Proceedings of the World Congress on Engineering 2014 Vol I,
WCE 2014, July 2 - 4, 2014, London, U.K.

Swarm of Intelligent Control Objects in Net-centric Environment

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***Abstract*—Group movement of the intelligent control objects with the formation of a swarm is discussed. It is demonstrated that the control in these conditions is a kind of the net-centric control. The new approach consists in the description of the swarm movement process using the neural networks with the assembly organization. The trajectory of each swarm object is determined by the aggregate of the excited neurons combined in a network. The swarm appears as a neural assembly, whose characteristics describe the swarm shape, size and distribution of the objectsin space**

***Index Terms*—Swarm, control object, agents, collective behavior, neural networks, assembly.**

I. Introduction

In practice, there are the tasks when a single control object cannot execute the main goal for some reasons. These tasks occur in complex situations in video monitoring of extended areas of the earth surface, fulfillment of various tasks by robot collectives, movement of vehicles under dangerous meteorological and radiation conditions, etc., To resolve the tasks, it is expedient in this case to use not a single control object but a group of objects. They may have similar characteristics, accomplish a common mission, and form complex space structures in the process of movement and maneuvering. A swarm of control objects is a part of such structures. It is necessary to simulate the processes of the swarm decision-making, control, movement, maneuvering, etc.

The paper [1] discusses the motion of a swarm of flight vehicles with a weight of up to 100g in the outer space, at a height of over 500km, subject to the change in the orbit parameters due to the resistance of the atmosphere. The task of minimization of the fuel consumption for maneuvering to keep the preset relative distance between hundreds of space vehicles is resolved here. In the described situation, the space vehicles are not linked to each other informationally. The model describes the motion of each space vehicle of the swarm using thedifferential equations, which requires individual computations for each space vehicle.

The paper [2] discusses the coordination of the swarm motion using the algorithm of particle swarm optimization (PSO). It is characteristic that a leader, defining the path type and followed by the other objects, which use the PSO algorithm rules to generate the control, shows up in this case. The questions of formation of such structures as the line, column, wedge and diamond are resolved for five control objects. The control objects don't exchange the information here either.

In this paper, we try to consider the information exchange between the swarm objects. The number of objects was assumed knowingly significant. A swarm of such control objects acting in a given environment must function autonomously and pro-actively, have information about the motion environment, resolve the collective task using the capabilities of all the objects incorporated in the swarm, provide itself with information, account for the existing limitations, etc. On the other hand, such subjects as intelligent agents possess feature autonomous functioning, reactivity, pro-activity, basic knowledge, beliefs, desires, goals, intentions, commitments, and other properties. Generally, it is therefore convenient to consider a swarm as a group of intelligent agents in all such situations.

A swarm of biological species can be taken as the basis of this idea. Observing such as swarm (fish, birds, bees, etc.) is very interesting. Such a swarm can move fast and slowly, execute extreme maneuvers, and quickly respond to the emerging dangers. It is as if it had some intelligence and implemented collective behavior. Extension of the properties and behavioral algorithms of the living organisms to the man-made objects is a widely used research method of recent years. The conventional swarm algorithms limit the behavior of individual species reducing them to copying of the neighbor's motions. For the control objects swarms it is expedient to invest the objects with more extended functions, in particular with the function of monitoring the situation and generating its own suggestions for further motion with the collective behavior

II. Swarm as Group of Intelligent Agents with Collective Behavior

A swarm is now considered as a uniform structure. It is also assumed that distribution of the elements in the space occupied by the swarm is uniform. Each swarm object is not different from the others; however, it has no autonomy in its actions. The swarm appears when it is informed of the next neighbors only and the mission, tasks and motivation of the whole swarm are unavailable to the main elements of the swarm.

Consider the main characteristics of the control objects swarm. Let the capacity of the swarm is N uniform control objects.

Swarm shape (F). Depending on the number of objects and their distribution in space, the swarm may take different geometrical shapes. Ellipsoids, spheres, cones with different half-angles, elongated cylinders, and other solid figures with the complex layout geometry are such most common solid figures.

