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A Survey on Cooperative Mobile Robotics

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Abstract

Currently, various techniques and approaches are being used in cooperative mobile robotics such as CEBOT, ACTRESS, SWARM, and GROFER. There is a huge amount of knowledge related to those techniques and approaches which are wrapped up with several journals and conferences. But, due to the absence of a systematic analysis, the researchers are facing difficulties to acquire that knowledge. It provides a strong understanding that how cooperative mobile robotics is working and which technique and approach are useful for them. In this paper, a systematics analysis is discussed which specifies the characteristics of each technique and approach of the cooperative mobile robotics. This paper also describes the examples of existing technologies to each category for good understanding about the different techniques and approaches of cooperative mobile robotics.

Keywords: Mobile robotics; cooperative mobile robotics; communications technologies; geometric problems; applications

INTRODUCTION

Robotics is a field of engineering that deals with robots and study related to it. Robots are the man-made programmable devices, whose action must be planned controlled through programming and its interaction with surrounding should be without human intervention. Also, its motional behavior can be altered by "programming". Intelligent and smart robots can move successfully in safe interaction with an ambiguous surrounding. Nowadays, dependency of automobile manufacturing industry is continuously switching from human to robots on the assembly lines. Robots with high accuracy and speed are used for welding and painting purpose, but mobility is problem with these kind of robots [1]. In order to see the industrial robots, these robots have at least five parts i.e. *Sensors, Controller, Effectors, Actuators* and *Common effectors* or *Arms* whereas others robots use effectors and artificial intelligence to achieve mobility. Presently, usage of robots for military organizations is the major concern to save human's life in carrying out many risky operations that cannot be handled manually by the soldiers. Thus, different military robots are being exploited by military organizations. *Daksh, PackBot,Goalkeeper, Marcboat* are few of them which are widely used in the military organizations.

General motors are the first to introduce robots. Unmated was the world's first robot installed on production line by General motor. Shakey [33], Stanford Research Institute (SRI International) was the first institute to develop the first mobile intelligent robot between 1966 and 1971 .Shakey is the mobile robot with cameras and touch Sensors. . Large Remote Computers are used to control Shakey. It capitalized on progress in computer vision, language processing and planning to understand instructions and direct its own actions. Mobile robots are machines which are capable of moving freely and have infinitely wide operational area usually, they perform a task such as *surveillance, cleaning, monitoring* and task that are dangerous for a human to perform. The prime example is the *Mars Explorer*, which was particularly designed to roam on the surface of Mars. Mobile robots are very important for these types of missions. Robots that can perform mobile tasks with the help of wheels, tracks or legs are called mobile robotics.

A. Types of Mobile Robots:

Rolling robots: These types of robots are provided with wheels so that they can move around. The main limitation of such robots is that they are useful in plane areas only.

Walking robots: To overcome the limitation of rolling robots, walking robots came into play, they were used in rocky terrain. Mostly robots with 4 legs are used in this type.

Single robot: Instead of being capable, the development of corporative robot is still has spatially limited.

Cooperative Robots: This type of robots can be distinguished by its cooperative behavior. Its mechanism may be controlled either by the designer, structure of the interaction, specification of the task assigned or by the communication dynamics of the agent behavior. Collective behavior is generally described as the behavior of agents in a system having multiple agents. Cooperative robots are able to uphold (Contribute) with the other robots of identical or different architectures or robots with human operators to jointly perform common tasks are referred as cooperative robots.

In this paper, we have discussed how different technologies and approaches have been applied to different cooperative mobile robotics along with a comparative study. We have also described several problems faced by the mobile robotics in their journey.

With this objective, we have organized this paper as follows: In section 2, we have described a literature survey related to the different mobile robots and various techniques applied in this field. In section 3, we have described the literature survey based on several communications among the cooperative mobile robots. In section 4, we have described the literature survey based on several technological constrains in cooperative robots. In section 5, we have described the geometric problems faced by the cooperative mobile robots. In section 6, we have discussed several applications of cooperative mobile robots and in section 7, we conclude our paper with a future scope of the study.

