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Real Time Man-Robot Control of a Group of Specialized Mobile Robots

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Abstract: *A man-robot system for fire extinguishing is discussed in the paper. Mobile robots have achieved wide application in different areas of material production and social practice. Different tasks have arisen which have lead to widening of the application area of mobile robots. Their application is of great importance in cases of natural disasters, and especially in industrial accidents, such as fires, environmental pollutions and other aggressive environment, in which the presence of a human operation near the outbreaks of the disaster is dangerous and in many cases – even impossible. In many cases the mobile robots act together on the same site, so that they must be controlled and managed in the proper way. No doubt, there must be a human operator, coordinating and supervising the robots' actions.*

Keywords: *Fire fighting robots, robots optimal path control, network flow algorithms.*

1. Introduction

Mobile robots have obtained wide application in the last two decades in material production in various areas [4, 5, 6]. Different problems have appeared which have greatly enlarged the area of mobile robots application. An important place in them take some applications related to operation in aggressive environment in situations of disasters, floods, fires – where due to the high risk it is difficult for a human to penetrate.

The task of using mobile robots in high temperature zones is of considerable importance for carrying out fire extinguishing activities. In such cases it is often necessary to use not one, but a group of mobile robots. They carry out joint coordinated activity to perform the necessary fire fighting functions at different places on the site where fire outbreaks are located. The task arises of real time operative control of the fire fighting robots in a group which circulate between the sources of the fire extinguishing agent and the burning objects. The movement of the mobile robots is supposed to be carried out along predefined sections which are a part of a path network of known configuration. Besides this, it is necessary mobile robots to be loaded with fire extinguishing agents different in consistency and composition. Depending on the sequence of transportation of this agent by the mobile robots it is necessary that the requirements of averaging the composition of the fire extinguishing agent to be observed.

As the time for extinguishing the fire outbreaks is limited, it is necessary that the fire fighting robots move along separate paths so that their total run is minimized, which in its turn results in maximization of the supplied fire extinguishing agents. It follows from this that the combined control of the mobile robots group should be carried out on the basis of simultaneous observation of the following two criteria:

a) minimization of the total run of the mobile robots on the road network, which results in maximization of the transported fire extinguishing agent for the same period of time;

b) keeping the requirement that the composition of the fire extinguishing agent is not out of the admissible boundaries, i.e., effective averaging to be carried out for the agent composition.

It should be taken in mind that the mobile robots movement is of definitely stochastic character so that it cannot be performed by a provisional schedule which is strictly observed. The considerable stochastic character requires precise information about the location of each mobile robot and this is done best by using local or global positioning systems. With such layout each time a mobile robot reaches the end of a path section which bifurcates, the control system computes the new addresses on the path network for the mobile robots on the basis of existing information and control criteria.

2. The road network and control methods

In the present work approximate and exact methods are proposed for solving the problem described, based on the network flow interpretation of the current state of the group of controlled mobile robots on the transportation network [2, 3]. The first one of these methods allows “almost optimal control” to be achieved by using the method of the relative network flows. This method is of polynomial computational complexity. The second method is exact and the result is optimal control, but through algorithms of Integer Linear Programming (ILP), which are of pseudo polynomial computational complexity and require more computational time ad memory [2].

Further on we will use the graph theory terminology of the network flows without explicitly defining it [1]. If the mobile robot moves along a path section from its initial node x_i to node x_j along arc x_{ij} of "length" (time, distance) l_{ij}, a new, artificial (fictitious) node x_k is introduced with a new arc x_{kj} and length l_{kj} which exactly corresponds to the distance of this mobile unit to the end node x_j on the section of the network. Besides, $l_{kj} \leq l_{ij}$.

A general road network is conditionally shown in Fig. 1, with three loading points of fire extinguishing agent $T = \{x_1, x_2, ..., x_t\}$, two fire outbreaks $S = \{x_{t+1},..., x_s\}$, five intermediate points on the network $R = \{x_{s+1}, ..., x_r\}$ and five artificial nodes on the network, each one corresponding to a mobile fire fighting robot $D = \{x_{r+1}, ..., x_d\}$. The nodes of the sets T, S, R, D are denoted by the following indices:

$I_t = \{1, 2, ..., t\}$; $I_s = \{t+1, ..., s\}$; $I_r = \{s+1, …, r\}$; and $I_d = \{r+1, ..., d\}$. Numbering of $\{x_i\}$ in Fig. 1 is done in the same way. The lengths (times, values) of the corresponding arcs are encircled.

