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Multi-Robot Systems: A Review of Pattern Formation and Adaptation

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Abstract

Recent advances in robotics have started making it feasible to deploy large numbersof inexpensive robots for tasks such as surveillance and search. However, coordinationof multiple robots to accomplish such tasks remains a challenging problem. This reportreviews some of the recent literature in multi-robotsystems. It consists of two parts.In the _rst part, we reviewed the studies on the pattern formation problem, that ishow can a group of robots be controlled to getinto and maintain a formation. Thesecond part reviews the studies that used adaptation strategies in controlling multirobotsystems. Specifically we haveinvestigated (1) how learning (life-long adaptation)is used to make multi-robot systems respond to changesin the environment as well inthe capabilities of individual robots, and (2) how evolution is used togenerate groupbehaviors.

Introduction

Recent advances in robotics have started making itfeasible to deploy large numbers ofinexpensive robotsfor tasks such as surveillance and search. However, coordinationof multiple robots to accomplish suchtasks remains a challenging problem. Previousreviews on multi-robot systems (such as those written by Caoet al.[25] and Dudek etal.[7]) have taken a broad view.Different from these, this report has a narrow span andlimits itself to the recent literature on pattern formation and adaptation in multi-robotsystems.The report consists of two parts. In the first part, we reviewed the studies on thepattern formation problem, that is how can a group of robots be controlled to get intoand maintain a formation. The second part reviews the studies that used adaptationstrategies in controlling multi-robot systems. Specifically we have investigated (1)how learning (life-long adaptation) is used to make multi-robot systems respond tochanges in the environment as well in the capabilities of individual robots, and (2) howevolution is used to generate group behaviors.

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Pattern formation in multi-robot systems

The pattern formation problem is defined as the coordination of a group of robots toget into and maintain a formation with a certain shape, such as awedge or a chain.Current application areas of pattern formation include search and rescue operations,landmine removal, remote terrain and spaceexploration, control of arrays of satellitesand unmanned aerial vehicles (UAVs).Pattern formation is also observed in various animal species as a result of cooperativebehaviors among its members, wherethe individuals stay at a specific orientationand distance with respect to each other while moving, orfill a specific area as homogeneouslyas possible.Examples of pattern formation in animals include birdflocking,fish schooling, and ants forming chains[18].

We have classified the pattern formation studies intotwo groups. The first groupincludes studies where the coordination is done by a centralized unit that can overseethe whole group and command the individual robots accordingly. The second groupcontains distributed pattern formation methods for achievingthe coordination.

Centralized pattern formation

In centralized pattern formation methods, a computational unit oversees the wholegroup and plans the motion of the group members accordingly[3, 13, 23, 24]. Themotion of each robot is then transmitted to the robot via a communication channel.Egerstedt and Hu[13] propose a coordination strategy for moving a group of robotsin a desired formation over a given path. Path planning is separated from the pathtracking task. It is done in a centralized way and the tracking of virtual reference pointsare handled separately. The path for a virtual leader is computed as a reference point forthe robots to follow. They applied the method to coordinate the movement of simulatedrobots in a triangular formation while avoiding anobstacle. In this example, the robotsthat formed the corners of the triangle, went around an obstacle, which fell in betweenthe robots. The paper proves that, if the tracking errors of the robots are bounded ortracking is done perfectly, then the described method stabilizes the formation errorKoo and Shahruz [23] propose a centralized path-planning method to yy a groupof unmanned aerial vehicles (UAVs) in a desired formation. The path of each UAVis computed by a leader UAV, which is more capable than others. Only the leader

has cameras and sensors. It tells the other UAVs, via acommunication channel, whattrajectories they should track. What UAVs should do is to take off and _y toward theirtrajectories and lock onto them. Two cases are considered in experiments: the casewhere UAVs take off one by one, and where they do it simultaneously. Trajectorycomputation is the main focus of this study.Belta and Kumar [3] propose a centralized trajectory computation scheme that useskinetic energy shaping. Instead of using a constant kinetic energy metric, they employa smoothly changing the kinetic energy metric. The method generates smooth trajectoriesfor a set of mobile robots. The proximity between the robots can be controlled viaa parameter. However the method does not take obstacle avoidance into considerationand that is not scalableA target assignment strategy for formation building problem is described by Kowalczyk[24]. Starting with a scattered group of robots, the algorithm first assigns a targetpoint for each robot in the desired final formation. Then it generates necessary prioritiesand trajectories for the robots to avoid collisions while moving to their target points. Each robot has an area around its path that is forbidden to other robots withlower priorities. If the robot's trajectory crosses a forbidden area of a higher priorityrobot, the robot waits until the higher priority robot moves out of its way. The methodis tested with non-holonomic and holonomic robots. The method assumes the existenceof a global sensing ability and a centralized computation. The scalability of the method is not addressed.