RELATED RESEARCH STUDY

In this section, we have described different mobile robots and the techniques used in this field.

Wheeled robots [2]:For providing motion wheels are the best method to do so. Wheels can be of any size having three to four wheels. In three wheeled robots, two wheels are at one side to provide power and one for stability. For avoiding the robots to slip four and six wheeled robots are introduced. Use of often varied drive motors are the advantage to the robots. basically used to provide power. Few major advantages are usually low cost, easy design.

Tracked robots [2]: A principle design advantages of tracked over wheeled vehicles are that they have large surface area in contact with the solid surface of earth .which exerts much lower force per unit area on the ground. Robots have a large and continuous surface area in touch with the ground which avoid skid that might take place with the wheels. Evenly distributed weight helps the robots to tackle a variety of surfaces. Mechanical design and construction of robots are limited to the tracks are the disadvantages of this type of robots.

Legged robots [3]: Legged type robots superiorly move in natural terrains. The robots uses the different mechanism for different foots. These robots can easily move in irregular terrains by varying their legs configuration. These types of robots have less contact with the ground because of legs and arms. This led to less power consumption, some of the limitations of these types of robots are low speed, and mechanisms are heavy since they need large numbers of actuators.

Most of the work in cooperative mobile robotics field has been done in two approaches: intentional cooperation and swarm-type cooperation [4]. In swarm-type approach, a various number of simple physical robots are unaware of each other's actions [9]. Parallel nature jobs such as sorting mail and collecting rock samples on Mars are performed by robots working on swarm-type approach. Cooperation is working together of simple physical robot for common purpose or benefits. Swarm approach basically target to design protocols for each robots working collectively .Such that each interaction with the surrounding produce globally required behavior. In Intentional cooperation, a very few number of advance robots are used h. In this approach each and every robots are share information and they are aware of each other motion and action and uses this information to perform there job to best such as working on space station and moving furniture[10]. To achieve predefined goals of the robots every simple physical robot interact with the environment or robots of its type. Cooperation can be defined on local and global levels, in swarm approach global cooperation occurs. In intentional cooperation approaches [18], the logical or optimal order is used.

Mataric [9] defined the scope of explicit cooperation as one agent performing activities to reach benefits of another agent's objective. In variation, implicit cooperation is an approach to selfish motivation that helps an agent to attain its own aim, but also have an consequence on the environment that help other agents to arrive to their goals as well.

Matarić [9] conducted an experiment he took twenty similar robots and uses swarm approach. In performing homing behavior Swarm approach increases coordination between the robots. The results of her three experimental cases are as follows: ignorant coexistence, informed coexistence, and intelligent coexistence. In case of ignorant uses a traditional swarm approach in this approach robots are not able to detect the existance of other robots and hindrance caused by other robots. In this approach, robots consume a large amount its time avoiding collision with other robot. In case of informed each and every other robot is able to detect the presence other robot. This help to spend less time in avoiding collision and more on time homing. In case of intelligent, robots are able to find the any other robot with in 36inch radius and it work on the density of population around it and make it effort to avoid the collision and provide the isolation to each robot. In this approach robots have better understanding among them self which help in cooperating one another in completing of the task and reduce the time consumption. Also, it uses a homogeneous intentional cooperation approach on two six-legged box-pushing robots. It is compared with a single robot approach and two non-cooperating robots.

Halme ET. al. [19] used both intentional cooperation and swarm approach in a stone collecting experiment. Robots of different type used In this experiment, robots of two different type are used :work units, which accumulated stones and support units, which carried energy to the work units. The work units used implicit cooperation (swarm), whereas the support units used explicit cooperation (intentional).

