a relatively new research area inspired from biological systems such as ant or bee colonies. It composes a system consisting of many small robots with simple control mechanisms capable of achieving complex collective behaviours on the swarm level such as aggregation, pattern formation and collective transportation to name a few. However, more research is still required to apply swarm robotics in practice. Within the scope of our knowledge at the moment there are no swarm robotics applications for real-life problems. The current research tends to solve specific tasks in controlled laboratory environments. In this paper we survey the existing works on swarm robotics and their applications and also analyse the potential of their applicability to solve real-life problems

Keywords: swarm robotics, overview, practical applications, tasks of the swarm.

Introduction

Swarm robotics is a branch of multi-robot systems that embrace the ideas of biological swarms such as insect colonies, flocks of birds and schools of fish. The term “swarm” is used to refer “*a large group of locally interacting individuals with common goals*” [1]. Swarm robotics systems as well as their biological counterparts consist of many individuals exhibiting simple behaviors. While executing these simple behaviors, individuals are capable of producing complex collective behaviors on the swarm level that no individual is able to achieve alone. Ant colony can be viewed as an example – a single ant has limited sensing capabilities and relies only on local information, but by working together the colony is able to perform rather complex foraging, construction and transportation tasks.

Swarm robotics systems are characterized by simplicity of individuals, local sensing and communication capabilities, parallelism in task execution, robustness, scalability, heterogeneousness, flexibility and decentralized control [2]. Some researchers (e.g., in [3]) conclude that even simple passive entities (such as rice) are able to produce interesting behaviors (i.e., form patterns) if stimulated by external force. To analyze potential capabilities of robot swarms, swarm robotics has been studied in the context of producing different collective behaviors to solve tasks such as: aggregation [4], pattern formation [5], self-assembly and morphogenesis [6], object clustering, assembling and construction [7], collective search and exploration [8; 9], coordinated motion [10], collective transportation [11; 12], self-deployment [13], foraging [14] and others.

The analysis of the results of these studies shows that robot swarms are capable to solve these tasks satisfactory in controlled laboratory environments, at the same time there is no evidence of applying swarm robotics to solve real-life problems. The purpose of this paper is to take a step closer to bridging the gap between research in swarm robotics and their practical applications. We analyze the existing approaches in the field of swarm robotics and discuss their result applicability for solving real-life problems by outlining tasks that have been studied in the context of swarm robotics systems and analysing their potential practical applications. We also discuss how the tasks could be combined to achieve desirable practical results.

Tasks of the swarm

The potential applications of swarm robotics range from surveillance operations [15] to mine disarming in hostile environments [16]. We believe it is essential to identify the tasks that can be solved using swarm robotics. According to recent literature reviews [1; 2; 17-19], swarm robotics has been studied in the context of the following tasks:

Aggregation deals with spatially grouping all robots together in a region of the environment. Aggregation is used to get robots in a swarm sufficiently close together and can be used as a starting point for performing some additional tasks, such as communication with limited range. Aggregation near points of interest can be viewed as the first step of more complex tasks, such as collective transportation where objects of interest need to be transported by several robots. Research in aggregation include [4; 20; 21].

Pattern formation considers robot deployment into environment forming some sort of geometric pattern such as a circle, a square, a line, a star, a lattice, etc. Pattern formation is useful in preserving communication range and helping to overcome environment limitations (e.g., forming a chain to pass a narrow passage). Pattern formation is studied in [5; 22].

In *self-assembly* robots physically connect to each other to form a particular structure. Self-assembly is used to increase the pulling power of the robots, provide stability to the robot swarm while moving on rough terrains, form a connected structure to guide other swarm robots, assemble structures used to overcome holes that a single robot would fall into and to combine capabilities of heterogeneous robots. Self-assembly is studied in several large-scale research projects such as SWARM-BOTS [4; 5], Symbrion [6], Swarmanoid [23] and Replicator [24].

O*bject clustering and assembling* involves picking up objects that are spread across the environment and clustering or assembling them in specific regions. There is no connection among objects in a cluster while objects are physically linked together in assembling tasks. The techniques of clustering and assembling are used in *collective construction* to produce 2D and 3D structures (such as walls) [25-27].

