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Description Model and Qualitative Evaluation of Intelligence Characteristics of Unmanned Swarms

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Abstract. Offering a comprehensive description model and proper qualitative evaluation scheme of the intelligence characteristic of unmanned swarms poses a challenging basic theory and key technology problem. Firstly, this paper analyses and clarifies the concept of the intelligence characteristics of unmanned swarms. Subsequently, based on the existing description model of human intelligence and cooperative scheme based self-organization, it constructs a comprehensive model for describing the intelligence characteristic of unmanned swarms. Some anticipated intelligence characteristics for unmanned swarms are introduced and summarized. Following this, the qualitative evaluation process of the intelligence characteristics is abstracted as a hierarchical evaluation system, and the evaluation model based on multi-layer generalized operators is introduced for the sake of practical inference. Finally, taking the self-learning characteristic as a case, the qualitative evaluation process of intelligence characteristics and some key problems in testing are described and explicated. The result suggests that the intelligence characteristics of unmanned swarms can be evaluated qualitatively. The qualitative conclusions that are drawn from the description, test and evaluation can be considered to determine the presence of the intelligence characteristics in unmanned swarms, which also is the basic premise of the quantitative evaluation of the intelligence of unmanned swarms

Keywords: description model, intelligence characteristics, qualitative evaluation, unmanned swarms

1 Introduction

Unmanned swarm is a specific research field in swarm intelligence. Inspired by the macro intelligent behaviors of biological swarms such as ant colony, bee colony, fish swarm and bird swarm, etc. [1], researchers started investing efforts into the research and development of swarm systems. Unmanned swarm refers to an autonomous mobile system composed of a certain number of homogeneous or heterogeneous unmanned platforms, which can exhibit diverse cooperative behaviors among multiple individuals, adapt to dynamic environments and jointly complete specific tasks through information interaction and feedback, incentive and response [2]. It does not merely connect and combine multiple simple individuals but establishes a close coupling and efficient cooperation between them, forming a self-organized and highly stable distributed system to stimulate individual intelligence and raise swarm intelligence [3]. Compared with unmanned monomers, unmanned swarms have stronger environmental adaptability, more robustness, richer mission capabilities and higher work efficiency. Unmanned swarms can be distributed in sea, land, air and other operating spaces, including unmanned aerial vehicle(UAV) swarms, unmanned ground vehicle(UGV) swarms, unmanned surface vehicle(USV) swarms, unmanned underwater vehicle(UUV) swarms and some other mixed unmanned swarms with cross-domain collaboration. At present, the research and development of unmanned swarms in various countries mainly focus on UAV swarms [4], and some typical unmanned swarm projects mainly include Gremlins [5], OFFSET [6], Perdix [7], LOCUST [8], etc.

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Swarm intelligence is an important development direction in artificial intelligence. The performance of intelligent applications and systems must be evaluated on a regular basis to certify and foster discipline progress [9]. Over the past few decades, many researchers have studied the test methods of the intelligence of intelligent systems [10], but they often ignore an important premise, that is, how to define intelligence and intelligent systems. At present, a widely accepted view is that intelligent systems refer to those systems with intelligence characteristics and(or) adopting artificial intelligence theories, methods or technologies [11]. The latter requirement in this view is easy to understand and distinguish, but the former requirement is not easy. Tu Xuyan [12] firstly pointed out that the intelligence characteristics of intelligent systems refer to those characteristics simulating, extending and expanding human intelligence, such as learning, optimization, planning, coordination, etc. However, from today's perspective, this view is limited because it hard to cover the origins of the intelligence characteristics of swarm systems. Although a large number of theoretical results have been formed for unmanned swarms, few studies focus on how to describe and evaluate the intelligence of swarm systems.

