Self-Organizing Multi-Robot Assembly System

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Abstract

Changing manufacturing environment characterized by aggressive competition on a global scale and rapid changes in process technology requires creating production systems that are themselves easily upgradeable and into which new technologies and new functions can be readily integrated. In this paper the concept of Bionic Assembly System, as answer for these novel requirements, is presented. Bionic Assembly System is based on concepts of autonomy, co-operation and intelligence of its units. The system proposes use of autonomous mobile robots in production environment instead of using AGV's. Mobile robots are giving flexibility to the system and increase dynamics of the whole process. The paper presents different mobile robot types and focuses on transport mobile robots which are the backbone of a system and which serve as carrier of a palette on which product is going to be assembled. The most important ability of the system is possibility of constant reconfiguration in a self-organizing way.

1. INTRODUCTION

To be able to respond for a customers demand and stay competitive in the 21st Century, manufacturing companies must possess a new kind of manufacturing system that is capable of quick responding to global market; a system which is designed to be easily upgraded with new technology, easily adaptable for new kind of products and whose production capacity is adjustable. Today's systems, even called flexible manufacturing systems, do not have such characteristics. Today's global world market requires a change in existing manufacturing systems. Cost-effective, reconfigurable manufacturing systems, whose components are reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and diagnosis, are the cornerstones of 21st Century manufacturing systems [1]. These conditions require a responsive new manufacturing approach that enables (Next Generation Manufacturing Project 1997):

- the launch of new product models to be undertaken very quickly, and rapid adjustment of the manufacturing system capacity to market demands; manufacturing systems can not cope with changes in product design and manufacturing plans nor keep in pace with the dynamics of the market.
- rapid integration of new functions and process technologies into existing systems, flexibility to deal with replacement of equipment and the increasing complexity of the system itself; manufacturing equipment cannot be easily replaced nor can simultaneous use of new and old machinery be easily integrated, and
- adaptation to variable quantities of products.

The technologies needed to design such kind of a system are: information, communication, computer and autonomous mobile robots technology.

2. CONCEPT OF BIONIC ASSEMBLY SYSTEM

Two types of systems are dominating in production: machining and assembly systems. Modern machining systems produces the parts which are quite independent from the final product build up from those parts. That is the main reason why the machining systems are more universal and have higher level of automation than the assembly systems, leaving assembly as a most expensive phase in the production. One of the priority research tasks in the development of future assembly systems is finding a more flexible, efficient, robust system solution that allow much more re-use rate of assembly units. To fulfill this need a concept of Bionic Assembly System (BAS), was proposed by Katalinic [2]. The concept of the system (Figure 1) was developed on a real industrial demand to significantly reduce the production costs of electrical motors in mass production. Bionic Assembly System is based on concepts of autonomy, co-operation and intelligence. The behavior of autonomous mobile robots and a system as whole is inspired by biological life. Biological organisms are capable of adapting to environmental changes and sustain life through functions such as self-recognition, self-growth, self-recovery and evolution. They accomplish self-organization capability through communication and evolve intelligence through learning. All these characteristics of biological organisms serve as an example for the biologically inspired manufacturing systems i.e. for design of autonomous mobile robot's behavior in such systems. Table 1 presents similarities i.e. relations between Bionic Assembly System and biological life. Table uses several terms that are defined as follows [3]:

- unit - basic component which performs a task,
- task - specific operation to be accomplished,
- source - basic system in need of accomplishing a task,