In s*warm-guided navigation* robots of the swarm are navigated by other members of the swarm. Robots are not aware of their actual location or the location of the target. Instead, the swarm is guided by directions supplied by previously deployed robots forming a communication relay. Examples include robots forming a chain from a pray to the nest and indicating directions to other robots in a foraging task [28], navigation via exchanging navigation messages [29] and flying robots navigating wheeled robots [30].

Mapping is the process of obtaining a map of the environment using a robot swarm. Determining the position of robots or targets in the environment is called *localization*. Mapping and localization is usually addressed together since it is essential to know the positions of robots to obtain a map. Mapping has dual purpose. First, it is used to map previously unknown (or even hazardous) environments; second, it assists the navigation of robots reducing the need for beacons and swarm-guided navigation techniques. Mapping and localization is studied in [31-33].

Self-deployment addresses the problem of deploying robots (*disperse* them) in the environment by covering as much space as possible. This task is also known as *area coverage* task. The self-deployment problem is known to indirectly solve the mapping problem [18]. Potential applications of self-deployment include surveillance and security. Self-deployment is discussed in [34] and [35].

Coordinated motion task represents moving while preserving formation and is also referred to as *flocking*. This is useful in applications involving movement groups of robots since preserving formation allows avoiding collisions among robots and serves as a navigation mechanism. Coordinated motion is investigated in [10; 36; 37].

The aim of *obstacle avoidance* is to prevent robot collisions with environment and with each other. *Path planning* is used to navigate robots in the environment while avoiding obstacles. The research results dealing with path planning and obstacle avoidance are included in articles [38-41]. Obstacle avoidance is also coupled with coordinated motion in [42; 43].

Collective transportation task involves robot cooperation to collectively transport an object, given that the transportation of single object requires more than one robot. Research in collective transport is divided into pushing [44], grasping [45] and caging [46].

In *Consensus achievement and collective decision making* robots must agree on a common decision such as which path to take or which target to follow. Agreement is achieved by either direct communication via exchanging messages (e.g., voting) or indirect communication using local sensor information (e.g., follow nearest robot). Consensus achievement is examined in [47-49]. Potential applications include scenarios where a collective decision is necessary to successfully accomplish the task at hand.

In *foraging* task robots must find preys and bring them to the nest. This type of task is also known as *prey retrieval or gathering* task. Foraging can be viewed as a subset of object clustering where robots cluster preys at the nest. Research in foraging is described in [16; 50-52]. The potential applications of foraging in a real-world scenario are search and rescue operations.

In c*ooperative hole avoidance* tasks robots must travel through environment while avoiding holes. Hole avoidance for a single robot is viewed as a variant of obstacle avoidance task with holes representing the obstacles. However, robots in a swarm can be connected together while moving in formation, making this problem more difficult to solve. Robots may not only avoid the hole but also assemble into a larger structure and overcome the hole that a single robot would fall into. Hole avoidance is investigated [53; 54].

The objective of *cooperative stick pulling* is to use robots to pull sticks out of the ground. As a single robot cannot pull a stick by itself, there is a need for two or more robots to complete the task. The research results in cooperative stick pulling are published in [55-57].

Robot soccer is an experimental test-bed for multi-agent and multi-robot algorithms. To be successful in robot soccer, a team of robots must possess various skills and capabilities, combining existing research and introducing novel algorithms. Example of studies in robot soccer are [58] and [59]. From a practical application point of view robot soccer is interesting in terms of collaboration in competitive scenario. Ideas from robot football could be transferred to other applications such as military defense operations.

The abovementioned tasks are studied together or separately depending on the research conducted. We consider these tasks as basic building blocks to produce a swarm applicable in real-world scenarios. We agree with the authors of [19] in terms that new research should focus more on applications of previous work. The authors of [1] also mention that future swarm research should focus on addressing multiple issues, not just one. Considering the above mentioned we introduce an example of swarm application and analyse how the abovementioned tasks can be used to solve it.

Practical application of swarm tasks

We introduce an example of practical application where swarm robotics could be used and analyze which tasks can be applied for the swarm to be successful. The aim is to show how the tasks identified in the previous section fit into solutions for real-world problems and how they can be combined to achieve the desirable result. Consider an example of agriculture – a field that needs to be cultivated. The task is to mow cereals and deposit them at the warehouse. A swarm of robots with the appropriate capabilities (e.g., harvesters and transporters) is sent to complete the task. This is how the tasks contribute to successful completion of the mission.