Centralized pattern formation strategies rely on a central unit that oversee the wholegroup and assume the existence of a communication channel between the central unitand the individual robots. Such assumptions make the centralized strategy more costly,less robust to failures, and less scalable to the

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control of large number of robots. Analternative is to use decentralized pattern formation strategies

Decentralized pattern formation

Communication and completeness of information known by robots impose a trade-offbetween precision and feasibility of forming and maintaining the pattern and the necessityof global information and communication. Studies that require global informationor broadcast communication[29, 19, 12] may suffer from lack of scalability or highcosts of the physical setup but allow more accurate forming of a greater range of formations.

On the other hand, studies using only localcommunication and sensor data[21, 22, 10, 5, 17, 15, 9, 11] tend to be more scalable, more robust, and easier to build;but they are also limited in variety andprecision of formationsSugihara and Suzuki[12] achieved pattern formation by providing each robot theglobal positions of all others. In this study, an algorithm is developed for each pattern.The proposed method can uniformly distribute robots creating different patternformations (circles, polygons, line, filled circle, and filled polygon). It can also split a groupof robots into an arbitrary number of nearly equal sized groups. Despite the impressiveresults obtained by this decentralized algorithm, the global communication required toshare information among the whole group, makes it less scalableCarpin and Parker[19] introduced a cooperative leader following strategy for a teamof robots. The robots are able tomaintain a specific formation while simultaneouslymoving in a linear pattern and avoiding dynamicobstacles. The robots use local sensorinformation and explicit broadcast communication among themselves. The frameworkhandles heterogeneous teams, i.e. comprising of robots with different types of sensors, as well as homogeneous ones

Two levels of behaviors were implemented for tasks: team-level and robot-levelbehaviors. Transitions are made when necessary among specific behaviors in these twolevels. For example, when a member of the team faces an obstacle, the whole teamwaits together with that member for it to go away for a certain amount of time. If thistime is exceeded that member circumnavigates the obstacle and the team returns to itsmain task of moving in a formationBalch and Hybinette [21, 22] proposed a different strategy for robot formation thatis inspired from the way molecules form crystals. In this study, each robot has severallocal *attachment sites* that other robots may be attracted to. This concept is similarto molecular covalent bonding. Possible attachment site geometries include shapesresembling where the robot is the center of the shape and the attachmentsites are the ends of the line segments. Various robot formation shapes result fromusage of different attachment site geometries just as different crystal shapes emergefrom various covalent bond geometries. When a teamof robots moving in a formation,they avoid the obstacle by splitting around it and rejoining afterpassing. This approachis scalable to large robot teams since global communication is not used and that local sensing is sufficient to generate effective formation behaviors in large robot teams.

Another method similar to crystal generation which employs a form of probabilisticcontrol is proposed by Fujibayashi et al.[11]. This study makes use of virtual springsto keep two agents in close proximity. Each pair of robots within a certain range ofeach other, are connected via a virtual spring. Each agent is classifiedby the numberof neighboring agents within this range (number of connections). The robots formtriangle lattices that have random outlines. To obtain a desiredoutline, the virtualsprings among some robots are broken with a certain probability. The candidatespringsto be broken are chosen depending on the number of connections the robots it joinshave. This *breaking preference* and the probability of breakingchanges from formationto formation. The algorithm uses only local information and is decentralized. Onedisadvantage of the method is the difficulty ofchoosing custom parameters for eachformation.

A graph-theoretic framework is proposed by Desai[10] for the control of a teamof robots moving in an area with obstacles while maintaining a specific formation.The method uses control graphs to defined behaviors of robots in the formation. Thisframework can handle transitions between formations, i.e. between control graphs.Proofs of the mathematical results required to enumerate and classify control graphsare given. Although the computations for

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control graphs increase with the number ofrobots,the fact that these computations are decentralized allows the methods describedto be scalable to large groups