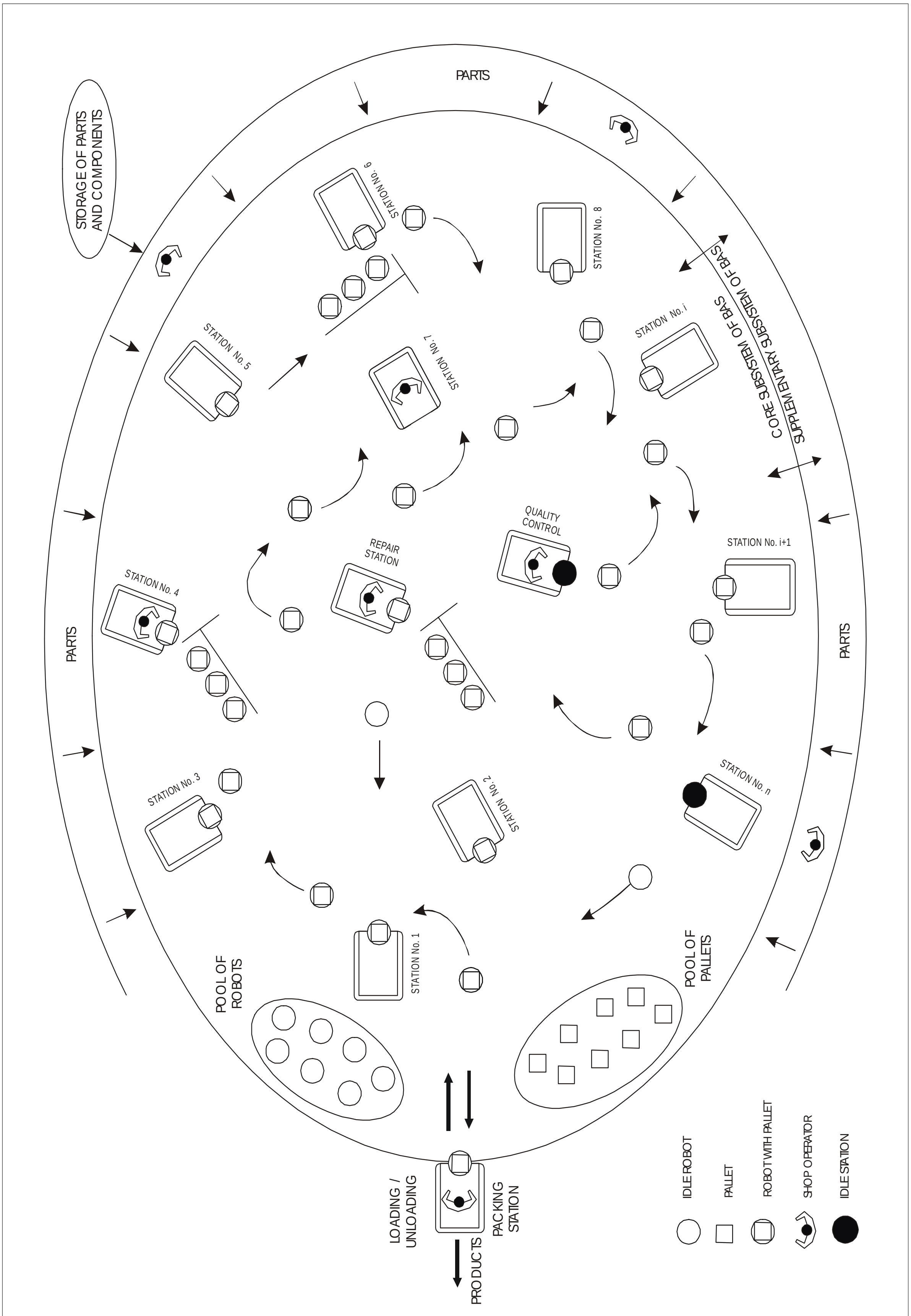

Fig. 1 The scheme of Bionic Assembly System

- performance - unit movement to source for task completion.

Table 1 Correlation between Bionic Assembly System and biological life

TERM	BAS ENVIRONMENT	BIOLOGICAL SIMILARITY
unit	transport mobile robot	organism (ant, bee etc.)
task	handling, processing	food supply, powdering
source	assembly station	flower, food
performance	transport mobile robot movement	movement of bee to specific flower

2.1. Mobile robot types in Bionic Assembly System

Industry applications of autonomous mobile robots is the area that has received little attention when compared with research performing in the context of other areas (surveillance, humanoid, soccer, hazardous environment …). The preponderance of the current research in mobility surrounding flexible manufacturing systems (FMS) involves the use of automated guided vehicles (AGV's) [4]. These vehicles simplify the problem of navigation by restricting their paths to striping the floor in some manner or by using buried cables. A major issue is just how "flexible" such systems are. The state-of-the-art of mobile robot technology and predictions of future development are giving a clear view that mobile robots are going to be essential part of every manufacturing process in not so far future [5]. Robots now can intelligently go from place to place and collect parts and take them to the appropriate work cell which opens up a new different way of structuring the manufacturing environment. The main advantage of mobile robots is their flexibility. In materials handling operations, this will eliminate the element of human error, reducing goods handling accidents and losses. To set up a robot for simple tasks is not so difficult, but for more demanding task, it takes a little bit of time, engineering and cost. So, the biggest problem is not the cost of robot, it is the cost of engineering the robot into the system. The robotics area should develop in such way to reduce the programming requirement and to increase the flexibility of mobile robots for different tasks. Keeping in mind these facts, Bionic Assembly System is completely structured of mobile robots. To realize Bionic Assembly System three mobile robot types are introduced (Table 2).