Manuscript received February 22, 2014; revised March 11, 2014. This work was supported by the Russian RFFI Fond under Grant 12-08-00721a. V.K.Abrosimov is Professor with the Moscow Aviation Institute - National Research University, Volokolamskoyeshosse 4, Moscow, 117997, Russia; tel. 7 (916) 815-3512; fax 8(495)363 01 34(e-mail: avk787@yandex.ru)

Swarm size (R). The size of the swarm quantifies its shape and extension in space. Sphere is characterized with radius; ellipse- with the direction of the central axis and dimensions of semi-axes; cone- with height and half-angle, etc.

Swarm structure (St). It is determined by the type of control objects incorporated in the swarm. The swarm may consist of uniform and non-uniform objects. For a non-uniform swarm, the control objects forming it are diverse, have different functions and are intended to resolve different tasks. One of the important characteristics is spatial distribution of the moving objects of the swarm. It is expedient to build these distributionsP_{xy}, P_{yz}, P_{xz} in three mutually perpendicular planes for the set time t^*. Joint processing of these distributions allows the assumption of the swarm structure.

Swarm hierarchy (L). The hierarchy determines the objects, which have the right to control the swarm, and the objected subordinated to them, i.e. controlled objects. When this subordination is not established, the swarm is considered as unorganized or self-organizing.

Swarm communicativeness (K). The communicativeness characterizes the presence of the informational links between the swarm objects. The information can be exchanged in different ways "each to each", "star", "sun", etc.

Swarm intelligence (I). The intelligence suggests that a) the swarm perceive and use the information, received via different channels, at the given space point; b) the swarm can independently evaluate the current situation; and c) the swarm makes decisions independently acting within the collective behavior rules.

Swarm motion style (Z). Depending on the motion organization principle, it is possible to distinguish a free, constraint, targeted, and other types of the swarm motion.

Thus, a uniform swarm of control objects is a group of elements with similar characteristics and parameters, which are subject to the uniform control laws and behavioral rules. In order to accomplish multiple goals G by implementing the strategies C at an arbitrary time point t, the swarm moves in a three-dimensional space in the Cartesian coordinates x, y, z; has the shape F (sphere, ellipsoid, cylinder, cone, etc.); size R; structure St with distribution P_{xy}, P_{yz},P_{xz}; hierarchical level I (e.g.: a particular leader or a group of leaders); communicativeness level K, described by the matrix of interaction of the object with each other; and features the intelligence I and motion style Z.

Let us ask a question- is it possible to consider each swarm object as an individual agent? It depends on the organization of the swarm control. For complex collective tasks, the swarm can be divided into the main elements and auxiliary elements supporting the fulfillment of tasks. In this case, the objects from the main group can be considered as individual agents. However, the main properties of the agents (e.g.: autonomy, autonomous functioning, intentions, etc.) degenerate in resolving simple collective tasks. Typical is the absence of the autonomy of each swarm object. Then, the collective behavior principle is implemented through the similar behavior of the objects.

In the most general case, the i-th intelligent control object of the swarm can be determined with the following state vector

$$< B_v,\, g_v,\, c_v, l_v\, ,E_{vw} > \forall\ v = 1, V,$$

where

$B_v$is the basic knowledge of the v-th object, formed preliminary and augmented in theprocess of motion,

$g_v$is a set of the determined or specifiedgoals of the v-th object ($g_v \in G$),

$c_v$is a set of the object's strategies $c_v \in \mathrm{C}$, which it selects for accomplishing the goal $g_v \in G$, in the process of motion and as a result of the receipt of information,

$l_v$is the structure of the object's commitments to the other objects,

$E_{vw}$is a multidimensional matrix,determining the description of the externallinks of the v-th intelligent control object.

III. Network-Centricity of Movement Environment

The swarm moves in a four-dimensional space – three independent coordinates of the selected system of coordinates and time. Our hypothesis consists in the fact that the control of the swarm is a kind of the network-centric control. The presence of the so-called "information grid" is distinguished in the network-centric control as the main element. It means that a single information field is formed and all events and data are fixed to it in the "coordinates-time" format. It is expedient to link some virtual information field to the motion space of the swarm and locate the information on the situation at the given point, received from the external facilities and sensors of the objects forming the swarm, at its each point. Then, by predicting the motion with allowance for this information field, it is possible to receive the information on the situation in the on-line mode and use it for making decisions. We suppose that all objects of the swarm deliver the information available to them to this "information grid". The "information grid" thus built is the most important part of the general concept of swarm control.