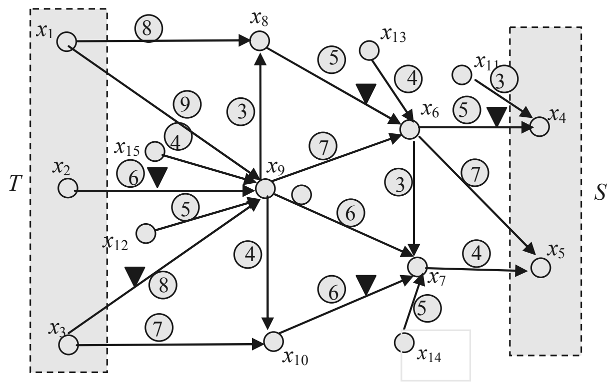

Fig. 1

If the Shortest Routes (SR) to each one of the fire outbreaks are apriori determined and encircled in the figure, and some technological constraints are presented on new arcs between nodes D and T, then the reduced network, shown in Fig. 2 will be obtained. In order to define a network flow on it, an additional node x_0 with arcs $x_{4,0}$ and $x_{5,0}$ with null values of the lengths $l_{4,0}$ and $l_{5,0}$ is needed.

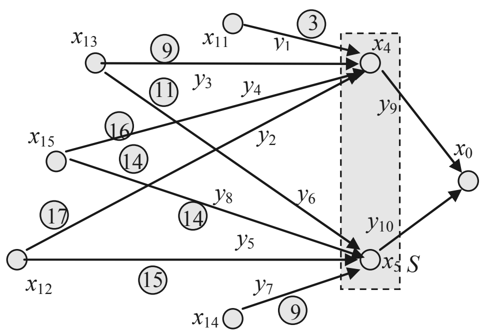

Fig. 2

It is supposed that only one type of fire extinguishing agent is loaded at each supply point that is different from the other points.

The following denotations will be introduced:

$X = \{T \cup S \cup D \cup D\}$, $X' = \{D \cup S \cup \{x_0\}\}$;

$I = \{I_t \cup I_s \cup I_r \cup I_d\}$, $I' = \{I_d \cup I_s \cup \{0\}\}$;

$f_{ij} = f(x_i, x_j)$ – an arc flow function on the arc x_{ij};

Γ^1 and Γ^{-1} – direct and inverse mapping on the graph;

M_{ij} – the set of the indices of all routes $\{\mu\}$ with an initial node x_i and a final node x_j;

$L_{ij} = \min_{\mu \in M_{ij}} l(\mu)$ – the shortest distance (time, value) between nodes x_i and x_j, at that $L_{ij} = 0$ if there does not exist any route or arc from x_i towards x_j;

(1) $$U' = U_1 \cup U_2,$$

where $U_1 = \{x_{ij} / L_{ij} > 0,\ i \in I_d,\ j \in I_s\}$; $U_2 = \{x_{ij} \mid i \in I_s,\ j = \{0\}\}$;

$G'(x', U')$ – a reduced network;

$I(i, j)$ – the set of the pairs of indices (i, j) on all arcs $\{x_{ij}\}$, belonging to the reduced network;

$k_i(t)$ – relative loading of the mobile robots with fire extinguishing agent content from points with index $i \in I_t$;

(2) $$0 \le k_i(t) \le 1;\ \sum_{j \in I_t} k_j(t) = 1,\ i \in I_t;$$

$k_i(s)$ – planned relative content of the fire extinguishing agent at the fire outbreak with index $i \in I_s$

(3) $$0 \le k_i(s) \le 1;\ \sum_{j \in I_s} k_j(s) = 1,\ i \in I_s;$$

$k_i(d)$ – relative content of the fire extinguishing agent on a loaded mobile robot with index $i \in I_d$,

(4) $$k_i(d) \in \{\bigcup_{j \in I_t} k_i(t)\},\ i \in I_d;$$

$k^1_i(d)$ – relative content of the fire extinguishing agent in a loaded fire fighting mobile robot $i \in I_d$ with respect to other loaded mobile robots, at that