There is a widely accepted view that the macro intelligence emergence of swarm systems needs to meet five basic principles including proximity principle, quality principle, diversity principle, stability principle and adaptability principle [13-14]. In the description of stigmergy, Duan Haibin [15] pointed out that the intelligent behavioral characteristics of swarm systems mainly include the distributed organization structure, the simplification of individuals, the flexibility of action modes and the intelligence of the whole system. Based on the analysis of biological swarm behaviors, Tang Xianlun [16] argued that the intelligence characteristics of swarm systems mainly include self-organization, self-recovery, indirect communication and learning, while Xiao Renbin [17] argued that intelligence characteristics of swarm systems mainly include systematicness, distribution, self-organization and positive feedback. Camazine [18] firstly proposed that biological swarms should meet three basic performance characteristics including robustness, adaptability and scalability. Erol [19] further defined these three characteristics as anticipated characteristics of unmanned swarms. Liu Yang [20] pointed out that stability also should be considered as one important performance characteristic of swarm systems. In addition, more and more researchers have paid attention to the self-perception [21-22], self-assembly [23-25], self-immunity [26-27], self-evolutionary [28-29] functions of swarm systems. According to the relation with the intelligence of swarm systems, these characteristics can be divided into three categories, as shown in Table 1.

Table 1. The classification of the characteristics of swarm systems

Category	Specific characteristics
Conditional characteristics	proximity, quality, diversity, distributivity, simplicity, stigmergy, systematicness, positive feedback, …
Procedural characteristics	self-organization, self-adaptation, self-recovery, self-learning, self-assembly, self-immunity, self-evolutionary, …
Consequential characteristics	robustness, flexibility, scalability, stability, reliability, security, autonomy, …

There is no doubt that the conditional characteristics and consequential characteristics provide great conveniences for us to understand, design and evaluate unmanned swarms, but these characteristics may not be able to reflect the real intelligence of unmanned swarms. If we only choose these characteristics to evaluate unmanned swarms, it is likely that the intelligence of unmanned swarms will be reduced to the pseudo intelligence or weak intelligence, thus hindering the development of real intelligence. Although researchers have designed and implemented various intelligent functions from different perspectives, there is no comprehensive model for uniformly describing them and some other anticipated intelligence characteristics. Due to the lack of reasonable and forward-looking standards, unmanned swarms are facing unplanned development. In the long run, this situation is not conducive to improve the intelligent development of unmanned swarms. Thus, it is necessary to carry out special research on the comprehensive description and qualitative evaluation of intelligence characteristics of unmanned swarms. The main challenges of this research lie in the need to combine engineering practice, discrete intelligence characteristics of unmanned swarms and the general cognition of human intelligence to reasonably construct the description model of intelligence characteristics of unmanned swarms and find the proper scheme to qualitatively evaluate the intelligence characteristics with different granularity.

2 Definition of Intelligence Characteristics of Unmanned Swarms

In any science, issues surrounding fundamental definitions and measurement methods play a central role and form the foundation on which theoretical advances as a field over the next 50 years [14]. At present, there is no reasonable and authoritative definition of the intelligence characteristics of unmanned swarms.

In order to define the concept reasonably, we must first clarify the concept of the intelligence of unmanned swarms. The intelligence of unmanned swarms comes from swarm intelligence but it is not exactly equivalent. Swarm intelligence refers to the collective intelligence which is emerged by a large number of simple autonomous agents [20]. Swarm refers to multiple agents that can communicate with each other directly or indirectly, which can cooperate to solve distributed problems. These individuals in swarms are not absolutely without intelligence or only with simple intelligence, but are relative to the intelligence emerged by the swarm. Swarm intelligence takes full advantage of the scale without the need for centralized control and a global model to provide a great solution for large-scale sophisticated problems. There are many limitations on the isomorphism, swarm scale, individual capability, communication mode of swarm robotic systems designed strictly according to swarm intelligence, while unmanned swarms are different. The concept of the intelligence of unmanned swarms can be explained more reasonably by the concept of system intelligence. System intelligence is composed of multiple intelligent modules which interact with each other through certain rules and emerge new functions at the overall layer. These intelligent modules can not only connect and interact with each other, but also emerge new functions based on individual functions [30]. There is no conflict between system intelligence and swarm intelligence. System intelligence inherits the reasonable core and advantages of swarm intelligence, and eliminates its restrictive constraints. Especially, there are no limitations in the isomorphism, swarm scale, individual capabilities, communication mode, etc. It has a wider range and stronger functions. System intelligence includes swarm intelligence and swarm intelligence exists as a discrete system intelligence.