Kube and Zhang [21] a group of box pushing robots were exposed to a homogeneous swarm approach and simulated follow –the-leader task .Each robot push the box as this is only allocated to single robot and it gives its hundred percent to push but actually multiple are working on the same task of pushing the box. For avoiding the robots to hit each other interference avoidance algorithm is used. For avoiding robots to hit each other from back side motion detector are used.

Hutin ET. al. [21] used heterogeneous intentional cooperation approach in two parallel experiments: exploration and mapping. Follow -the -leader task, in her these experiments have five representative—three robots, a map builder, and an interface is used. While the robots are homogeneous, the final system is heterogeneous. Table 1 describes a comparative study on several approaches used in mobile robotics along with several aspects.

Table 1. Comparison of approaches used

ATTRIBUTES (Researchers)	TYPE OF ROBOTS	APPROACH	EXPERIMENTAL CASES
Matarić [9]	Homogeneous, two six-legged box-pushing robots	Swarm	Ignorant coexistence, Informed coexistence, and Intelligent coexistence
Halme et. al.[19]	Work units and Support units.	Swarm and Intentional cooperation	Stone collecting experiment
Kube and Zhang[21]	Homogeneous	Swarm with follow the leader	Group of box-pushing robots
Hutin et. al.[21]	Heterogeneous	follow the leader	Exploration and mapping

B. Various Techniques in the Field of Cooperative Mobile Robotics

CEBOT (Cellular Robotics System): It has a decentralized and hierarchical architecture which is inspired by cellular organization of biological units. There are “master cells” in CEBOT hierarchy which are coordinated by subtask. Master cells are able to communicate among each other. Studies related to communication requirements are done on CEBOT architecture. Various methods are proposed to reduce the same by making the cells more intelligent.

The approach of autonomous robot unit provides method for designing of algorithms which enables the robotic units to achieve their tasks. The system is composed of a number of collectively, relatively complex tasks. None of the central controller, shared memory and synchronous clock are used in system. Reliability, self-organize and self-repair are the qualities that indicate the formation of the system. This is known as Cellular Robotic System or CRS. The insufficiency in theoretical framework for handling distributed robotic system was the reason for choosing this problem [24].

Cellular Automata theory, much research of T. Toffoli and N. Margolus, has been a problem in applying it to the actual robotic systems until now.

The importance of developing a theoretical foundation for CRS is for designing and building CRS methodology. Self-organization of robotic units is essential in many applications. Carrying out tasks under central control is unfeasible and impractical, in many situations. There were several reasons why the solution to the issue of CRS has not been created. The first problem was distributed computing theory, second was cellular automata. A system capable of self-organization indulge itself in remodeling the problem rather than finding out new mathematical methods within current paradigms. If it is introduced, then most of the other properties can also be deduced

ACTRESS (ACT or-based Robot and Equipment Synthetic System): ACTRESS, an autonomous and distributed robot system, consisting of multi-robotic elements. It was basically designed as maintenance robot system. Its main purpose is to develop technology used in syntheses of multiple robotic elements. It is applicable in maintaining and complicating tasks in the confined environment such as under-water, natural calamity, bio industry, space and desert.

The aim for organizing the formation of ACTRESS was based on the Universal Modular ACTOR Formalism which provides a computational model in processing of data and formalism. Actor is an object used in representing data structures,control structures and message passing among them. In parallel processing, formalism is used. The ACTRESS is composed of a set of robots which may or may not have different structures and functions.

The ACTRESS is reliable, extensible, flexible, efficient and adaptable. Reliability of ACTRESS can be achieved by replacing the defected robots in the case of trouble. Each robots can act independently, extending ACTRESS is easy in normal conditions . The transmission between any robots is assumed in the ACTRESS. The ACTRESS is flexible, as it deals not only with any change of requirements, but also generalizes the application. Multiple robots can achieve their tasks parallelly. Manifold tasks can be attained by arbitrary combinations of robots. As the ACTRESS includes any robots and equipment, it is adaptive for existing facilities. The stratified protocol is provided in the ACTRESS as when the robots act independently, it is only required to record the state of other robots with occasional communication. However, when a robot executes a task cooperating with other robots, it is required to portion the control signals with regular communication.

