Flocking Factors' Assessment in Case of Destructive Impact on Swarm Robotic Systems

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***Abstract*—This paper dwells on exposures' analysis of open-environment operated swarm robotic systems. Flocking algorithms for swarm robotics, which use alignment and averaging of direction in local communication radius (after C. Reynolds' model) are considered. The problem where a small group of informed robots has to guide the swarm along a desired direction is also considered. Couzin I. D. et al. (2005) showed that even a minority of informed individuals is able to move the group toward the target. Hereafter great number of swarm robotics' flocking algorithms were developed in order to increase swarm system's handiness. Several implicit leadership algorithms for distributed robotic systems were proposed. The idea of this paper is to study and simulate the operation of such kind of above mentioned algorithms in the situation when there are saboteurs which destructively impact swarm system. Specially developed by authors simulation software allows to vary the parameters of system operation, which can be rather the number of agents or their interaction features or etc. On the basis of the experimental data the authors produce the analysis of features in order to determine their relevance to the algorithm**

I. Introduction

Nowadays multi-agent systems (MAS) and Swarm Robotics (SR) cause great research interest [1]. A significant amount of work on this topic is devoted to distributed flocking algorithms, which provide a coherent movement of robots in the group, modeled by the example of flocks of birds, fish, migrant pack animals, etc. [2].

It is expected that these algorithms will find their application in the organization of movement of autonomous devices for various applications, including air drones, autorun cars, etc.

Seminal works in this direction are the algorithms of C. Reynolds, T. Vicsek [3], A. Jadbabaie et al. [4], etc. Basic models of flocking behavior, proposed by C. Reynolds at 1987 ([5]), are controlled by three simple rules: 1) separation - avoid crowding neighbors (short range repulsion); 2) alignment - steer towards average heading of neighbors; 3) cohesion- steer towards average position of neighbors (long range attraction).

Hereafter this model formed the basis of the self- propelled particles model, announced by T. Vicsek in [3]. This paper describes the algorithm of motion of autonomous agents, which move with a constant speed and adopt (at each time increment) the average direction of motion of the other particles in their local neighborhood up to some added noise.

At the same time agents' movement directions averaging is a powerful tool for finding common group consensus about the direction of the community movement as a whole. This can happen in the case of originally random directions of traffic participants and the presence in some parts of the information required by the target motion.

A. Jadbabaie et al. in 2003 [4] extend the model by adding a special agent Vicsek'a leader with a fixed movement direction. The agent never updates (not averages) its direction of motion, and thus affects on the calculation of the nearest neighbors, which extends then to the whole system.

Thus, based on the averaging mechanism indirectly influence on the set of agents is possible. This is achieved through the integration of this group a certain number of informed agents, which spread the set direction on the entire system.

It should be noted that similar mechanisms of aggregating behavior are widely represented in nature. The paper of Couzin I. D. et. al. [6] states that animal groups are moving smoothly to the target (for example, found a food source), even in cases where most of the individuals are not aware of it. The work shows that even quite small percentage of informed individuals in the schools of fish is enough to make collective "decision" of the movement direction by means of local information exchange. In this case the specified percentage has been steadily decreasing with increasing staff numbers.

Hereafter flocking algorithms with the presence of informed agents were developed in a number of scientific studies. Informed agents have the ability to non-legislative action on the system as a whole, which makes a similar mechanism of interest both from the point of view of management and decision-making. Engineers created numerous algorithms [7], [8], [9], [10], [11], aimed at improve the efficiency of the impact of informed robots on the rest of the swarm. The creators of swarm systems are trying to overcome the limitations of control and increase the response of the system to the introduction of several further parameters – i.e. to ensure rapid reorientation of the swarm to a new challenge and finally the possibility of flexible management.

II. Problem Statement and Assumptions

It should be noted that the Swarm technology does not involve direct control system. After reporting a swarm all initial parameters, control of robots activity is limited, if you follow the logic of the swarm of self-organisation. This general thesis can create confusion about the source of security in SR and nonsusceptibility of technology to outside influence.