(5) $$k^1_i(d) = \frac{k_i(d)}{\sum_{j \in I_d} k_j(d)},\quad i \in I_d;$$

$k^2_i(d)$ – normalized relative content of the extinguishing agent in a loaded mobile robot with index $i \in I_d$ with respect to other loaded mobile robots,

(6) $$k^2_i(d) = \frac{k^1_i(d)}{\max_{j \in I_d} k^1_i(d)},\ i \in I_d;$$

g_{ij} – maximal density of the flow between nodes x_i and x_j, which accounts the distances (times, values) between these two nodes and the normalized relative content of the extinguishing agent in a loaded mobile robot with index $i \in I_d$,

(7) $$g_{ij} = \frac{k^2{}_i(d)}{L_{ij}}, \ i \in I_d, \ \ j \in I_s;$$

$g(i)$ – maximal density of the flow from mobile robots with index $i \in I_d$ towards the closest one among fire outbreaks S, where

(8) $$g\,(i) = \max_{j \in I_s} \ g_{ij}, \quad i \in I_d;$$

$h(i)$ – the maximal possible relative flow of the fire fighting robots with index $i \in I_d$ towards the closest fire outbreak points in S,

(9) $$h(i) = \frac{g(i)}{\sum_{j \in I_d} g(j)}, \ i \in I_d;$$

h_{ij} – the maximal possible relative flow of mobile robots with index $i \in I_d$ towards fire outbreak points with index $j \in I_s$

(10) $$h_{ij} = \frac{g_{ij}}{g_i} h(i), \ i \in I_d, \ \ j \in I_s;$$

$I^1{}_d \subseteq I_d$ – the set of the indices of the mobile robots already addressed to any fire outbreak points from S;

$q(j)$ – the sum of the relative flows of the mobile robots with indices from $I^1{}_d$ already addressed to fire outbreak point $x_j \in S$,

(11) $$q\,(j) = \max_{i \in I_d \setminus I'_d} h_{\,i,j}, \ j \in I_s,$$

where in case $I^1{}_d = I_d$, $q\,(j) = 0$;

$\xi\,(j)$ – the difference between the planned relative content of the fire extinguishing agent towards a fire outbreak with index $j \in I_s$ and the relative flows towards the same fire point

(12) $$\xi\,(j) = k_j\,(s) - q\,(j), \quad j \in I_s;$$

$\xi\,(j^*)$ – the maximal value of the values $\xi\,(j)$

(13) $$\xi\,(j^*) = \max_{j \in I_s} \xi\,(j);$$

$h\,(i^*)$ – a value indicating the relative flow at optimal addressing of the mobile robots with index $i^* \in I_d$ towards fire outbreak points with index $j^* \in I_s$, at that

(14) $$h\,(i^*) = \max_{i \in I_d \setminus I^1{}_d} h_{\,i,j} \ \text{ and } j = j^*.$$

The upper and lower bounds of the admissible fluctuation of the total content of the fire extinguishing agent at the fire outbreak places is defined by the following inequalities:

(15) $$k_j(s) - \varepsilon \le \frac{\sum_{i\in I_d} k_i(d) f_{ij}}{\sum_{m\in I_d}\sum_{n\in I_s} k_m(d) f_{m,n}} \le k_j(s) + \varepsilon,\ j\in I_s,$$

where ε is the admissible deviation of the corresponding fire extinguishing agent from the planned content at $x_j\in S$.

Besides this, if z_{ij} denotes the volume of the fire extinguishing agent content from i-th point directed towards j-th fire outbreak point, then quite often additional technological constraints arise

(16) $$w_{ij} - w \le \frac{z_{ij}}{\sum_{m\in I_d} z_{mj}} \le w_{ij} + w,\ i\in I_d,\ j\in I_s,$$

where $\{w_{ij}\}$ are coefficients depending on the current situation and w is a parameter indicating the probable fluctuations of the different extinguishing agent consistencies at the fire outbreak points with respect to the planned average values.