IV. Formal Characterization of the Control Objects Swarm as a Neural Assembly

Formation of the behavior and computation of the trajectory for each object causes some computational problems in determination of the swarm motion. Sequential computation is inexpedient for a significant number of the objects incorporated in the swarm, high speeds of the motion and limited time for resolving of the task. The analysis shows that the "curse of dimensionality", caused by an exceptionally great variety of situations, evolving in the description of the swarm motion and maneuvering, can be easily encountered when describing and mathematically simulating the motion of the control objects swarm.

For description of the motion of the control objects swarm, we propose to use the neural networks with the ensembles. [3,4]. There is a very important advantage of the neural networks over the conventional systems of adaptive and optimal control: the implementation doesn't require the traditional model of the control object. The rules describing the object behavior become determining.

The basis of the neural presentation of the swarm trajectories parameters is the concept of neural-state. Assume that the four-dimensional phase space F^4, in which the swarm is moving, can be represented with an arbitrary large aggregate of neural-states (ns). Introduce the Cartesian coordinate system, where each point of the subspace can be determined with coordinates x, y, z. Fill the hole space, in

ISBN: 978-988-19252-7-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

which the swarm objects are moving and maneuvering, with ns-states with the required discreteness degree. Each such ns-state is characterized by numerical values of its activity $\propto \in [0,1]$, where $\propto = 1$ means that the swarm object is at the space point described by the ns-state; $\propto = 0$ means that the swarm object is not in the ns-state; and situation $0 \leq \propto \leq 1$ characterizes the possibility or probability of the swarm location in the ns-state. Three types of ns-state are thus introduced in the approach: deterministic, probabilistic and fuzzy. Call the situation when the neuron receives the numerical value $\propto \in [0,1]$ the neural exciting.

Then, the arbitrary ns-state can be clearly describe with the sequence $ns_{ijk} = \{x_i, y_j, z_k, \alpha_{ijk}\}$, where i=1,2,3…,I; j=1,2,3…,J; k=1,2,3…, K. are the indices of the serial number of the neuron according to the respective coordinate axes and α_{ijk} is the degree of exciting.

Assume that under the action of the control $\overline{u}$, a swarm object can transit from one ns-state to another $ns_{ijk} \rightarrow ns_{rsf}$. Determine the conditions of this transition as the links of ns-states and describe them with the state transfer matrix Ω with the elements $(\beta, \Delta t)$. In presentation of the swarm as an agent, this matrix was determined as the matrix M and it determined the links between the object inside the swarm. Element $\beta_{ijk\rightarrow rsf}$ is intended for description of the physics of the process of transition from one state to another, where $\beta = 0$ in the absence of any link; $\beta = 1$ in the presence of a deterministic link; and $\beta \in [0,1]$ for probabilistic or fuzzy link. Time interval $\Delta t_{ijk\rightarrow rsf}$ will determine the time of transition from ns_{ijk} to another ns_{rsf}.

In the process of simulation, we will assume the change in the values of the elements of the matrix Ω. This will enable responding to different situations evolving in the process of motion. Formally, these changes can be written as follows:

$$\beta^{t+\varepsilon}_{ijk\rightarrow rsf} = \beta^{t}_{ijk\rightarrow rsf} + \delta\beta, \Delta t^{t+\varepsilon}_{ijk\rightarrow rsf} = \Delta t^{t}_{ijk\rightarrow rsf} + \delta\tau \ ,$$

where t is the moment of making a decision to the change in the link characteristics; ε is a discrete, consistent with the discreteness of the space partition, small value; and $\delta\beta$ and $\delta\tau$ are the values of increments to the values $\beta_{ijk\rightarrow rsf}$ and $\Delta t_{ijk\rightarrow rsf}$. Note that it is necessary to consider the existing limitations, imposed on the appearance, control system and conditions of the swarm objects use, when generating this matrix.