Table 2 Mobile robot types in BAS

TYPE	FUNCTION	REALISATION
Transport	Place of assembly, carrier of assembling product.	Autonomous mobile robot with exchangeable palette.
Supply	Delivering of assembly parts to assembly stations.	Autonomous mobile robots adapt to transport assembly parts in quantities.
Energy	Changing batteries of the transport robot at the actual position and transporting of these to the charging station.	Autonomous mobile robots adapt to transport and exchange batteries.

Such robots should be able to function autonomously and smoothly in order to cope up with unstructured and highly complex working environment of BAS.

3. TRANSPORT MOBILE ROBOTS

3.1. Decentralized System

As the number of mobile robots in a system increases, planning and control of the system becomes increasingly complex. The methods to handle such complexity include a centralised control method and a decentralised control method. More specifically, in a centralised control method all planning and decision-making functions are handled by a single control centre. Each mobile robot contains only sensors for localisation and obstacle avoidance, actuators for movements and manipulation, and communication facility for communicating with the control centre. All the movements of mobile robots in the system are controlled from this centre and conflicts among multiple robots are easily solved. This method has been widely adopted in manufacturing industry and warehouses where multiple mobile robots are used to transfer parts and clean warehouses. One major disadvantage of the system is that whole system will stop functioning immediately if the control centre fails. That is a reason of applying a decentralized control method in Bionic Assembly System and one of the system's key advantages.

There are a great number of robots functioning independently in the factory environment. All robots have own controller and are equally important, i.e. there are no highly ranked robots or controllers which are giving orders. The transport mobile robot will have general knowledge of the plant layout and will determine its position with a global positioning system. The local environment around the vehicle will be detected using sensors mounted on the robot. This enables the robot to avoid dynamic and unexpected static obstacles. In any unforeseen situation, the robot is able to plan a new path or find a solution without waiting for commands from the control centre. The function of the control centre is only limited to the broadcasting of traffic flow information received from all robots and the allocation of tasks in the system.

Inter-robot communication becomes necessary since competition for resources should be avoided and sharing experience could improve system performance. In a decentralized control system, co-ordination of multiple mobile robots is needed to achieve cooperation behavior.

Co-ordination of multiple mobile robots needs to address three main issues [6]:

- how to appropriately divide the functionality of the system into multiple robots,
- how to realize the dynamic configuration of the system, and

- how to achieve co-operation behavior.

Communication behavior is important design issue for coordination of transport mobile robots in the system. The communication may take place directly via explicit communication facility or indirect (pseudo communication method) through one robot sensing a change in other robots or its environment [7]. Communication between several robots can be done using wireless LAN, Bluetooth or a radio system. We can equip the individual mobile robots with a proper communication system so that each mobile robot individually senses the obstacles and passes on the information to other robot in the system.

Transport mobile robot might use broadcasting to announce its location or some other information to the whole system, or might use unicasting to communicate directly with another robot (Fig. 2).

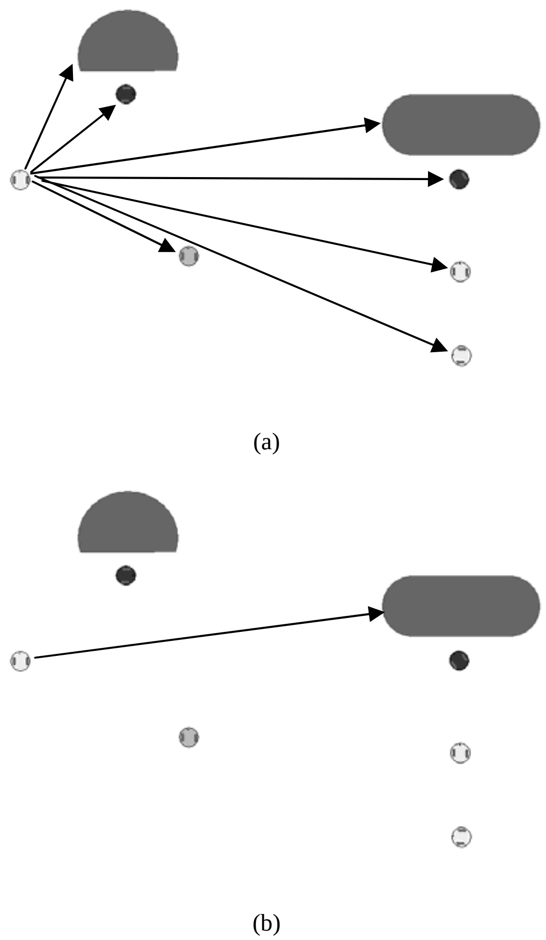

Fig. 2 Communication in Bionic Assembly System; (a) Transport mobile robot is broadcasting the message; (b) Transport mobile robot sends message "point-to-point" to specific assembly station