Another graph-based approach to *moving in formation* problem is introduced byFierro and Das[17]. They proposed a four-layer modular architecture for formationcontrol. Group control layer is the highest layer generating a desired trajectory forthe whole group to move. Formation control layer implements a physical network, acommunication network, and a computational network (control graph). It maintains theformation by using local communication and relative position information. Kinematicscontrol layer deals with the required linear and angular velocities of robots. Finally, thedynamic control layer handles the task of realizing the necessary speeds given by the kinematics control layer. This four-layer architecture provides an abstraction amongtasks required at different levels. For example, a robot with different mass, inertia,and friction can be used only by changing the dynamic control layer. Furthermorea modular adaptive controller is described which can manage control of robots withunknown dynamics and learns the robot dynamics on-the field. Hence using a different robot requires no change in the system. The method described is scalable (controlalgorithms scale linearly) and flexible (it allows various formations). Centralized anddecentralized versions of control graph assignment algorithm is also described in the study.

only local communication and sensor information. Obstacle avoidance is also providedin this method. It extends ordinary behavior-based approaches with the application ofsocial roles that represent positions in the formation and with the use of local communication to improve performance. As new agents join the formation, the shape is *fixed* bylocal communications and role changes where necessary. The locally communicatedinformation reaches the leader, i.e. the front most robot, which knows the whole shapeof the current formation and which decides on the changes necessary. This informationis then propagated to the necessary followers, and the formation is updated. There is noneed to predefine social roles or positions for robots. Everything is done dynamicallyas the formation grows. This method supports various formations and also switchingbetween them, therefore it is flexible as well as being scalable and local.Dudenhoeffer and Jones[5] designed and implemented a tool to model and simulatecollective behavior and interactions of a group of thousands of robots. Usingthis simulationtool, the problem of hazardous materialdetection by thousands of micro-robotsscattered around a region is tackled. Social potential _elds are utilized for coordinatedgroup behavior where robots are desired to stay at a specific distance from others toobtainoptimum coverage of the area. They are also required to wander in this formationto search other parts. The desired behavior is obtained by using a subsumption architecture.This study also validates the proposed method in cases where it is possible foragents to die and where agents have imperfect sensorreadings. The method uses onlylocal information and is scalable to very large groups of robots.Mataric and Fredslund [9] used local information to establish and maintain formationsamong robots. Each robot has a unique ID and a designated friend robot whichit can see through a .friend sensor.. There is also minimal communication betweenrobots: heartbeat signals (robots broadcast their IDs), swerve signals (changing direction),and formation messages. Each robot can learn the number of robots in formationand the type of formation using broadcasted messages. For each formation, each robothas a specified angle which determines the angle it should keep between its front directionand the direction of its friend. This angle is calculated locally. The detailsof this calculation are given in [9]. This study accomplishes the task of establishingand maintaining formations using only local information and minimal communication.

However the possible formations are limited to chain-shaped ones that do not make abackward curve

One of the major reasons why multi-robot systems are preferred over single-robotsystems is their robustness in performance. The robustness of multi-robot systems can be improved by incorporating adaptation mechanisms that can respond to continuingchanges in the environment as well as in the capabilities of individual robots.

Adaptation in multi-robot systems

In this section we review the studies that used adaptation strategies in controlling multirobotsystems. Specifically we have investigated (1) how learning (life-long adaptation)is used to make multi-robot systems respond to changes in the environment as well

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inthe capabilities of individual robots, and (2) how evolution is used to generate groupbehaviors.
In multi-robot systems, adaptation can be achieved at two levels: group level andindividual level. We classify the recent studies into these levels and review them in thefollowing subsections

Individual level adaptation

Reinforcement learning models become useless when the state space is too large. Usingmultiple learning modules for different states instead of a single complicated learningmodule is one approach to solve this problem. Takayashi's work[26] is one such study.The problem studied in his work is a reduced version of robo-soccer challenge. Opponentsare assumed to have different modes of operation each with a different policy.Modules consist of predictors and planners. Predictor predicts the next action of opponentbased on its previous behavior. Planner on the other hand generates optimalmove based on this prediction. Predictors compete for better accuracy and only bestpredicting module is reinforced. This creates specialized modules for different modesof operation of the opponent.The problem used in this work is ball chasing in presence of a random moving opponent.The results show improvement over single module learning. Reinforcementlearning converges to optimal policy given *sufficient* trials but it is often the case that these *sufficient* trials are too large to be feasible. Piao[20] proposes an improved reinforcementlearning method to improve learning speed of learning. This method iscombination of rule learning, reinforcement learning and *action level selection* whichis basically behavior rules for specific states.The rule base consists of instances that are states passed through a fixed interval.These instances are labeled after each epoch using information gathered through theepoch. These instances are then combined to create rules. These rules are used as aprohibitive guide to inhibit useless or harmful actions. *Action level selection* is composedof hard coded rules to govern general strategy of robots. *Action level* is alsofed into reinforcement level together with sensor data to generate the state information.Finally reinforcement learning module uses sensory information and *action level*to generate state and learns to generate actions. Piao applies this method to the robosoccerproblem. He assumes only one agent is learning at a given time and reportsimproved performance on learning with multiple robots over standard Q learning.