In ACTRESS, communication scheme, protocol used in the communication, should be defined in coordination control between multiple robots. Some communication methods are like ad hoc scheme are already reported [23]. There are two kinds of protocols used for communication, formation of connection with assurance of data transmission and other for identifying and perceiving the content of transmitted data. The communication protocol must be adaptable with the LAN protocol considering that the ACTRESS includes the communication between computers. OSI (Open System Interconnection) Reference Model is a general framework of computer networks, where tree-like architecture with several layers is defined [24]. The architecture of the information equate fairly well to one of robot languages, which convey as a hierarchy of command level, object level, and task level [25].

An experimental system using micromouse and a micromouse stimulator was done, and proper synthetic system was found. Considering the experimental results, practical improvement of robotic components and the increase in kinds and numbers of the components were the future problems.

SWARM [26]: The word swarm intelligence first coined [23] as a "buzz word" for denoting a branch of cellular robotic systems.Swarm robotics is the application of swarm intelligence to multi-robot systems. It emphases on physical embodiment of the elements and realistic interactions among the elements and between the elements and the surrounding.

As per Jim et al, SWARM is a distributed system having a large number of autonomous robots occupying one or two-dimensional environments and performing tasks such as pattern generation and self-organization.

SWARM intelligence is "a property of systems of non-intelligent robots exhibiting collectively intelligent behavior" [27].

It has a distributed architecture, with no differentiation among members [27], where two different types of robots were used. Interaction takes place by each cell reacting to the state of its nearest neighbors. Examples include large-scale displays and distributed sensing [27].

Swarm robotic systems are appropriate for the tasks that are related with the state of a space. Environmental monitoring (or tracking the well-ness) of a lake, would create a good domain of application.It provides the ability for immediate detection of hazardous events, like leaking of chemical accidentally. There are two major advantages of sensor networks that can be considered as immobilized swarm robotic systems. First, capability to "focus" on the location of the problem by activating its members towards the source of the problem. This will allow the swarm for localizing and identifying the nature of the problem. Second, it can assemble itself by forming a patch that could block the leakage.

GOFER: Caloud et al. in 1990 and LePape in 1990 used the GOFER architecture for the analysis of distributed problem. Multiple mobile robots with traditional AI technique were used in an indoor environment. For providing a global view for the tasks that are to be executed and for the communication of the robots there was a system named as central task planning and scheduling system (CTPS) was used. To produce a plan structure (template for an instance of a plan) and to inform all available robots of the pending tasks was the role of CTPS. Task allocation algorithm like the Contract Net Protocol [29] is used to find out roles for robots. Tasks assigned are achieved by using standard AI planning techniques. The GOFER architecture was used by two physical robots for tasks like box-pushing, and wall-tracking in a corridor.

Many problems regarding the design of non-conflicting sensor system, man-robot and robot-robot communication systems and protocols, contingency-tolerant motion control, multi-robot motion planning, multi-robot task planning and scheduling raised during the process.

The hardware of GOFER consists of a 12-inch diameter mobile base and interface modules. The three-wheeled two DOF mobile base is equipped with two DC motor, four 6V gel-cell batteries and an 8-bit microcomputer for low-level control. The base has a belt-driven synchro-drive mechanism allows the base to translate and rotate independently.

The overall multi-robot system should be "task able" i.e. it should accept task descriptions which specify what the users want to do rather than how to do.

Currently, there are three robots that are provided with odometric, touch and infrared proximity sensors which can accomplish simple tasks such as pushing a box, tracking walls in a corridor and following each other.