Following this, we also need to refer to the concept of the intelligence characteristics of intelligence systems. Intelligent systems refer to those systems with anthropomorphic intelligence characteristics and(or) adopting artificial intelligence theories, methods and technologies [15], in which anthropomorphic intelligence characteristics are those characteristics simulating, extending and expanding human intelligence, such as learning, optimization, planning, coordination, etc. Due to human intelligence characteristics are multi-layer and multi-faceted, so are anthropomorphic intelligence characteristics.

By simulating the definition of intelligence characteristics of intelligent systems, we argue that the intelligence characteristics of unmanned swarms refer to those bionic collective intelligence characteristics simulating, extending and expanding biological swarm intelligent behaviors, such as self-organization, self-recovery, self-learning, self-adaption, self-assembly, etc. In addition, the conception includes the following meanings. 1) The conception include different requirements for individuals and swarms, that is, the individuals in the swarm are required to be autonomous, and the individual intelligence is relatively simple relative to the swarm, while the individuals are cooperative, and the whole swarm can emerge higher than the sum of individual intelligence. 2) Specific characteristics included in the conception can be divided into different layers and dimensions by analogy with human intelligence characteristic structure. 3) The conception is the collection and integration of a series of specific characteristics, which can be summarized and described from different granularity. 4) Specific characteristics included in the conception should be measurable and comparable, and can distinguish the intelligence level of unmanned swarms.

3 Description of Intelligence Characteristics of Unmanned Swarms

At present, there is no comprehensive description of the intelligence characteristics of biological and bionic swarms, and we need to further refer to the description model of human intelligence characteristics we are familiar with. The analysis method is not bold and unusual. Many researchers [31-32] also use the analysis method to analyze the autonomous levels of unmanned systems including unmanned swarms. Moreover, from the practical point of view of engineering point, the description of the intelligence characteristics of unmanned swarms need to be closely related with the cooperative control scheme based on self-organization.

3.1 Description Model of Human Intelligence

The source of artificial intelligence is natural intelligence. Human intelligence is the most mature, perfect and advanced intelligence in natural intelligence. The simulation of human intelligence has always been the ultimate goal of artificial intelligence. Human intelligence mainly depends on the nervous system composed of hundreds of billions of neurons. These nerve cells have almost identical structures and functions. Human intelligence is realized through the simple interactive rule among these never cells. Therefore, in terms of the nature of intelligence, there is no difference between swarm intelligence and human intelligence.

Humans include the multi-layer and multi-faceted intelligence characteristics of individuals and groups. Generally speaking, human intelligence characteristics can be divided into three layers as shown in Fig. 1 [33].