F. Higgins et al. ([12]) is dedicated to the problems of SR information security, describes the vulnerability of systems operating in the open unprotected environment. On the side of attacker it is possible to capture and modificate or replace robotic device, what is lightened by their cheapness and simplicity of design.

Suppose that the system operates in an open environment using the algorithm which maximizes the impact of a small group of devices that promotes any direction of movement for the entire swarm. It is obvious that in this case the possibility of non-legislative influence is accessible not only to legitimate informed agents, but also to the alleged attacker, implemented in the system a certain number of foreign devices.

This research is related to simulated attack on an algorithm based on averaging of the direction of movement of swarm and the presence of the targets of informed agents' movement.

The essence of the attack is the following. First of all goes the introduction of illegitimate agents to swarm system who take on the role of informed agents and are involved in local computations. These agents are promoting an alternative direction (to some false target).

The aim of the study is a parametric study of swarm system, which operates according to the claimed algorithm in the presence of hostile agents, perceived as legitimate by other robots. The expected result is the definition of the set of parameters, the variation of which has a significant impact on system performance.

It is advisable to consider the following factors in determining swarm's system efficiency with the described algorithm:

- communication range (studied by Jadbabaie [4]),
- total number of swarm robots and the percentage of informed agents (Couzin I.D. et al [6]),
- awareness-informed agent (discussed in detail in the works [9] and [11]).

III. SIMULATIONS

A. Preamble

During this research it was suggested to identify the impact of the above factors on the results of the swarm system efficiency in the presence of attacker. To do this, it was necessary to create such program simulator that allows reproducing the operation of the swarm robotics system and analyzing the results.

The simulator for SR presented two types of motion target: True and False. False target is such kind of target where saboteurs are directed and this target fulfillment means that the task set before the swarm is not performed. Achieving true target is the execution of system's task. The criterion for the task achievement, therefore, is the amount (percentage) of the agents who had come to the true target. The task is completed when the number came to the true- target agents is equal to 95% of the initial amount of legitimate robots (it is obvious that the saboteurs will never come to the true target and their number in this case is not taken into account).

B. Development of simulation program

Developed simulation program should provide the following functionality:

- generation of robots' groups;
- generation of targets;
- placement robots and targets for working space simulator;
- the organization of robots interaction within the group.

Created in simulation program robots have the following set of feature $\{i, T, L, KL\}$, where i - robot ID, T - type, L - coordinate, KL - awareness. The robots are divided into three main types:

1) robots saboteurs which are trying to lead the swarm to the false target,
2) informed agents that in one degree or another are sure to coordinate true target,
3) conventional robots, which determine their movement, based on the direction of movement of its neighbors.

The level of awareness shows how much agent is sure where the target is before the swarm takes values [0,1], where 0 means that the robot is absolutely not sure where to go, therefore, chooses the direction, based on the movement of the neighbors, and 1 means that robot is absolutely sure where to go, not paying attention to other agents.

At the beginning of each experiment one need to generate a swarm of robots X, characterized by a set of features $\{n, ni, nd, CR, CD, SD\}$, where n is the number of conventional agents, ni is the number of informed, nd is the number of saboteurs, CR is interaction range, CD is the minimum distance between the agents, SD is the distance between robots during the initial placement of the workspace. interaction radius defines a distance at which the agent can communicate with each other, the minimum distance is approximately the distance between robots, which are observed during each iteration of the experiment.

The interaction of robots involves determining the direction of movement of the agent, located within radius of interaction of the current robot and check the distance between the nearest neighbors.

The main feature of SR behavior's simulating for the task is that in fact it does not require to fix several parameters at a certain level.

B. Movement and calculations

The mechanism of movement and settlement which is applied in the simulator, is based, primarily, on the algorithms proposed in [8] and [9]. These algorithms use Reynolds motion model and method of virtual physical strength for robots.