The present version of the planning and execution system is written in COMMON-LISP. All the experiments are performed on a DEC-3100 workstation [30] with the help of a simulator designed to simulate actions of autonomous agents. Table 2 describes a comparative study on the usage of different technologies related to the several aspects of cooperative mobile robots.

Table 2. Comparison of technologies used

Techniques	Architecture	Communication	Task Performed	Application
CEBOT (Cellular Robotics System)	Decentralize, Hierarchical	"Master cells"	Collectively and relatively complex task	Cellular Pay Structure
ACTRESS(ACTOR-based Robot and equipment Synthetic System)	Universal Modular ACTOR Formalism	Especially Protocol used	Cooperative task	Micro mouse development
SWARM	Distributed Architecture	Dynamic communication networks	Pattern Generation and self-organization.	Environmental Monitoring
GROFER	GROFER Architecture	Central Task Planning and Scheduling system(TCPS)	Allocation Algorithm	Pushing a box and Tracking walls

COMMUNICATION BETWEEN COOPERATIVE MOBILE ROBOTS

Explicit and implicit communication is used in cooperative tasks [8]. Explicit communication take place with the twenty individual purpose of conveying a message, such as speech, growls, gestures, or radio transmissions. Implicit communication is concern to as indirect coordination of communication in biology [9]. It arises through a knowledge of the reaction of other actions—a "through the world" approach.

A. Related work showing communication among robots

Implicit communication was used by Dadios and Maravillas [10] in a team of two soccer playing robots. Fuzzy logic is included into robotic algorithms which gives the concept that humans communicate in non-exact manner. For implicit communication an overhead camera is used by both robots, but the robots are not permitted to explicitly communicate with each other. In paralleling, the robots are efficient of passing and shooting the ball into a goal in the existence of contrary party which are represented by motionless obstacles.

Explicit communication was used by Asama ET. al. [11] in putting laptops, provided with wireless modems, on each mobile robot. It was a high cost and bulky approach which permit a large quantity of data such as global maps, to be passed and processed.

Simsarian and Matarić [12] also used explicit communication. They furnished two box-pushing robots with radio communication. Along with each robot's sensory data, they send "my turn, your turn" messages. They can productively push a box in the direction of a moving infrared-emitting origin. These types of communication were not well grounded in certain environments.

Arkin and Diaz [13] seek to solve this issue in a multi-robot study task with a restriction that the robots must continue line-of-sight.

TECHNOLOGICAL CONSTRAINTS IN COOPERATIVE ROBOTS

Scope of application of cooperative multiple robotics has been limited due to some constraints. For modeling of agents, we require efficient sensors to cooperate; if these are not good enough for the implementation then they cause rejection of such robots. On the other hand, hardware is another factor on which these robots are rejected for coming in practice. Due to these difficulties, some assumptions have been drawn to make these robots to come in practice.

The main problem in cooperative mobile robotics was to differentiate between different agents, to resolve such issues researchers used radio communication [7].

GEOMETRIC PROBLEMS FACED BY COOPERATIVE MOBILE ROBOTS

Since multiple robots can move and interact with the surrounding there are some problems they have to face during the motion.

Resource conflict: When there is a request for a single resource to be used by multiple robots, the problem of resource conflict arrives. With multiple robots working collectively there is a need to share resources such as space, communication channel, objects. This sharing can be achieved by some of the basic techniques such as wireless LAN, broadcast etc. Traffic control problem can be classified into three types: (i) restricted path, (ii) multiple options for robots to select the path (iii) multiple options with centralized traffic control. These can prevent conflict between robots [14].

Asama et al.[15] resolves resource conflict by defining simple protocols that give priority, based on performance. Yuta and premvuti[16] overcame this issue by, stopping the robots at the intersection and indicating the no. of robots and their path. If a deadlock appears, priority is set to free the deadlock.