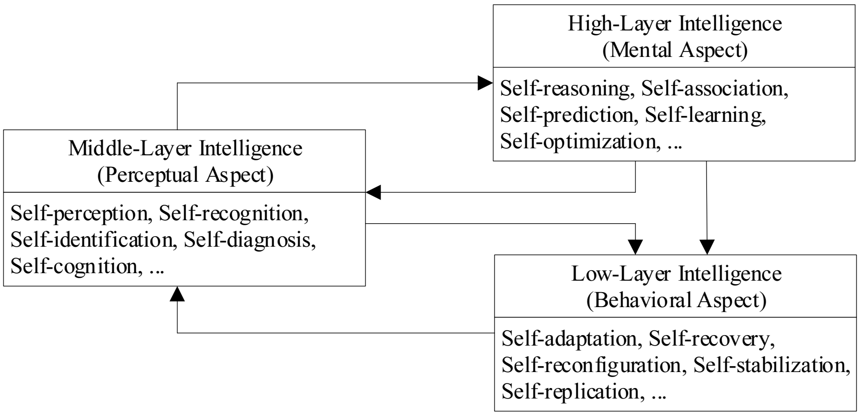

Fig. 1. Description model of human intelligence

In the above model, high-layer intelligence characteristics refer to those reflected in mental aspects, such as self-reasoning, self-association, self-learning, self-optimization, self-planning, self-coordination and self-prediction, etc., which take the “will center” of the high-layer central nervous system such as the cerebral cortex as the main material basis. Middle-layer intelligence characteristics refer to those reflected in perceptual aspects, such as self-perception, self-recognition, self-identification, self-diagnosis, and self-cognition for words, images, sounds, language, scenery, expression, movement, posture, temperature, pressure and smell, which take the advanced central system such as the “sensory center” thalamus and other advanced central systems, the external afferent sensory nerves and various sensory organs as the main material basis. Low-layer intelligence characteristics refer to those reflected in behavioral aspects, such as self-adaptation, self-recovery, self-reproduction and self-stabilization, which take the hypothalamus of “motor center”, “brain stem of life center”, “spinal cord and peripheral efferent motor nerve and various effectors,” “humoral center”, hypothysis and endocrine system as the main material basis.

3.2 Cooperative Control Scheme Based on Self-organization

In general, there are two different cooperative control schemes for unmanned swarms from the view of engineering. One is based on a hierarchical structure, the other is based on self-organization. The hierarchical scheme was first put forward by Salidis [34], which is mainly composed of organization layer, coordination layer and execution layer. The structure follows the principle of increasing precision with decreasing intelligence. Inspired the structure, a hierarchical cooperative control scheme is proposed [35]. The scheme mainly adopts the top-down solution, which effectively reduces the difficulty of solving complex control problems. However, the process of decomposing the complex problem layer by layer also makes it difficult to real-time control and decision-making. Instead, the scheme based on self-organization realizes fully distributed control by simulating, extending and expanding collective intelligent behaviors of biological swarms. By using a bottom-up data-driven and modeling strategy, multiple simple individuals are formed into a large set, and the global intelligent behavior is realized through their aggregation and coordination. The research and development of unmanned swarms mainly focus on military applications. According to the famous OODA(Observe, Orient, Decide, Act) loop in the process of military operations [36], the cooperative control scheme based on self-organization is proposed as shown in Fig. 2 [37].

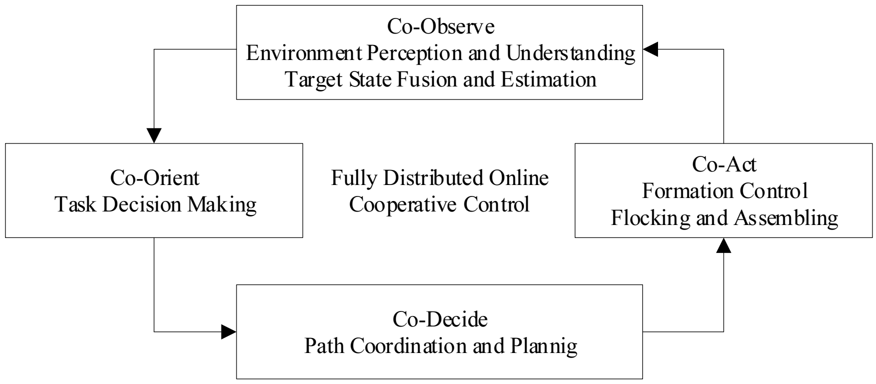

Fig. 2. Cooperative control scheme based on self-organization

The scheme mainly includes four functional units. 1) The Co-Observe unit is responsible for distributed cooperative environment perception and understanding, distributed target state fusion and estimation. 2) The Co-Orient unit is responsible for distributed cooperative task decision-making. 3) The Co-Decide unit is responsible for distributed path coordination and planning. 4) The Co-Act unit is responsible for formatting control, flocking and assembling, etc. Different from the hierarchical scheme, this scheme based on self-organization emphasizes the dynamic response of individuals to the environment and the rule-based behavior coordination among multiple individuals to achieve global intelligent behavior. Therefore, it has the advantages of simple calculation, good robustness and high flexibility, etc.