3. Approximate method

The denotations introduced enable the proposal of the following approximate method and procedure of the relative network flows for efficient addressing and control of the robotized transport processes, in which minimal transport distances are sought, simultaneously observing requirements (15) and (16) for averaged fire extinguishing agent contents at the fire sites. This iterative method can be described by the following three steps:

Step 1. Applying relations from (6) up to (10) the parameters $\{g_{ij}\}$, $\{g(i)\}$, $\{h(i)\}$, $\{h_{ij}\}$ are defined and it is assumed that $I^1{}_d = \varnothing$, where $\varnothing$ is the symbol of an empty set.

Step 2. Using relations from (11) up to (14) the values $\{q(j)\}$, $\{\xi(j)\}$, $\{\xi(j^*)\}$ and $h(i^*)$ are computed and the mobile robot with index $i^*\in I_d$ is addressed towards fire outbreak point with index $j^*\in I_s$. With this it is directed to the next section of the route, leading to the respective final fire point. The following alterations are made:

$$k_{j^*}(s) := k_{j^*}(s) - h_{i^*j^*},\quad I^1{}_d := I'_d \cup \{i^*\}.$$

Step 3. In case $I_d = I^1{}_d$ **Stop**, otherwise go to **Step 2**.

All transportation units with indices in I_d are successively addressed with the help of this iterative procedure. Each time when an alteration occurs in the general situation, the complete iterative procedure is started and successive new addressing of the mobile robots is realized. It is quite probable that the new addresses of some mobile robots may coincide with the preceding ones.

A numerical example demonstrating the operation of the method of the relative network flows will be presented, using the reduced network in Fig. 2 and the data from Tables 1, 2 and 3.

Table 1 gives all the data used to execute Step 1, including the values of the coefficients $\{k_i(d)$, $\{k^1{}_i(d)\}$ and $\{k^2{}_i(d)\}$.

Table 1

x_{ij}	L_{ij}, g_{ij}	x_4	x_5	$k_i(d)$	$k_i^1(d)$	$k_i^2(d)$	$g(i)$	$h(i)$
x_{11}	L_{ij}	3	–	0.2	0.133	0.4	0.133	0.38
	g_{ij}	0.133	–					
x_{12}	L_{ij}	17	15	0.5	0.334	1.0	0.066	0.19
	g_{ij}	0.059	0.066					
x_{13}	L_{ij}	9	11	0.3	0.200	0.6	0.066	0.19
	g_{ij}	0.066	0.054					
x_{14}	L_{ij}	–	9	0.2	0.133	0.4	0.044	0.12
	g_{ij}	–	0.044					
x_{15}	L_{ij}	16	14	0.3	0.200	0.6	0.043	0.12
	g_{ij}	0.038	0.043					

Table 2 displays data for the parameters $\{g_{ij}/g(i)\}$, $\{h_{ij}\}$, as well as the final results after application of the iterative algorithm, indicating at what iteration a given mobile robot is directed to any fire outbreak point. The solutions selected are shadowed in the table.

Table 2

x_{ij}	S k_{ij}(s) R	x_4	x_5	Addresses	Iteration No
		0.6	0.4		
x_{11}	$g_{ij}/g(i)$	1	–	x_4	1
	h_{ij}	0.38	–		
x_{12}	$g_{ij}/g(i)$	0.9	1	x_5	2
	h_{ij}	0.17	0.19		
x_{13}	$g_{ij}/g(i)$	1	0.83	x_4	3
	h_{ij}	0.19	0.16		
x_{14}	$g_{ij}/g(i)$	–	1	x_5	5
	h_{ij}	–	0.12		
x_{15}	$g_{ij}/g(i)$	0.9	1	x_4	4
	h_{ij}	0.10	0.12		
Total		0.67	0.31	–	–

Table 3 indicates the relative densities $\{q(i)\}$, the planned relative extinguishing agent compositions $\{k_i(s)\}$ at every fire outbreak point, as well as the differences $\{\xi(j)\}$ between the actual and the planned situation of the network. This table shows the data from the first iteration of the algorithm proposed when the mobile robot with an initial node x_{11} is directed towards fire point x_4. In this case $\xi(4) = 0.22$, greater than $\xi(5) = 0.21$, i.e., a decision must be made for addressing towards a fire outbreak point with a bigger difference, namely $\xi(4)$.