Reinforcement learning is intended for single entities, therefore it doesn't haveany mechanisms to support cooperative behaviors. Tangamchit'swork[16] tackles thisproblem. This work addresses the distinction between action level and task level systems.To solve problems, action level systems generate reactive behaviors. On the otherhand task level systems generate tasks composed of subtasks possibly distributed overmultiple agents. Tangamchit defines cooperation as a task level activity, where robotscan share resources and duties.Two different schemes of reward are considered: global and local. In the global rewardscheme, the reinforcement received by a unit is distributed to the whole group. Incontrast, in the local reward scheme the reward is not distributed among the membersof the group. Two learning algorithms are considered: Q-learning and Monte Carlolearning. Q-learning uses cumulative discounted rewards whereas Monte Carlo learninguses averaging to assess the value of each action in each state. Reward is samefor each state action pair in an episode. This scheme is slower since it disregards theimportance of latter actions in episode which are usually more effective in obtainingreward.

The case examined for this study is puck collecting behavior which a subclass offoraging problem. Robots are required to collect pucks and to deposit them into thebin. Each action has a negative reward except the action of depositing a puck. The field consists of a home region, which doesn't contain any pucks, a deposit bin, andpucks distributed around the region. Two heterogeneous robots are used for this task.The first robot moves and collects better in the region outside the home region. Thesecond robot is limited in movement to home region but can accomplish bin depositaction more efficiently. Optimal strategy requires robots to cooperate and first to bringpucks into home region and second to deposit them. This requires task level learning.

Results indicate that task-level cooperation can't be learned well using local rewardsor discounted cumulative rewards as in Q learning. In opposition global rewardscoupled with average rewards result in cooperative policies for this task.Reinforcement learning only requires feedback for applied sequence

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of actions toincorporate domain knowledge. This is usually incorporated by choice of reward functions.Mataric[14] discusses reward functions in a foraging task. Although single goalsare mathematically simple to analyze, they cause problems through acquisition of behavior.

Especially contingent and sequential behaviors are hard to convert into monolithicgoal functions. Instead of this, separate goal functions are used, each describinga subgoal of agent. A second improvement is progress estimators. These estimatorsgive a rough idea of how well a specific goal is going on. These two improvementsgreatly increase the usage of domain knowledge in the topic (by designing appropriatesubgoals and estimating progress of the subgoals). They also give much more reinforcementthan standard methods, since not only the final goal but also intermediate steps are reinforcedThis improved method is tested on real robots working on a foraging task. Robots are to collect pucks and to deliver them to *home*. Robots are also responsible to bepresent at *home* at certain intervals. Robots are given some simple reactive behaviorsto reduce state space of learning problem to a manageable size. These behaviors arecollecting pucks when it is immediately before agent, avoiding obstacles and droppingpucks when at *home*. Experiments are compared with optimal policy generated byhand. Results indicate the benefit of both improvements purposed. An interesting notein this paper is the interference caused by agents. Increasing number of learning agentshas detrimental effect on general learning speed and convergence

Parker's[6] L-ALLIANCE model uses multiple behavior sets and global communicationsto achieve cooperation. Each behavior set has a monitor. These monitorscheck required conditions for activation of behavior sets, also assess the capability ofagent and other agents. Parker introduces two motivations: impatience and acquiescence.Impatience correspond to tendency to take a task being done by other robotsand acquiescence describes tendency to give up a task to be performed by anotherrobot. L-ALLIANCE architecture changes these motivational parameters during learning.The architecture requires robots to broadcast current actions to other robots. Thisarchitecture assumes that when a robot declares an action, the changes in environmentthat can be caused by result of that action are attributed to that robot. This handlescredit assignment problem.L-ALLIANCE architecture can handle heterogenous groups and can adapt to failuresor changes in robot abilities which are desired properties. On the other hand,L-ALLIANCE requires global communication and makes a strong assumption to solvecredit assignment problem.

Goldberg et al. [4] propose *Augmented Markov Models* (AMM).AMMis a Markovmodel improved by additional statistics about transitions. It is designed to learn thestatistics of the environment rather than to generate a policy. AMM's assume actionbeing performed can be known perfectly, so it is differentiated from Hidden MarkovModels

AMM's are first order Markov models but they are built incrementally. This incrementalbuilding gives them ability to better approximate such higher order trasitionsin the system. Their work combines AMM's with behavior based robotics [2]. Eachbehavior is monitored using AMM's with different time scales. This allows system torespond both slow and fast changes in the environment.