3.3 Description Model of Intelligence Characteristics of Unmanned Swarms

Drawing lessons from the description model of human intelligence and the cooperative control scheme based on self-organization, this paper presents a comprehensive description model of the intelligence characteristics of unmanned swarms, as shown in Fig. 3. There are various correlations between these intelligence characteristics. Although some intelligence characteristics have not yet been realized, they are not unexpected in the long run.

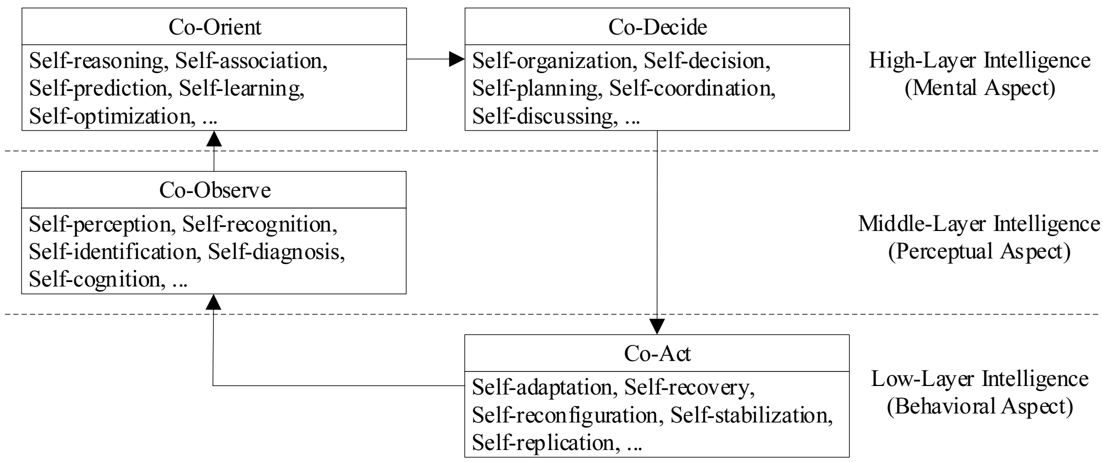

Fig. 3. Description model of the intelligence characteristics of unmanned swarms

High-layer Intelligence Characteristic. Some intelligence characteristics reflected in the thinking aspect can best reflect the intelligence of swarm systems. Therefore, they can be considered as high-layer intelligence characteristics. In biological swarms, these characteristics are mainly based on the simple calculation made by individual brain nervous systems and the information interaction between individuals. Refer to the Co-OODA loop, some specific characteristics and their general description in the Co-Observe unit and the Co-Orient unit are as shown in Table 2 and Table 3 respectively.

Table 2. Specific characteristics and their general descriptions in the Co-Orient unit

Specific characteristic	General description
Self-reasoning	Unmanned swarm can autonomously and collaboratively carry out knowledge reasoning including inductive, deductive and analogical reasoning, etc.
Self-association	Unmanned swarm can autonomously and collaboratively carry out associative thinking including close association, similar association and contrast association, etc.
Self-prediction	Unmanned swarm can autonomously and collaboratively predict the change of controlled objects and environmental conditions, such as motion direction, velocity and acceleration, etc.
Self-learning	Unmanned swarm can autonomously and collaboratively acquire knowledge to improve work efficiency and capability.
Self-optimization	Unmanned swarm can autonomously and collaboratively find the most satisfactory working mode or running state.