Path-planning: Planning out routes that do not intersect with each other while interacting with one another. Latombe [17] taxonomy says that there are two types of planning: "centralized planning" where planning takes into account all robots where as a "decoupled planning" is planning of paths for each independent robot. This type of planning is divided into two: (i) prioritized planning which considers single robot at a time according to the global priority and (ii) Path planning which considers the configuration of space- time resources.

APPLICATIONS OF COOPERATIVE MOBILE ROBOTICS

The scale of applications of mobile robots is enormous. It consists of agricultural robot applications, material transport in factories, warehouses, hospitals, indoor and outdoor security system, inventory verification, hazardous material handling and its cleanup, underwater applications, and many military applications.

Traffic control: When more than one agent is involved in a common environment, they tend to colloid. To resolve such issues traffic rules, communication design or priority should be at concern. In other words, path planning should be done, taking into consideration the environment and the agents involved. For doing so, we need to modify the group architecture of the agents. We can reduce the cost of the designing; avoid collision and deadlocks in the system. Achieving collision-avoidance behavior is the solution of collision avoidance among multiple robots [5].

Box-pushing: Task allocation, fault-tolerance and learning are the main focus of the work of [7].This technique of cooperative manipulation of large objects can be achieved, without acknowledging robots about each other [6].

Foraging: In this method, robots are made to collect all the objects thrown in the environment. This task can be performed by each robot independently. By using cooperative robot technique we are testing to achieve a performance gain.

CONCLUSION

We have surveyed the theoretical bases in research in cooperative mobile robotics field. Mechanism and techniques used in this field are surveyed in our work. We have also found technical constraints that have created a boundary in the future research in the area of cooperative mobile robotics. We have identified some relevant disciplines to cooperative mobile robotics which continue to provide the reveling concept of cooperative mobile robotics, Such as distributed artificial intelligence.

In future, we will work on a detailed survey related to the different aspects of mobile robots.

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REFERENCES

[1] Siegwart, R., Nourbakhsh, I. R., & Scaramuzza, D. (2011). *Introduction to autonomous mobile robots*. MIT press.

[2] Bruzzone, L., & Quaglia, G. (2012). Locomotion systems for ground mobile robots in unstructured environments. *Mechanical Sciences*, *3*(2), 49-62.

[3] Machado, J. T., & Silva, M. F. (2006, April). An overview of legged robots. In *International symposium on mathematical methods in engineering*. Ankara, Turkey: MME Press.

[4] Arkin, R. C., & Bekey, G. (Eds.). (2013). *Robot colonies*. Springer Science & Business Media.

[5] Brooks, R. (1986). A robust layered control system for a mobile robot. *IEEE journal on robotics and automation*, *2*(1), 14-23.

[6] Sen, S., Sekaran, M., & Hale, J. (1994, October). Learning to coordinate without sharing information. In *AAAI* (pp. 426-431).

[7] Dudek, G., Jenkin, M., Milios, E., and Wilkes, D. 1993. Taxonomy for swarm robots. In IEEE/RSJ IROS, pp. 441–447.

[8] Parker, L. E. (2000). The current state of the art in distributed autonomous mobile robotics. In *Distributed Autonomous Robotic Systems 4* (pp. 3-12). Springer Japan.

[9] Matarić, M. J. (1995). Issues and approaches in the design of collective autonomous agents. *Robotics and autonomous systems*, *16*(2-4), 321-331.

[10] Dadios, E. P., & Maravillas, O. A. (2002). Cooperative mobile robots with an obstacle and collision avoidance using fuzzy logic. In *Intelligent Control, 2002. Proceedings of the 2002 IEEE International Symposium on* (pp. 75-80). IEEE.

[11] Asama, H., Ozaki, K., Itakura, H., Matsumoto, A., Ishida, Y., & Endo, I. (1991, November). Collision avoidance among multiple mobile robots based on rules and communication. In *Intelligent Robots and Systems' 91.'Intelligence for Mechanical Systems, Proceedings IROS'91. IEEE/RSJ International Workshop on* (pp. 1215-1220). IEEE.