Finally, combine the neurons into assemblies. A set of neurons, combined with the mutual exciting links such that the whole assembly is excited when it is exciting, is called a neural assembly [3]. Describe the subset A_s, i.e. assembly of ns-states, incorporated in some regions of the space H, and connect all neurons of the set A_s with mutual firing links using the matrix S with the elements $(\mu, \Delta\gamma)$. At that, the structure of S is congruent with the matrix Ω, but μ in this matrix means the firing degree of the ns-state from the set A_s and is always equal to 1 and the time internal $\Delta\gamma$ is alwys equal to zero. Take one neuron ns_h from the assembly A_s and assign to it, using the matrix S, the function to excite all ns-states of the assembly A_s when it is fired over some level $\mu > \mu^{fix}_{abc}$. Then, all other elements, described by the matrix S and forming the assembly A_s will be fired instantly. The stated presentation becomes a very good imaging of the swarm behavior physics, as the biologists for example assert that there are species in the swarm behavior, the change in the behavior of which puts the whole swarm in motion.

Parameters of the swarms' motion can be significantly different depending on the conditions of the conflict situation in the simulation. Use a special "intensification-weakening" system (IWS) to adjust the activity of neurons [3]. Its main functions are the directed change in the neural links ("break" of some and "establishment" of others). The IWS has some threshold sensitivity (activity) characteristic. It can be "activated" only upon receipt of a signal that one (or more) ns-states exceed this threshold. In this case, the values $\pm\nabla\beta$, $\pm\nabla\tau$, and $\pm\nabla\propto$ can be sent to the network, assembly, or selected part of the network and the formal operations are implemented:

$$\beta^{t+}_{ijk\rightarrow rsf} = \beta^{t}_{ijk\rightarrow rsf} + \nabla\beta \ ,$$
$$\Delta t^{t+}_{ijk\rightarrow rsf} = \Delta t^{t}_{ijk\rightarrow rsf} + \nabla\tau,$$
$$\propto^{t+}_{ijk} = \propto^{t}_{ijk} + \nabla\propto,$$
$$\mu^{t+}_{abc} = \mu^{t}_{abc} + \nabla\mu,$$

where $t^{+}$is is the moment of making a decision to the change in the link characteristics, time for passing the link or activity level of ns-states. This system simulates well the collective decision-making by the aggregate of objects forming a swarm.

The IWS is intended for simulation of all features of the swarm motion. In fact, it enables a directed change in the motion using the value $\nabla\beta$ (value of the strength of the link of ns-states in order to adjust the matrices Ω); change in the speed value using the value$\nabla\tau$ (due to the change in the time to reach the ns-state); change in the probability of location of the swarm object in the given space region using the value $\nabla\propto$ (activity of the ns-state); and the change in the number of neurons, which - by means of the matrix S - form the assembly A_s, using the value $\nabla\mu$ and thus the adjustment of the swarm shape and size (number of the objects in the respective ns-states).

The proposed neural model of the swarm described its motion from the point of view of the swarm observer as well. In this context, appearance of the swarm in some region of the observed space, disappearance of the swarm and its sudden appearance in another region of the space again can be simulated using the acceleration-braking system and changes in the values of the matrix Ω.

V. Decision-Making and Swarm Maneuver

The swarm occupies some region in space. Assume the swarm movement in space as the changing of the location of the assembly As. The swarm trajectory will be thus described by a set of active (i.e. excited) ns-states and temporary transitions between them (Fig 1.). A special trajectoryis then formed for each object as a set of neural states and temporary transitions between them $\mathrm{ns}_{ijk} \rightarrow \mathrm{ns}_{rsf} \rightarrow \mathrm{ns}_{\mathrm{abc}}$.