Table 3. Specific characteristics and their general descriptions in the Co-Decide unit

Specific characteristic	General description
Self-organization	Unmanned swarm can autonomously and collaboratively form the required system according to the task, objective requirements and environmental conditions.
Self-decision	Unmanned swarm can autonomously and collaboratively make decisions and generate control intention according to the purpose, task requirements and environmental conditions.
Self-planning	Unmanned swarm can autonomously and collaboratively formulate behavioral plans according to decision-making.
Self-regulation	Unmanned swarm can autonomously and collaboratively coordinate individual actions according to task requirements.
Self-discussing	Unmanned swarm can autonomously and collaboratively discuss problem-solving solutions.

Middle-layer Intelligence Characteristic. Some intelligence characteristics reflected in the perceptual aspect can better reflect the intelligence of swarms systems. Therefore, they can be considered as middle-layer intelligence characteristics. In biological swarms, these characteristics are mainly based on the external afferent sensory nervous system and various sensory organs. Refer to the Co-OODA loop, some specific characteristics and their general descriptions in the Co-Observe unit are as shown in Table 4.

Table 4. Specific characteristics and their general descriptions in the Co-Observe unit

Specific characteristic	General description
Self-perception	Unmanned swarm can autonomously and collaboratively perceive the natural information of internal states and external environments of the system.
Self-recognition	Unmanned swarm can autonomously and collaboratively recognize the natural information mode inputted by the system and extract the features.
Self-identification	In the presence of background noise or false target interference, unmanned swarm can autonomously and collaboratively identify the authenticity of the target, remove the false and retain the true, and track.
Self-diagnosis	Unmanned swarm can autonomously and collaboratively diagnose the internal fault, determine the cause and location of the faults.
Self-cognition	Unmanned swarm can autonomously and collaboratively perceive a variety of natural information for space-time integration from perceptual knowledge to rational understanding.

Low-layer Intelligence Characteristic. Although some intelligence characteristics reflected in the behavioral aspect can also reflect the intelligence of swarm systems to a certain extent, they can only reflect some marginalized intelligence. Therefore, they can be considered as low-layer intelligence characteristics. In biological swarms, these characteristics are mainly based on the individual peripheral nervous system and various effectors. Refer to the Co-OODA loop, some specific characteristics and their general descriptions in the Co-Act unit are as shown in Table 5.

Table 5. Specific characteristics and their general descriptions in the Co-Act unit

Specific characteristic	General description
Self-adaptation	Unmanned swarm can autonomously and collaboratively adapt to the changes of external environmental conditions and characteristics of controlled objects, adjust and correct, and maintain the optimal or normal state of the system.
Self-recovery	Unmanned swarm can autonomously and collaboratively eliminate faults from individuals and environment.
Self-reconfiguration	Unmanned swarm can autonomously and collaboratively construct new configurations according task and environment requirements.
Self-stabilization	Unmanned swarm can autonomously and collaboratively resist external environment disturbance.
Self-replication	Unmanned swarm can autonomously and collaboratively reproduce, replicate and generate individuals with similar or better function and structure.

4 Evaluation Model Based on Multi-layer Generalized Operators

It is not easy to evaluate the intelligence characteristics of unmanned swarms, so designing a special evaluation system can help us deal with the process more effectively. Considering the logical relations of various intelligence characteristics, practical inferences can be handled by using multi-layer generalized operator model.

4.1 Structure of Evaluation System

The evaluation process of the intelligence characteristics of unmanned swarms can be roughly divided into four steps including the description, test and evaluation. Such an evaluation system can be divided into three layers including the organization layer, coordination layer and test layer, as shown in Fig. 4. The organization layer directly connects with users and provides services to them. At the entrance, the user describes specific application scenarios and expected intelligence characteristics of the unmanned swarm under test correctly. At the exit, the evaluation system returns those verified intelligence characteristics to the users. In the coordination layer, the distributor allocates those expected intelligence characteristics into four aspects: Co-Observe, Co-Orient, Co-Decide and Co-Act, and the coordinator is responsible for the coordination tasks among the four aspects. The main responsibilities of the test layer are to determine the contents and methods of the test and return to the qualitative conclusion.