[12] K. T. Simsarian and M. J. Matarić, Learning to Cooperate using two six-legged mobile robots, In Proceedings of the 8th European Conference on Machine Learning, 1995.

[13] Arkin, R. C., & Diaz, J. (2002). Line-of-sight constrained exploration for reactive multiagent robotic teams. In *Advanced Motion Control, 2002. 7th International Workshop on* (pp. 455-461). IEEE.

[14] Grossman, D. D. (1988). Traffic control of multiple robot vehicles. *IEEE Journal on Robotics and Automation*, *4*(5), 491-497.

[15] Asama, H., Ozaki, K., Itakura, H., Matsumoto, A., Ishida, Y., & Endo, I. (1991, November). Collision avoidance among multiple mobile robots based on rules and communication. In *Intelligent Robots and Systems' 91.'Intelligence for Mechanical Systems, Proceedings IROS'91. IEEE/RSJ International Workshop on* (pp. 1215-1220). IEEE.

[16] Yuta, S. and Premvuti, S. 1992. Coordinating autonomous and centralized decision making to achieve cooperative behaviors between multiple mobile robots. In Proc. of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems, Raleigh, NC, pp. 1566–1574

[17] Arkin, R. C., & Bekey, G. (Eds.). (2013). *Robot colonies*. Springer Science & Business Media.

[18] Jennings, J. S., Whelan, G., & Evans, W. F. (1997, July). Cooperative search and rescue with a team of mobile robots. In *Advanced Robotics, 1997. ICAR'97. Proceedings., 8th International Conference on* (pp. 193-200). IEEE.

[19] Halme, A., Jakubik, P., Schonberg, T., & Vainio, M. (1993, November). The concept of robot society and its utilization. In Advanced Robotics, 1993. Can Robots Contribute to Preventing Environmental Deterioration? Proceedings, 1993 IEEE/Tsukuba International Workshop on (pp. 29-35). IEEE.

[20] Hung, H., Sood, N., & Sreenath, K. (2016, October). Determining Minimum and Maximum Number of

Agents Required for Planar Cable-Suspended Aerial Manipulation. In *ASME 2016 Dynamic Systems and Control Conference* (pp. V002T23A008-V002T23A008). American Society of Mechanical Engineers.

[21] Fukuda, T., & Nakagawa, S. (1988, April). Dynamically reconfigurable robotic system. In *Robotics and Automation, 1988. Proceedings., 1988 IEEE International Conference on* (pp. 1581-1586). IEEE.

[22] Beni, G., & Wang, J. (1993). Swarm intelligence in cellular robotic systems. In *Robots and Biological Systems: Towards a New Bionics?* (pp. 703-712). Springer Berlin Heidelberg.

[23] Kohonen, T. (1988). An introduction to neural computing. *Neural networks*, *1*(1), 3-16.

[24] Shin, K. G., & Bonner, S. (1982). A comparative study of robot languages.

[25] Bonabeau, E., Dorigo, M., & Theraulaz, G. (1999). *Swarm intelligence: from natural to artificial systems* (No. 1). Oxford university press.

[26] Hackwood, S., & Beni, G. (1992, May). Self-organization of sensors for swarm intelligence. In *Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on* (pp. 819-829). IEEE.

[27] Wang, J., & Beni, G. (1988, August). Pattern generation in cellular robotic systems. In *Intelligent Control, 1988. Proceedings., IEEE International Symposium on* (pp. 63-69). IEEE.

[28] Wang, J., & Premvuti, S. (1995, May). Distributed traffic regulation and control for multiple autonomous mobile robots operating in discrete space. In *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on* (Vol. 2, pp. 1619-1624). IEEE.

[29] C. Le Pape, (1990) Stimulating Actions of Autonomous Agents.

[30] Nilsson, N. J. (1984). *Shakey the robot*. SRI INTERNATIONAL MENLO PARK.