At the beginning of the mission robots *aggregate* on the field to achieve the starting point of the mission. To effectively cover the field while performing the mowing operation, robots *form patterns,* e.g., lines of harvesters. Harvesters *self-assemble* with transporters providing harvester-transporter combo. Ideas from *object clustering and assembling* are used in two phases of the mission. First, mowed cereals are clustered by harvesters in specific points of the field for them to be later picked up by transporters. Second, at the warehouse object clustering and assembling are used to store the goods in an effective way. To overcome drawbacks (or lack of) GPS signals, robots use moving beacons for *navigation* on the field. A precise *map* of the field is constructed during the mission and used to overcome environment limitations, e.g., large rocks in the field. After the initial aggregation at the beginning of the mission, robots use techniques from *self-deployment* to cover the field in the most effective way. While mowing, robots sustain a *pattern of harvesters moving in lines* to effectively cover the field. Robots *avoid obstacles* such as rocks and trees and use *planning techniques* to construct collision-free paths. Depending on a situation it might be beneficial for a group of transporters to *collectively transport* a large amount of goods at once instead of transporting smaller amounts several times. Harvesters and transporters *collectively decide* upon the most beneficial way to act upon a field. Harvesters either cluster goods at specific regions of the field where transporters pick them up later of self-assemble with transporters to provide harvester-transporter combo. The entire scenario can be abstracted as a *foraging task* where robots go into the field, forage for goods and then return to the warehouse carrying their gain. Robots use techniques from *cooperative hole avoidance* to avoid ditches and ponds. *Cooperative stick pulling* is applied to load the goods into transporters. While there are no real "sticks", the cargo loading operation can be viewed as a stick-pulling task, given that more than one robot is required to successfully perform the operation. Techniques from *robot soccer* can indirectly be applied in harvester operation, e.g., ball dribble from the robot soccer can be adapted for movement of goods at short distances. As it can be seen from this example, the potential of practical application of the identified task types of the swarm is rather high. The question is how to fully exploit this potential.

Conclusions

In this paper we have summarized tasks that have been studied in the context of swarm robotics and discussed the practical applicability of these tasks. To take a next step towards practical application of swarm robotics, a research on combining multiple task types should be conducted. The task types studied in the context of swarm robotics can be considered the basic building blocks to produce more complex behaviours with bigger potential of practical applications. We agree with the conclusion of the authors in [19] indicating that new research in swarm robotics should focus more on applications of the previous work. One of the possible steps in this direction is to combine studies in the existing task types to obtain new ones aiming at specific practical applications. For example, by combining the ideas of coordinated motion, obstacle avoidance and cooperative hole avoidance might be possible to produce "safe motion" behaviour. Combining mapping and localization and swarm-guided navigation would produce "safe navigation" behaviour. Combing safe navigation with safe motion would produce a swarm capable of safely travelling through environment while being aware of the position of individual robots. Such swarm has direct application in surveillance and patrolling applications. This is just an example of the possibilities that can be exploited by combining different task types. We believe this research topic is of great potential.