3.2 Working scenario

At the beginning of assembly process every transport mobile robot should get an order which kind of product should be assembled. When the transport mobile robot has the type of the product it has to go to the storage of empty palettes to take one palette on which the product should be assembled. Then it has to go from one assembly station to another in order to have the final assembled product on it. It serves as a carrier of a palette on which the product is assembled. After the product is assembled it has to go to the storage of final product and leave the palette on a predefined place. At this moment, transport mobile robot has fulfilled his assembly mission and it is going back to the initial position (robot pool) and waits for new order to come.

Since there is not just one assembly station which can perform same assembly step (some parts of a product are same for all products), transport mobile robot should decide on each assembly step to which assembly station it should go. At the beginning of each assembly step transport mobile robot is contacting all assembly station with a question which station could perform next assembly step. Assembly stations which can perform that are sending the answer with following information contained:

- time needed to perform assembly step (not every station has the same operating speed),
- its position in environment (needed to calculate transport time from actual transport robot position to the station),
- time of waiting (there is a queue of transport mobile robots waiting for assembly in front of every assembly station).

On the basis of these three values (Fig. 3) transport mobile robot decides which assembly station to choose, i.e. where to go.

Fig. 3 Three time values which impact the decision of transport mobile robot to which assembly station to go

Basically, the robot is calculating the total time summing the all three values:

$$T_T = T_O + T_{TR} + T_W \,, \qquad (1)$$

where

T_T - total time,

T_O - operating time,

T_{TR} - transport time,

T_W - waiting time.

For every assembly station transport mobile robot is calculating this total time and searches for the minimum one:

$$\min\left(\sum_{i=1}^{3} t_i\right) \qquad (2)$$

If assembly station does not send any message to the transport mobile robot, it knows that this station is malfunctioning (error) and in that case:

$$T_O = \infty \,. \qquad (3)$$

One of the most important aspects of Bionic Assembly System is the use of priorities [8]. That means that to every transport robot priority is assigned (importance of finishing assembly process in matter of time in relation to other transport mobile robots) and the robot with higher priority has always an advantage over one of lower priority. Priority is expressed in levels and so:

- Priority level 1 – it means that the transport mobile robot is carrying a product with highest priority. It has advantage in relation to robots that have lower priority level.
- Priority level 2 – this level expresses high priority. It has advantage in relation to all robots that have lower priority level, but has to leave all higher priority robots to go in front of it.
- Priority level 3 – low priority. All robots have advantage in front of transport mobile robots having this level of priority.

Robots are always waiting in a queue in front of assembly station. This queue is formed so that robots with highest priorities are always in front of the others (Fig. 4). This figure shows three assembly stations and nine transport mobile robots. Robots that are first in the queue are currently in assembly process, i.e. on them is performing assembly step. Other robots are waiting in a queue. At each time step, every transport mobile robots is communicating with every assembly station asking three time values mentioned before.