Record the start of motion by exciting the selected neural leader. Assembly As, that is the whole swarm, will be excite according to the matrix S. Values of the elements of the matrix S will determine the swarm shape and size; spatial distribution of the objects inside the swarm will be specified using the IWS when necessary. Switch on the timer and set a task to the swarm to arrive from region Ho to region Hk. According to the matrix Ω, at the next step of the process we will have a new firing assembly A_{si}describing the new state of the swarm. The path of the motion of the whole swarm is recorded with the sequence of the motion of the assemblies $A_{s1} - A_{s2} - A_{s3} - etc.$ Synchronize the motion of other elements of the swarm with the motion of the leader. In fact,

ISBN: 978-988-19252-7-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

both the motion and maneuvering are in principle limited to the changing of coordinates. Coordinates x and z characterize the change in the horizontal plane and coordinate y – in the vertical one. The synchronization algorithm consists in the determination of the difference in the coordinates of ns-states, determining the location of the leader at the moment t and t+Δt. Record these increments at the next step of the process. Coordinates of ns-states, to which the other swarm objects must move at the similar motion speeds, are changing to the stated increment values.

Form a virtual “information grid” of the swarm assuming that all objects of the swarm deliver to it in the on-line mode the information on the environment state available to them (e.g.: motion danger level). Different information can be also provided by the facilities of the motion data support (e.g.: by the space tracking systems for flight vehicles operating at a height of up to 20-30km). Each ns-state will be assigned with a similar node of the “information grid”. The leader, by analyzing at each current moment of time the data of the “information grid” on the danger of the further motion and based on the possibilities of maneuvering, evaluates the situation and makes a decision to change the path of motion to the goal, i.e. to maneuver. When necessary, other control objects can be involved in decision-making to implement the collective behavior principle (an “advising” system will be formed in this case).

Maneuver, as well as motion, is simulated with the changing of the values of the matrix Ω. Changing of the coordinates in space is schematically described above. Changing of the speed vector in the process of maneuvering is simulated with the changing of the time for passing the link between the neurons, i.e. changing of the value $\Delta t_{ijk\to rsf}$ with the respective sign. Change in the swarm shape is simulated similarly. The time moment t^{fix}, by which the swarm must have another form and numbers of ns-states, in which the objects must be by that moment, is determined at that. A special path is then formed for each object as a set of neural states and temporary transitions between them $\mathrm{ns}_{ijk} \to \mathrm{ns}_{rsf} \to \mathrm{ns}_{abc}$. Values $\Delta t_{ijk\to rsf}$ are determined from the conditions of reaching the ns-state ns_{abc} by the moment of time t^{fix}.

The figure schematically shows a part of the space, in which a maneuvering swarm is moving. The “information grid” is integrated in this space. In each node, there is an ns-state with some degree of firing. Ho is the initial region of the swarm location; Hk region is the motion goal. White circle in the region Ho designates the neural leader (initiator of the assembly formation). Assembly As of neurons, fired according to the matrix S and forming the swarm, is marked with black circles.

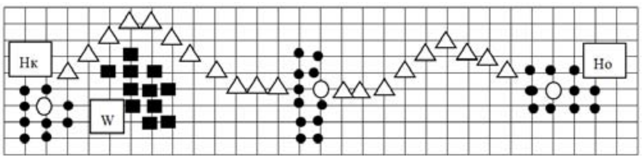

Fig. 1. The trajectory of control object’s swarm with maneuver

Motion restricted zone is the part of the information grid marked with black squares (zoneW). White triangles designate the motion path of the swarm leader. The swarm with the geometry, changed in the process of maneuvering, is conventionally shown in the middle of the path.

VI. Conclusion

The paper discusses in brief a new approach to the simulation of the movement of a control objects group particularly arranged in a swarm. Control objects are considered as intelligent agents. It is demonstrated that the swarm control is a kind of the network-centric control. It is assumed that there is a virtual information grid, to which all the swarm objects deliver the information available to their sensors. It is shown that the swarm movement process can be formally characterized on the bases of neural networks with the assembly organization. The whole movement space is decomposed – with the preset discreteness – into subspaces, in the centers of which there are so-called neural-states. Trajectory of each swarm object is determined by the aggregate of the firing neurons combined in a network. The swarm itself appears as a neural assembly, whose characteristics describe the swarm shape, size and distribution of the elements inside the swarm.

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ISBN: 978-988-19252-7-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)