References

1. Barca, J.C., Sekercioglu, Y.A.: Swarm robotics reviewed. Robotica 31, pp. 345-359 (2013)
2. Yogeswaran, M., Ponnambalam, S.: Swarm Robotics: An Extensive Research Review. Advanced Knowledge Application in Practice, Igor Fuerstner (Ed.) (2010)
3. Grossman, D., Aranson, I.S., Jacob, E.B.: Emergence of agent swarm migration and vortex formation through inelastic collisions. New Journal of Physics 10, 023036 (2008)
4. Dorigo, M., Trianni, V., Şahin, E., Groß, R., Labella, T.H., Baldassarre, G., Nolfi, S., Deneubourg, J.L., Mondada, F., Floreano, D., Gambardella, L.M.: Evolving self-organizing behaviors for a swarm-bot. Autonomous Robots 17, pp. 223-245 (2004)
5. Trianni, V., Tuci, E., Ampatzis, C., Dorigo, M.: Evolutionary Swarm Robotics: a theoretical and methodological itinerary from individual neuro-controllers to collective behaviours. In: I., H., P., H. (eds.) The Horizons of Evolutionary Robotics. MIT Press, MA (2010)
6. Baele, G., Bredeche, N., Haasdijk, E., Maere, S., Michiels, N., Peer, Y.V.D., Schmickl, T., Schwarzer, C., Thenius, R.: Open-ended on-board evolutionary robotics for robot swarms. Proceedings of the Eleventh conference on Congress on Evolutionary Computation, pp. 1123-1130. IEEE Press, Trondheim, Norway (2009)
7. Nitschke, G.S., Schut, M.C., Eiben, A.E.: Evolving behavioral specialization in robot teams to solve a collective construction task. Swarm and Evolutionary Computation 2, pp. 25-38 (2012)
8. Venayagamoorthy, G.K., Grant, L.L., Doctor, S.: Collective robotic search using hybrid techniques: Fuzzy logic and swarm intelligence inspired by nature. Engineering Applications of Artificial Intelligence 22, pp. 431-441 (2009)
9. Hereford, J.M., Siebold, M.A.: Bio-inspired search strategies for robot swarms. From Biology to Robotics 1 (2010)
10. Ferrante, E., Turgut, A.E., Cristi, #225, Huepe, n., Stranieri, A., Pinciroli, C., Dorigo, M.: Self-organized flocking with a mobile robot swarm: a novel motion control method. Adaptive Behavior - Animals, Animats, Software Agents, Robots, Adaptive Systems 20, pp. 460-477 (2012)
11. Zhang, D., Xie, G., Yu, J., Wang, L.: Adaptive task assignment for multiple mobile robots via swarm intelligence approach. Robotics and Autonomous Systems 55, pp. 572-588 (2007)

12. Chaimowicz, L., Campos, M.F.M., Kumar, V.: Dynamic role assignment for cooperative robots. In: Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on, pp. 293-298 vol.291. (2002)
13. Couceiro, M.S., Figueiredo, C.M., Portugal, D., Rocha, R.P., Ferreira, N.M.F.: Initial deployment of a robotic team - a hierarchical approach under communication constraints verified on low-cost platforms. In: Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on, pp. 4614-4619. (2012)
14. Campo, A., Gutiérrez, Á., Nouyan, S., Pinciroli, C., Longchamp, V., Garnier, S., Dorigo, M.: Artificial pheromone for path selection by a foraging swarm of robots. Biological Cybernetics 103, 339-352 (2010)
15. Mullen, R.J., Monekosso, D.N., Barman, S.A., Remagnino, P.: Autonomous control laws for mobile robotic surveillance swarms. In: Computational Intelligence for Security and Defense Applications, 2009. CISDA 2009. IEEE Symposium on, pp. 1-6. (2009)
16. Martinson, E., Arkin, R.C.: Learning to role-switch in multi-robot systems. In: Robotics and Automation, 2003. Proceedings. ICRA '03. IEEE International Conference on, pp. 2727-2734 vol.2722. (2003)
17. Brambilla, M., Ferrante, E., Birattari, M., Dorigo, M.: Swarm robotics: a review from the swarm engineering perspective. Swarm Intelligence 7, 1-41 (2013)
18. Bayindir, L., Şahİn, E.: A Review of Studies in Swarm Robotics. Turkish Journal of Electrical Engineering & Computer Sciences 15, 115-147 (2007)
19. Miner, D.: Swarm robotics algorithms: A survey. (2007)
20. Soysal, O., Bahçeci, E., Sahin, E.: Aggregation in swarm robotic systems: Evolution and probabilistic control. Turk J Elec Engin 15, (2007)
21. Soysal, O., Sahin, E.: Probabilistic aggregation strategies in swarm robotic systems. In: Swarm Intelligence Symposium, 2005. SIS 2005. Proceedings 2005 IEEE, pp. 325-332. (2005)
22. Maxim, P.M., Spears, W.M., Spears, D.F.: Robotic chain formations. In: Proceedings of the IFAC workshop on networked robotics, pp. 19-24. Citeseer, (2009)
23. Dorigo, M., Floreano, D., Gambardella, L.M., Mondada, F., Nolfi, S., Baaboura, T., Birattari, M., Bonani, M., Brambilla, M., Brutschy, A.: Swarmanoid: a novel concept for the study of heterogeneous robotic swarms. IEEE Robotics & Automation Magazine (2012)
24. Kernbach, S., Meister, E., Schlachter, F., Jebens, K., Szymanski, M., Liedke, J., Laneri, D., Winkler, L., Schmickl, T., Thenius, R., Corradi, P., Ricotti, L.: Symbiotic robot organisms: REPLICATOR and SYMBRION projects. Proceedings of the 8th Workshop on Performance Metrics for Intelligent Systems, pp. 62-69. ACM, Gaithersburg, Maryland (2008)
25. Melhuish, C., Welsby, J., Edwards, C.: Using templates for defensive wall building with autonomous mobile antlike robots. In: Proceedings of Towards Intelligent Mobile Robots (TIMR'99). (1999)
26. Justin, W.: Extended Stigmergy in Collective Construction. In: Radhika, N. (ed.), vol. 21, pp. 20-28 (2006)
27. Werfel, J., Petersen, K., Nagpal, R.: Distributed multi-robot algorithms for the TERMES 3D collective construction system. URL http://www.eecs.harvard.edu/ssr/publications/. Last checked on November (2012)
28. Nouyan, S., Dorigo, M.: Path Formation in a Robot Swarm Self-Organized Strategies to Find Your Way Home. Swarm Intelligence 2, 1-23 (2008)
29. Ducatelle, F., Di Caro, G., A., Pinciroli, C., Mondada, F., Gambardella, L.: Communication assisted navigation in robotic swarms: Self-organization and cooperation. In: Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on, pp. 4981-4988. (2011)
30. Ducatelle, F., Di Caro, G., A, Pinciroli, C., Gambardella, L., M.: Self-organized cooperation between robotic swarms. Swarm Intelligence 5, 73-96 (2011)
31. Hofmeister, M., Liebsch, M., Zell, A.: Visual self-localization for small mobile robots with weighted gradient orientation histograms. In: 40th International Symposium on Robotics (ISR), pp. 87-91. (2009)
32. Alboul, L., Abdul-Rahman, H., Haynes, P., Penders, J., Tharin, J.: An Approach to Multi-robot Site Exploration Based on Principles of Self-organisation. In: Liu, H., Ding, H., Xiong, Z., Zhu,