Let $\boldsymbol{h}$ be vector of average direction of surrounding robots, $\boldsymbol{g_j}$ - direction vector for the $\boldsymbol{j}$ target, where $\boldsymbol{j} = \{0, 1, 2\}$. ($\boldsymbol{j} = 0$ is used in the case of uninformed robots, then the direction of the target is $\boldsymbol{g_0} = 0$, $\boldsymbol{j} = 1, 2$ are used in the case of informed robots), $\boldsymbol{g_1}$ – direction to the first target, $\boldsymbol{g_2}$ - the direction of the second target, $\boldsymbol{w}$ - confidence in the targets.

Vector h is obtained by averaging the directions of movement of all robots, and the movement angle of the robot in step is the following:

$$\theta_{s_i} = \angle[wg_j + (1 - w)h] \tag{1}$$

While developing of the model, the term that is responsible for the attraction and repulsion of robots in the swarm (modeled K. Reynolds models) was added to the vector $\boldsymbol{h}$. The vector h can be obtained using the formula:

$$h = \frac{\sum_{j=0}^{k} e^{\theta_{s_j}}}{k+1} + \sum_{i=0}^{k} \frac{r_j - r_i}{|r_j - r_i|} \tag{2}$$

C. Prove-out on the basis of past research

Couzin E. D. et al. in the paper [6] have shown that with increasing of swarm dimension decreases the share of informed agents which is needed to make the main part of the swarm system to reach the target. Reproductioning a similar pattern was one of the indicators of the satisfactory software operation for the authors.

The criterion for achieving targets by SRS was chosen the following dimension: at least 95% of swarm's agents who came to the target by the end of experiment. Fig. 1 shows the number of required informed agents for 95% of SRS' robots to reach the target.

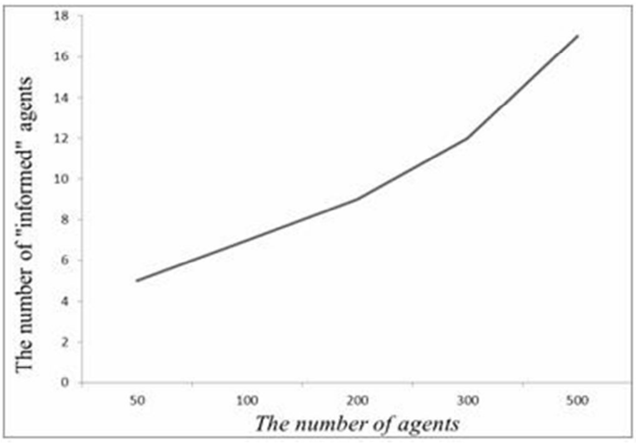

Fig. 1. The number of informed agents' dependence on the total number of agents to ensure the achievement of atask

Fig. 2 shows the number of agents with respect to the total number of the swarm. As can be seen from Fig. 1 - 2, developed software allows us to follow a similar with the work [6] trend: with the growth of the swarm from 50 to 500 agents, the percentage of informed agents shows stable tendency to reduce from 10 to 3.4%.

Besides the reducing number of neighbors by percentage, there can be pointed the reducing of the required agent's interaction radius, as with the increase of the number of agents of the swarm the increase of the density of the location of the agents, not the increase of the interaction surface, has been assumed by authors.

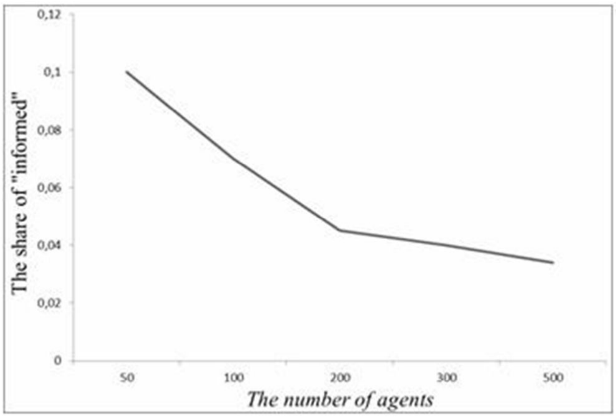

Fig. 2. The dependence of informed agents' share and the total number of agents

However, it is worth noting that the fact of reducing of the required agent's interaction radius is correct only if we deal with static surface swarm's location and, on the basis of this condition, the number of neighbors is not changing.