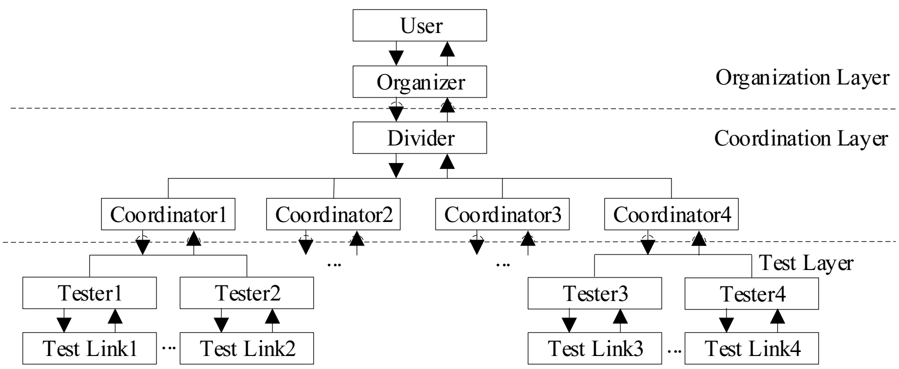

Fig. 4. Structure of evaluation system

4.2 Generalized Operator Model

The generalized operator model mainly describes the transformation function or transfer relations between input and output outside the system [38], as shown in Fig.5. Its most remarkable characteristic is that it can describe a system which only knows its external functional characteristics but not its internal structural state.

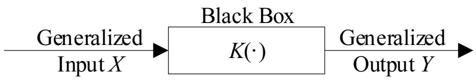

Fig. 5. Generalized operator model

The generalized operator model can be expressed as formula 1.

$$Y = K(\cdot)X. \quad \textbf{(1)}$$

In the above formula, $K(\cdot)$ represents a generalized operator, which can be either an intelligent operation of qualitative knowledge reasoning or a quantitative mathematical operation in the frequency domain or time domain. X and Y represent generalized input and output respectively, and they can be quantitative data, qualitative knowledge, static state, dynamic process, spatial pattern, time function, fuzzy concept, random variable, etc. The symbol "=" indicates that the generalized output Y is the result of the generalized input X being transformed and transferred by the generalized operator $K(\cdot)$, which can express the meanings of equality, implication, approximation, equivalence, similarity, etc.

4.3 Multi-layer Generalized Operator Model

The same system from different perspectives and granularity will get different conclusions. Multi-layer generalized operator model is composed of multiple generalized operator models and generalized relation operator models, which is suitable for large-scale systems. The evaluation process of the intelligence characteristics of unmanned swarms can be described by multi-layer generalized operator model as shown in Fig. 6.