X. (eds.) Intelligent Robotics and Applications, vol. 6425, pp. 717-729. Springer Berlin Heidelberg (2010)
33. Rothermich, J., Ecemiş, M.İ., Gaudiano, P.: Distributed Localization and Mapping with a Robotic Swarm. In: Şahin, E., Spears, W. (eds.) Swarm Robotics, vol. 3342, pp. 58-69. Springer Berlin Heidelberg (2005)
34. Howard, A., Matarić, M., Sukhatme, G.: An Incremental Self-Deployment Algorithm for Mobile Sensor Networks. Autonomous Robots 13, pp. 113-126 (2002)
35. McLurkin, J., Smith, J.: Distributed Algorithms for Dispersion in Indoor Environments Using a Swarm of Autonomous Mobile Robots. In: Alami, R., Chatila, R., Asama, H. (eds.) Distributed Autonomous Robotic Systems 6, pp. 399-408. Springer Japan (2007)
36. Hayes, A.T., Dormiani-Tabatabaei, P.: Self-organized flocking with agent failure: Off-line optimization and demonstration with real robots. In: Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on, pp. 3900-3905 vol.3904. (2002)
37. Hettiarachchi, S., Spears, W.M.: Moving Swarm Formations through Obstacle Fields. In: IC-AI, pp. 97-103. (2005)
38. Gerasimos, G.R.: Distributed gradient and particle swarm optimization for multi-robot motion planning. Robotica 26, pp. 357-370 (2008)
39. Garro, B.A., Sossa, H., Vazquez, R.A.: Evolving ant colony system for optimizing path planning in mobile robots. Proceedings of the Electronics, Robotics and Automotive Mechanics Conference, pp. 444-449. IEEE Computer Society (2007)
40. Hettiarachchi, S., Spears, W.M.: Distributed adaptive swarm for obstacle avoidance. International Journal of Intelligent Computing and Cybernetics 2, pp. 644-671 (2009)
41. Van Den Berg, J., Ferguson, D., Kuffner, J.: Anytime path planning and replanning in dynamic environments. In: Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on, pp. 2366-2371. IEEE, (2006)
42. Desai, J.P., Kumar, V., Ostrowski, J.P.: Control of changes in formation for a team of mobile robots. In: Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on, pp. 1556-1561 vol.1552. (1999)
43. Yaochu, J., Yan, M., Hongliang, G.: A morphogenetic self-organization algorithm for swarm robotic systems using relative position information. In: Computational Intelligence (UKCI), 2010 UK Workshop on, pp. 1-6. (2010)
44. Yamada, S., Saito, J.: Adaptive action selection without explicit communication for multirobot box-pushing. Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on 31, pp. 398-404 (2001)
45. Gross, R., Mondada, F., Dorigo, M.: Transport of an object by six pre-attached robots interacting via physical links. In: Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on, pp. 1317-1323. (2006)
46. Zhidong, W., Hirata, Y., Kosuge, K.: Control a rigid caging formation for cooperative object transportation by multiple mobile robots. In: Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on, pp. 1580-1585 Vol.1582. (2004)
47. Wessnitzer, J., Melhuish, C.: Collective Decision-Making and Behaviour Transitions in Distributed Ad Hoc Wireless Networks of Mobile Robots: Target-Hunting. In: Banzhaf, W., Ziegler, J., Christaller, T., Dittrich, P., Kim, J. (eds.) Advances in Artificial Life, vol. 2801, pp. 893-902. Springer Berlin Heidelberg (2003)
48. Garnier, S., Gautrais, J., Asadpour, M., Jost, C., Theraulaz, G.: Self-organized aggregation triggers collective decision making in a group of cockroach-like robots. Adaptive Behavior 17, pp. 109-133 (2009)
49. Montes de Oca, M., Ferrante, E., Scheidler, A., Pinciroli, C., Birattari, M., Dorigo, M.: Majority-rule opinion dynamics with differential latency: a mechanism for self-organized collective decision-making. Swarm Intelligence 5, pp. 305-327 (2011)
50. Tangamchit, P., Dolan, J.M., Khosla, P.K.: The necessity of average rewards in cooperative multirobot learning. In: Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on, pp. 1296-1301 vol.1292. (2002)
51. Liu, W., Winfield, A.F., Sa, J.: Modelling swarm robotic systems: A case study in collective foraging. Towards Autonomous Robotic Systems (TAROS 07) pp. 25-32 (2007)