D. Conclusions on the simulator

The developed simulator is able to support the implementation of experiments that are able to fulfill the assigned tasks. It is worth noting that the studied model is a simplified version, as it doesn't take into account several practical aspects:

- availability of several targets;
- change of agents' confidence in the target coordinates.

Despite this fact, developed simulator allows to identify the main relevant parameters in the case of basic model version which makes it possible to assess the sustainability model and to conduct further experiments on more complex versions of the algorithm.

Thus, the developed software allows to carry out experiments in accordance with the interests of the research.

Among other things, the developed simulation program is the convenient mean for further experiments in the field of swarm's motion simulation, as it provides the correct functionality of agent's movement in the simulated space and data exchange between agents.

IV. ANALYSES OF THE EXPERIMENTAL DATA

A. Description of experiments

The first step was carried out determination of the adequacy of the performance created by the simulator. One of the criteria by which you can check on the accuracy of the simulator is the number of agents who came to the target in the absence of saboteurs.

Such kind of experience allows to get an idea of the adequacy of the model in the absence of latent destructive information impact. Based on the simple logical reasoning, the number of agents which had reached the goal, should strive to the initial number of agents. Of course, this statement is true only if the number of informed agents exceeds the threshold value figured in previous experiments.

It should also be noted that the differences between the agents which have reached the goal, and the initial size of the swarm should not be significant even if one fails to observe the term of the minimum number of knowledgeable agents.

To make the measurement reproducible and accurate, experiments were carried out using various data, which was specified randomly. This helps to cover different types of situations and to check the adequacy of simulator's operation much more accurate.

During simulator's work in order to test the adequacy the following parameters were varied: the number of agents, the number of informed agents, the number of saboteurs, the interaction radius, the minimum distance between the agents, the initial distance between the agents.

Established during these experiments, the sample will verify the correctness of the movement of agents, counting the number of agents who came to the target and general mechanisms that exist in the system at the time of its existence. Under such conditions, there were about 1,000 experiments, the results of the experiments are shown 300 in Fig. 3.

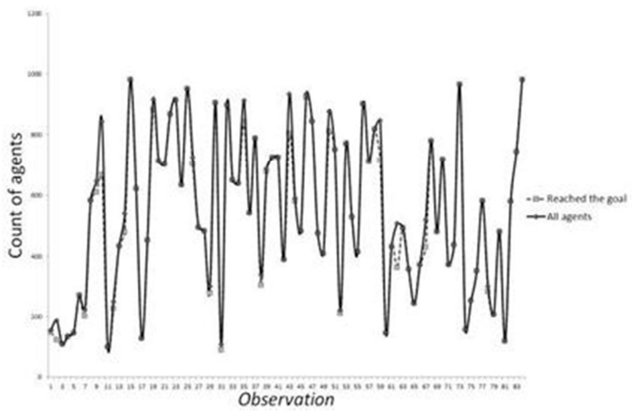

Fig.3. The ratio of the initial amount of bots and robots, which have reached the target

The presented graph shows that the number of the robots and the number of robots, which have reached the target in most cases is the same. In other cases, where these amounts are different, we can talk about some error, because the difference between the amounts of the robots are not significant, and the number of cases in which these values are significantly different, less than 1%, therefore they can be attributed to emissions which are cut out while analyzing. All values meet the previously announced terms. It should be noted that for better model control, the number of informed agents is always above zero.

B. Analytical method

To determine the influence of the factors used by linear regression, i.e. investigated factors presented itself as a linear equation of the form:

$$Y = a_0 + \sum_{i=1}^{7} a_i X + \varepsilon \tag{3}$$

Thus, the constant term (α_0) is added to the equation, and the effect of each factor is measured by α_i coefficients.

The form of presentation of results allows to interpret the existing dependence best of all. It should be noted that the interpretation of the coefficients of this equation is possible only when the value of R^2 is greater than appr. 0.6. If test results show a lower value, it will be impossible to make global conclusions about the model efficiency.