Group level adaptation

Reinforcement learning is by definition centralized which is inefficient to implement inmulti-robot systems. Yanli's study[27] on opportunistically cooperative neural learningproposes a trade-off for centralized versus decentralized learning debate. In pure decentralizedlearning models each agent keeps its learning experience hidden from otheragents. This seriously affects performance of the group since the experience can notbe shared. Yanli solves this problem by adding 'opportunistic' search. This strategyis similar to survival of fittest concept in genetic algorithms. Less _t networks copyhighly _t networks to improve their performance.

Yanli reports the comparison of three cases, central, distributed and opportunisticallydistributed. These cases are tested on searching task where agents are requiredto cover as much of a given space as possible avoiding multiple passes as much aspossible. The best strategy clearly is one that utilizes cooperation. All agents act simultaneouslyand plan their movements ahead of action. Agents also share their planswith other agents. These plans are used to predict the next action of all other agentsby each agent. Learning takes

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place in these predictors. When the next action of otheragents can be predicted precisely reward can be calculated
Results show that central learning is superior to all this methods in performance.However central learning has many problems in fault-tolerance and communication.OCL (opportunistically cooperative learning) performs almost as well as central learningand both perform remarkably better than distributed only case.

Agah[1] combines both individual and group adaptation in his work. Agah usesso called *Tropism Architecture* to approach multi robot learning problem. Tropismarchitecture serves as a learning module between senses and actions. Each tropism isdefined as a tendency to elicit a response for a given stimuli. Tropism architecture keepsa list of learned tropisms (i.e. state, action, tendency pairs). Agents make decisionsbased on matching tropisms to current state. A stochastic process is used to determinewhich actions to apply biased on the tropism values.

Both kinds of learning are applied using this architecture. In individual learningScheme,the list of tropisms are updated based on feedback obtained from environment.These updates include adding a new valid action for current state, increasing tropismvalue for a pair which has been positively reinforced and changing action when aninvalid or negatively reinforced action is encountered

In population learning, the tropism lists for each agent is converted into variablelength bit strings. Using these bit strings, a genetic algorithm is run. The fitness ofeach individual is calculated based on the rewards it received during individual learning.Results indicate success of this twofold method even in absence of reinforcementpropagation as in Q-learning.

It is not always possible to have behaviors beforehand and even behaviors shouldbe learned in certain cases. Hexapod locomotion is such a case. Parker[8] studieson learning a cooperative box pushing task in hexapod robots. The main problemhe is facing is the locomotion problem, since moving hexapod robot requires morecomplicated operations than wheeled robots. For this task Parker purposed CyclicGenetic Algorithms (CGA), which handles requirements of such complicated control.The motivation behind CGA's is evolving a sequence of operations instead of simplestimulus-response pairs. CGA encodes a series of activations which are to be repeatedby the agent.Fitness of each chromosome for a given task is calculated by using a computersimulation where the chromosome to be evaluated is paired with the best known solutionto the problem. The success of the group is used as the fitness measure for thechromosome. Results indicate the effectiveness of purposed method.

Cooperation requires coordination among robots, which requires communication.Early approaches to cooperation used peer-to-peer communication models. This, althoughpossibly required for optimal solution, requires increasing computational powerand bandwidth for increasing number of robots in the system.Local communication reduces bottlenecks in communication but not totally solves this problem. Stigmergy,that is communication through environment, is a possible solution to communicationbottleneck. This implicit communication scheme allows scalability and is observed insocial insects.

Yamada's[28] work provides a working implementation of an implicit communicationsystem for cooperation in robot groups. This scheme is applied to the box pushingproblem. Goal is identified with a light source and robots are assumed to be capable ofthe following: detecting whether box being pushed is moving or not, presence of otherrobots and presence of walls. Here walls are modeled as unmovable boxes so they areignored in the end. The authors generate situations to solve implicit communicationproblem. Situations abstract models of state of the world, which are computed usingthe sensor data and some very crude memory (such as counters for some sensor readings).Robots have sets of rules for each situation. These rules are applied according tosensor readings.

Conclusion

We reviewed the recent studies on the pattern formation and adaptation in multi-robotsystems. The pattern formation studies are classified into two groups. The first groupincludes studies where the coordination is done by a centralized unit that can overseethe whole group and command the individual robots accordingly. The second groupcontains distributed pattern formation methods for achieving the coordination. Thestudies that used adaptation strategies in controlling multi-robot systems were classifiedinto two levels: group level and individual level.

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