52. Groß, R., Nouyan, S., Bonani, M., Mondada, F., Dorigo, M.: Division of Labour in Self-organised Groups. In: Asada, M., Hallam, J.T., Meyer, J.-A., Tani, J. (eds.) From Animals to Animats 10, vol. 5040, pp. 426-436. Springer Berlin Heidelberg (2008)
53. Trianni, V., Dorigo, M.: Emergent collective decisions in a swarm of robots. In: Swarm Intelligence Symposium, 2005. SIS 2005. Proceedings 2005 IEEE, pp. 241-248. (2005)
54. Trianni, V., Nolfi, S., Dorigo, M.: Cooperative hole avoidance in a swarm-bot. Robotics and Autonomous Systems 54, pp. 97-103 (2006)
55. Ijspeert, A., Martinoli, A., Billard, A., Gambardella, L.: Collaboration Through the Exploitation of Local Interactions in Autonomous Collective Robotics: The Stick Pulling Experiment. Autonomous Robots 11, pp. 149-171 (2001)
56. Martinoli, A., Easton, K., Agassounon, W.: Modeling swarm robotic systems: A case study in collaborative distributed manipulation. The International Journal of Robotics Research 23, pp. 415-436 (2004)
57. Li, L., Martinoli, A., Abu-Mostafa, Y.: Emergent Specialization in Swarm Systems. In: Yin, H., Allinson, N., Freeman, R., Keane, J., Hubbard, S. (eds.) Intelligent Data Engineering and Automated Learning — IDEAL 2002, vol. 2412, pp. 261-266. Springer Berlin Heidelberg (2002)
58. Duan, Y., Liu, Q., Xu, X.: Application of reinforcement learning in robot soccer. Engineering Applications of Artificial Intelligence 20, pp. 936-950 (2007)
59. Stone, P., Veloso, M.: Layered Learning. In: López de Mántaras, R., Plaza, E. (eds.) Machine Learning: ECML 2000, vol. 1810, pp. 369-381. Springer Berlin Heidelberg (2000).