This form of analysis was chosen as the initial guess: the use of this type of equation was only intended as a basic option to start the experiment, but further calculations showed that it was possible to give up other options for the regression.

C. Initial data preparation

Initial data for analysis was formed on the basis of the following parameters of the model:

- Radius of interaction: from 4 to 20 units(X_1).
- Swarm size from 100 to 1,000 agents(X_2).
- Number of informed agents: from 5% to 50% of the size of the swarm(X_3).
- Number of saboteurs, from 5% to 30% of the size of the swarm(X_4).
- Confidence: from 0 to 1(X_5).
- Minimum distance: from 3 to 5 units(X_6).
- Initial distance: from 3 to 5 units, but more and equal to the minimum radius(X_7).

It should be found impact these parameters on the count of agents, which reach the goal (Y). This parameters' choice allows to describe available functions within the swarm best of all, without studying particular cause of the specific MAS implementation.

The total number of carried out experiments is more than a few thousand, but for regression analysis only data from about 700 experiments is used as other experiments were carried out to eliminate any shortcomings of the simulator or with fixed parameters for adjusting the model, which don't use the data for analysis.

D. Verifying initial characteristics

Before performing regression analysis it is necessary to conduct correlation analysis, which cuts off the factors that have an influence on each other.

As can be seen from the Table I, there is a relationship between the initial distance and the radius, as well as between the initial distance and minimum distance. It seems logical to remove the variable initial distance of the studied parameters. More detailed results of the correlation analysis are presented in the Table II (given in Appendix)

TABLE I. ANALYSIS OF DEPENDENCIES BETWEEN PARAMETERS

	Initial distance	Communication range	Critical distance
Initial distance	1		
Communication range	0,22	1	
Critical distance	0,67	0,02	1

There is also the relationship between number of saboteurs, informed agents and total number of agents. The authors of this report believe that it is possible to analyze the subject taking into account the "number of saboteurs" factor, as it doesn't significantly affect any indicator. After checking the initial characteristics investigated regression of the following form was compiled:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 \quad (4)$$

In this equation, the factors (X_i) are given in the manner described in the correlation matrix. Further analysis will determine the coefficients of the factors (α_i) and identify those factors that have a significant effect on the studied values.

The results of this analysis are presented in Appendix (Table III). The results show that R^2 is equal to 0,93, so the model is adequate and effective instrument. However, setting the minimum distance is not significant at the 5% level of significance. It is necessary to build another regression, removing this option.

Obtained results (Table IV in Appendix) do not differ in general from the previous, but now all the parameters are significant, so we can make a conclusion about the final form of the equation:

$$Y = -35{,}46 + 1{,}64X_1 + 0{,}54X_2 + 1{,}53X_3 - 0{,}87X_4 + 40{,}93X_5 \quad (5)$$

By the analysis of this model, the value of R^2 was also about 0.93. This value indicates that the original shape of the model has been chosen correctly, the relationship between the parameters can indeed be described by a linear function with high accuracy level.

E. Discussion

In interpreting this result, it is worth noting in particular the impact of levels of saboteurs and informed robots: the presence of one robot self-location targets affect the final amount came to the true target of robots is two times more than the presence of one of the robot saboteur. Increased interaction radius increases by 1% in the number of robots to target 1.64%, i.e. increasing the number of robots, which is based on the average motion vector, can increase the number of robots that came to your target. Free member reduces the amount came to the target robot 35 default units, perhaps it is some indicator that shows the average influence of factors which were not taken into account in the model. It seems logical that in a swarm of large dimension, this parameter will have no significant impact on the final result. The level of confidence a significant effect on the equation, but it is worth noting that, unlike the other indicators, this parameter is a quality that shows less influence it in absolute values at the output of the model.

In any case, one need not to take these values literally, since the situation, when there are no other factors that affect the final number of surviving robots which reached the target, is impossible, and this figure is used largely to adjust the results.

V. CONCLUSION

The tool to carry out experiments on the behavior of agents in SR not only under the existing conditions, but also in some versions of the algorithms was developed during the research. Performed experiments allowed to get an equation that described the behavior of SR system in terms of saboteurs' attack.