Table 3

Parameter	x_4	x_5	Sum along rows
$k_j(s)$	0.60	0.40	1
$q(j)$	0.38	0.19	0.57
$\xi(j)$	0.22	0.21	0.43

As following from Table 2, the total run of all five transportation units is only 2% longer compared to the case when they move along the shortest routes of the network. This insignificant increase of the run is due to the additional requirements for averaging of the extinguishing agent composition in the liquid volume transported.

It follows from Tables 1 and 2 that according to the solution obtained the average content of the extinguishing agent at the two fire outbreak points is 0.54 for fire outbreak point x_4, and 0.47 – for point x_5 respectively. The values planned for the two fire points are 0.6 and 0.4 accordingly, i.e., the deviation is smaller than the admissible value $\varepsilon = \pm\, 0.1$.

The proposed method of relative network flows is insensible towards any probable altering in the number of the fire fighting mobile robots. This is due to the fact that the comparisons between the planned and the actual indicators are accomplished in relative units.

The proposed approximate iterative algorithm for finding "almost optimal" control is realized by a reasonable number of computing operations with polynomial complexity which is important for its computer realization in dispatchers' systems.

4. Exact method

The optimal control of the mobile robots can be realized with the help of the suggested exact method that minimizes the total run of all mobile robots, keeping the requirements for averaging of the extinguishing agent composition in the transported liquid volume. It uses the same denotations as the former method of relative network flows.

The method is reduced to solving the following problem of integer network flow programming with additional linear constraints referring to the reduced network presented in Fig. 3 [5]:

(17) $$L = \sum_{(i,j)\in I(u)} l_{ij} f_{ij} \to \min$$

under the constraints: for every $i \in I'$

(18) $$\sum_{j\in\Gamma_i^1} f_{ij} - \sum_{j\in\Gamma_i^{-1}} f_{ji} = \begin{cases} 1 \text{ if } i \in I_d, \\ -|D| \text{ if } i = 0, \\ 0 \text{ in the remaining cases;} \end{cases}$$

(19) $$(k_j(s) - \varepsilon) \sum_{m\in I_d} \sum_{n\in I_s} k_m(d) f_{m,n} - \sum_{i\in I_d} k_i(d) f_{ij} \le 0,\ \ j \in I_s;$$

(20) $$\sum_{i\in I_d} k_i(d) f_{ij} - (k_j(s) + \varepsilon) \sum_{m\in I_d} \sum_{n\in I_s} k_m(d) f_{m,n} \le 0,\ \ j \in I_s;$$

(21) $$f_{ij} \geq 0,\ (i, j) \in I(i, j),$$
where functions $\{f_{ij}\}$ accept integer values only and $|D|$ denotes the power of set D. From the equations of flow preservation it follows that

(22) $$|D| = \sum_{i \in I_s} f_{i,0}.$$

The complementary linear constraints (19) and (20) are a direct sequence of requirements (15).

5. Solution results

If the example given in Fig. 3 is considered, using the output data presented in Table 1, the problem presented by relations (17) up to (22) will take the form

(23) $$L=3y_1 + 17y_2 + 9y_3 + 16y_4 + 15\,y_5 + 11y_6 + 9y_7 +14y_8 \rightarrow \min$$
under the constraints:

(24) $$y_9 - y_1 - y_2 - y_3 - y_4 = 0;$$
(25) $$y_{10} - y_5 - y_6 - y_7 - y_8 = 0;$$
(26) $$y_1 = 1,\ y_2 + y_5 = 1,\ y_3 + y_6 = 1,\ y_7 = 1;$$
(27) $$y_4 + y_8 = 1,\ y_9 + y_{10} = 5;$$
(28) $$-0.2\,y_1 - 0.5\,y_2 - 0.3\,y_3 - 0.3\,y_4 + 0.5\,y_5 + 0.3y_6 + 0.2y_7 + 0.3y_8 \leq 0;$$
(29) $$0.06\,y_1 + 0.15\,y_2 + 0.09\,y_3 + 0.09\,y_4 - 0.35\,y_5 - 0.21\,y_6 - 0.14\,y_7 - 0.21y_8 \leq 0;$$
(30) $$0.2\,y_1 + 0.3\,y_3 + 0.3\,y_4 \leq 0.9;$$
(31) $$0.5\,y_5 + 0.2\,y_7 \leq 0.8;$$
(32) $$y_i \in \{0, 1\},\ i = 1, 2, \ldots, 8.$$

Functions y_9 and y_{10} accept integer values.