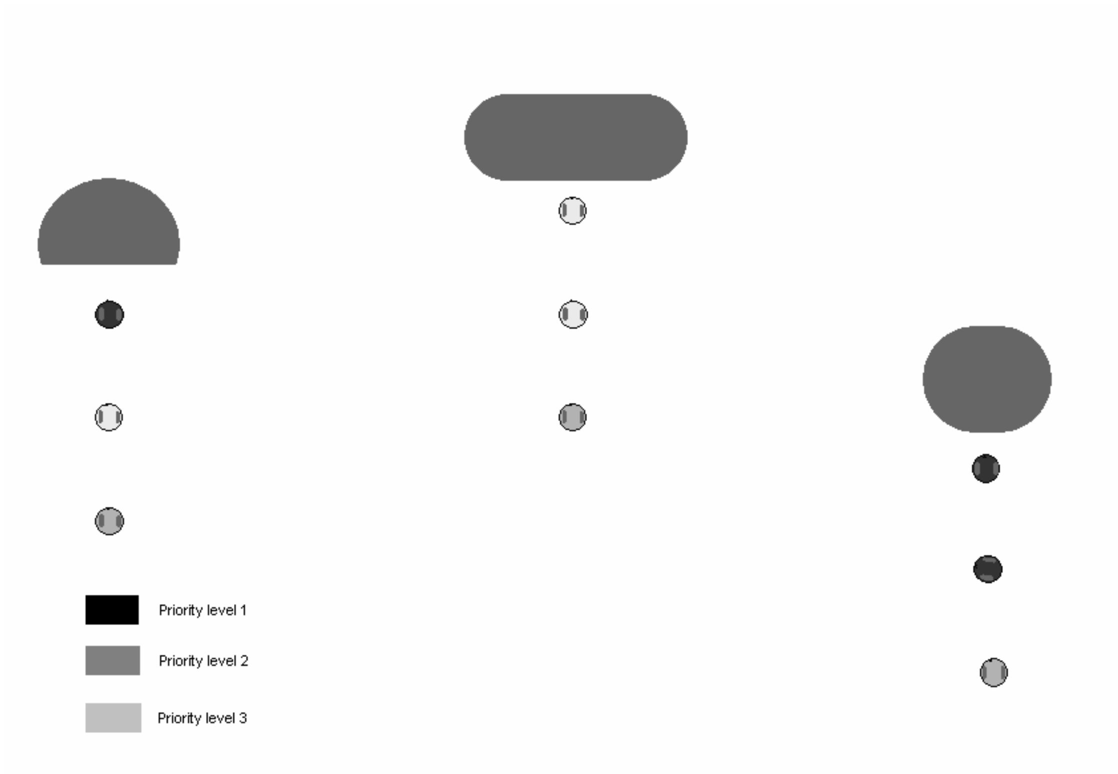

Fig. 4 Queues of transport mobile robots

Every assembly station knows a "situation" in front of it, i.e. knows how many transport mobile robots are waiting in a queue and structure of the queue (priority level of each robot). Information about time values are stored in vectors T_i^j.

Table 3 Vector of time values for assembly station 1

	1	2	3	4	5	6	7	8	9
1									

For example:

T_O^1 (1) contains operating time of robot 1 on assembly station 1.

T_O^3 (8) contains operating time of robot 8 on assembly station 3.

T_W^2 (4) contains how much time transport robot 4 must wait in front of assembly station 2 in order to start performing assembly step. When assembly step on one transport mobile robot is finished, this robot is going to search for other assembly station for next assembly step or the product is assembled and it goes to the storage. At this time all robots in queue in front of this assembly station are moving for one place in front and whole matrix of waiting time is changing.

T_T^3 (6) contains how much time robot 6 needs to come to its place in front of assembly station 3. Robot's priority is considered, since robot is going behind the last robot of its own priority.

Based on this values transport mobile robots are deciding whether to stay in the queue or it is more worth full (in time matter) to go in front of other station.
If transport mobile robot decides to go in front of other station, it contacts the assembly station to send him position vector S_i^j which contains list of current robots in its queue (Table 4).
For example, position vector of assembly station 1 could be:

$$S_1 = \begin{bmatrix} 1 \\ 2 \\ 4 \\ 7 \\ -1 \\ -1 \\ -1 \\ -1 \end{bmatrix} \quad (4)$$

S_1^3 =4 means that on the third position in front of assembly station 1 is transport mobile robot 4.
Or S_1^6 =-1 means that on position 6 in front of assembly station 1 there is no robot.
Based on this value transport mobile robot is searching for the last robot in queue which has its priority level and goes behind it.

4. CONCLUSION

Existing manufacturing systems can not cope with globalisation of industry and highly demanding customer orders. As companies move toward more flexible production lines for smaller batch sizes and shorter product cycles, more advanced systems are needed. The new manufacturing systems must be rapidly designed, able to convert quickly to the production of new models, able to adjust capacity quickly, and able to integrate new technology and to produce an increased variety of products in unpredictable quantities. The main disadvantage of existing systems is their inflexibility. Reason for that is use of AGV's. AGV can not interact with environment; can not cope with unexpected obstacles in its way. With rapid development of autonomous mobile robots technology, it becomes possible to incorporate them in production environment. Mobile robots are giving a new dimension of flexibility to the system - dynamics to the whole process. System is capable of quickly responding to customer demands, can adapt to any changes in working environment and can incorporate new parts of the system without stopping the production process. To accomplish all these needs Bionic Assembly System is presented. Bionic Assembly System enables:

- easy adaptation for launching of new product models, and rapid adjustment of the manufacturing system capacity to market demands;
- rapid integration of new technologies into existing systems;
- easy adaptation to variable quantities of products to be assembled.

With incorporation of priority levels, different kind of products could be easily assembled. With use of mobile robots, reconfiguration of the whole assembly process is possible at any time. Transport mobile robots are just selecting on which assembly station to go according to spend less time in the whole process. In this way self-organisation of the system is realized. Next step is to develop simulation of reconfiguration of mobile robot queues and in that way develop algorithms and controllers which could be used on real, physical robots.

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