Based on the regression analysis we established the significance of the influence of the following parameters: the radius of interaction between the agents (the local communication radius) (1), the proportion of agents of different categories (legitimate informed agents, saboteurs, the total number of agents in the system) (2) and the informed agents' assurance degree in the promoted targets (3). Detection of hidden dependencies and features of this system will not only determine its main vulnerabilities, but also develop approaches to reverse the consequences of the attacks on SR.

It seems interesting that the linear form of the equation is able to predict with reasonable accuracy the behavior of the model.

It is planned to continue conducting similar experiments but with more complex algorithms, namely, the addition of a number of possible targets and changes in the degree of confidence while driving robots to the targets.

Besides it is planned further to study the resulting equation depending on the number of agents who came to the target on various features (the interaction radius, the number of agents, the number of informed and the number of saboteurs). Work on the detection of hidden dependencies and features of this system will not only determine its main vulnerabilities, but also will develop approaches to reverse the consequences of the saboteurs' attacks.

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TABLE II. ANALYSIS OF DEPENDENCIES BETWEEN PARAMETERS

	Initial distance	Communication range	Critical distance	Total number of robots	Number of informed robots	Number of saboteurs	Level of confidence
Initial distance	1						
Communication range	0,223173958	1					
Critical distance	0,66998788	0,019209119	1				
Total number of robots	0,020929896	-0,011582941	0,036684643	1			
Number of informed robots	0,038543711	-0,05549475	-0,000585691	0,088537793	1		
Number of saboteurs	0,056927053	-0,010862127	0,02273297	0,195718554	0,34946335	1	
Level of confidence	-0,021142025	0,033705889	-0,036021774	0,030510239	-0,001647117	-0,004406018	1

TABLE III. THE RESULTS OF THE PRELIMINARY REGRESSION ANALYSIS

Summary Output

Regression Statistics	
Multiple R	0,966156274
R Square	0,933457946
Adjusted R Square	0,93282118
Standard Error	51,67677533
Observations	634

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	23488587,85	3914764,642	1465,935446	0
Residual	627	1674396,671	2670,489109		
Total	633	25162984,52			

	Coefficients	*Standard Error*	*t Stat*	*P-Value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Constant term	-25,62	9,38	-2,73	0,01	-44,04	-7,20	-44,04	-7,20
Communication range	1,66	0,40	4,12	0,00	0,87	2,45	0,87	2,45
Critical distance	-3,31	1,79	-1,85	0,06	-6,82	0,20	-6,82	0,20
Total number of robots	0,54	0,01	46,46	0,00	0,52	0,56	0,52	0,56
Number of informed robots	1,53	0,02	79,37	0,00	1,49	1,57	1,49	1,57
Number of saboteurs	-0,87	0,03	-28,93	0,00	-0,93	-0,81	-0,93	-0,81
Level of confidence	41,42	7,67	5,40	0,00	26,36	56,48	26,36	56,48

TABLE IV. THE RESULTS

Summary Output

Regression Statistics	
Multiple R	0,965968272
R Square	0,933094703
Adjusted R Square	0,932562017
Standard Error	51,77635895
Observations	634

ANOVA

	df	SS	MS	F	Significance F
Regression	5	23479447,56	4695889,512	1751,680346	0
Residual	628	1683536,965	2680,791346		
Total	633	25162984,52			

	Coefficients	Standard Error	t Stat	P-Value	Lower 95%	Upper 95%	Lower 95,0%	Upper 95,0%
Constant term	-35,46	7,74	-4,58	0,00	-50,66	-20,27	-50,66	-20,27
Communication range	1,64	0,40	4,08	0,00	0,85	2,44	0,85	2,44
Total number of robots	0,54	0,01	46,39	0,00	0,52	0,56	0,52	0,56
Number of informed robots	1,53	0,02	79,44	0,00	1,49	1,57	1,49	1,57
Number of saboteurs	-0,87	0,03	-28,90	0,00	-0,93	-0,81	-0,93	-0,81
Level of confidence	40,93	7,68	5,33	0,00	25,84	56,01	25,84	56,01