The arc flow functions $\{y_i | i = 1, 2,\ldots, 10\}$ corresponding to $\{f_{ij}\}$, are presented in Fig. 3. The values of $\{l_{ij}\}$ are taken from the same figure. The inequalities (28) and (29) correspond to (19) and (20), the relations (30) and (31) – to (16) and their coefficients $\{k_j(s)\}$ and $\{k_i(d)\}$ are accepted from Table 1 and Table 3 respectively. It is assumed that $\varepsilon = \pm 0.1$.

Solving the example formulated in (22) up to (32), an optimal solution presented in Table 4 is obtained. WebOptim software system is used for this problem solving [3].

Table 4

y_i Fire point	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}
x_4	1	1	1						3	
x_5							1	1		2

If in the pair (x_i, x_j) the symbol x_i denotes the number of the addressed mobile robot and x_j – the fire outburst point it is directed to, then the optimal solution from Table 4 corresponds to (x_{11}, x_4); (x_{12}, x_4); (x_{13}, x_4); (x_{14}, x_5) and (x_{15}, x_6).

The solution with the help of the approximate algorithm gives the following addresses: (x_{11}, x_4); (x_{12}, x_5); (x_{13}, x_4); (x_{14}, x_4) and (x_{15}, x_5), i.e., the two solutions differ in the addresses of the mobile units x_{12} and x_{15} only.

If the distances values on the reduced network given in Fig. 2 are used, as well as the data from Table 1, then for the exact algorithm the total run of the addressed mobile robots towards fire outbreak point x_4 is equal to 29 units, and towards x_5 – to 23 units, i.e., 52 units of distance totally.

In the solution obtained by the approximate algorithm these indicators are 28 units towards x_4 and 24 units towards x_5, i.e., total run of 52 distance units as well.

If the technological constraints are observed, in the exact algorithm the relative value of the transported fire extinguishing agent towards fire outbreak x_4 is 0.667 and towards x_5 – 0.333. The approximate algorithm gives a solution of 0.533 towards x_4 and 0.467 – towards x_5. The two solutions lead to equal difference of ±0.667 with respect to the planned values that are 0.6 for x_4 and 0.4 – for x_5 respectively. This is smaller than the admissible deviation of ±0.1.

Hence, the two solutions obtained by the exact and by the approximate algorithm, are optimal and equivalent. However, the approximate algorithm is of polynomial computing complexity, while the exact algorithm is of exponential computing complexity. This makes the approximate algorithm preferable in many cases. Of course, there might be situations, when the approximate solution does not lead to optimal, but to "almost optimal" solutions, but even then the difference would be slight and negligible in practice.

6. Conclusion

The present paper discusses the problem of combined real-time control of mobile robots, specialized for operation in extremely high temperature environment, when it is necessary to put out fires. The criteria for such control are minimization of the total run of the mobile robots, as well as the necessity to average the extinguishing agent content in the liquid, transported by the mobile robots.

An exact network flow method is suggested for optimal addressing of the mobile robots observing the technological requirements towards the content of the extinguishing agent transported by them.

An approximate network flow method is developed that on the basis of relatively simple procedures of polynomial complexity obtains solutions, close to the optimal ones.

A numerical example is presented illustrating the efficiency of the two methods proposed for operative control of the transportation of fire extinguishing agent from the loading points towards the fire outbreak points.

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Управление в реальном времени группой мобильных роботов при помощи системы человека–робота

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(Р е з ю м е)

В работе обсуждается система человек–робот для погашения пожаров. Мобильные роботы применяются в разных областях материального производства и социальной практики. Появились новые задачи, которые расширили применения мобильных роботов. Их использование очень важно в случаях природных бедствий или промышленных аварий, такие как пожары, загрязнение среды, когда присуствие человека в агрессивной среде опасно и в многих случаях – невозможно. В множестве таких случаев мобильные роботы действуют совместно на одной и той же локации, так что ими надо правильно управлять. При этом, присуствие человека безсомненно необходимо, чтобы координировать и наблюдать действия роботов.