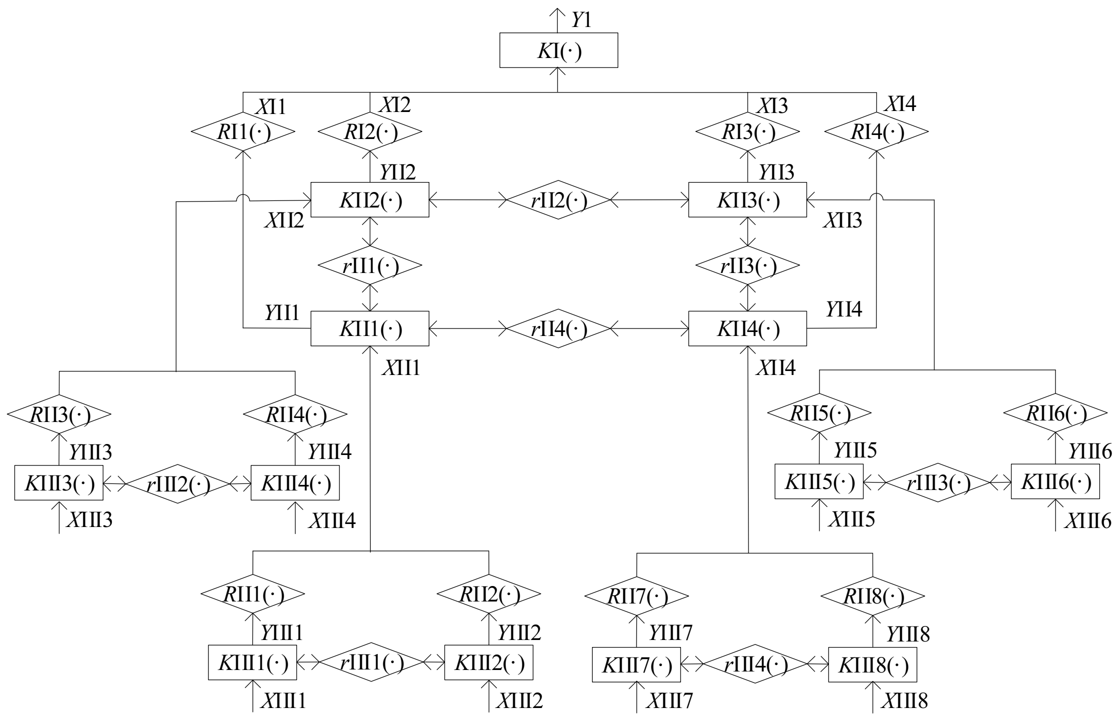

Fig. 6. Multi-layer generalized operator model

In the above model: (1) $K(\cdot)$ refers to the generalized operators with different granularities for evaluating the intelligence characteristics of unmanned swarms. $K\text{I}(\cdot)$ represents the coarse-grained generalized operator for qualitatively evaluating the intelligence in unmanned swarms, which corresponds to the organizer in the organization layer of the evaluation system. $K\text{II}i(\cdot)$ represents the medium-grained generalized operators for qualitatively evaluating the intelligence in the Co-Observe unit, Co-Orient unit, Co-Decide unit and Co-Act unit, which corresponds to the coordinators in the coordination layer of the evaluation system. $K\text{III}i(\cdot)$ refers to the fine-grained generalized operators for qualitatively evaluating specific intelligence characteristics such as self-organization, self-learning and self-adaptive, which corresponds to the testers in the test layer of the evaluation system. (2) $R(\cdot)$ represents the vertical relation operators between the generalized operators with different granularities. $R\text{I}i(\cdot)$ represents the vertical relation operators between $K\text{I}(\cdot)$ and $K\text{II}i(\cdot)$. $R\text{II}i(\cdot)$ represents $K\text{II}i(\cdot)$ and $K\text{III}i$. (3) $r(\cdot)$ represents the horizontal relation operators between the generalized operators with same granularity. $r\text{II}i(\cdot)$ represents the horizontal relation operators between $K\text{II}i(\cdot)$ and $K\text{II}j(\cdot)$. $r\text{III}i(\cdot)$ represents the relation operators between $K\text{III}i(\cdot)$ and $K\text{III}j(\cdot)$. (4) X and Y represent generalized input and generalized output represent the input and output of $Ki(\cdot)$ respectively. $X\text{II}i$ and $Y\text{II}j$ represent the input and output of $K\text{II}i(\cdot)$ respectively. $X\text{III}i$ and $Y\text{III}i$ represent the input and output of $K\text{III}i(\cdot)$ respectively. According to the evaluation model, we can deduce the horizontal relation model and the vertical relation model respectively.

(1) Vertical relation models:

$$X\text{I}i=R\text{I}i(\cdot)Y\text{II}i. \tag{2}$$

$$X\text{II}i=\{ R\text{II}j(\cdot)Y\text{III}j, R\text{II}k(\cdot)Y\text{III}k\}. \tag{3}$$

(2) Horizontal relation models:

$$X\text{II}\text{i}=r\text{II}j(\cdot)Y\text{II}j. \tag{4}$$

$$X\text{III}i=r\text{III}j(\cdot)Y\text{III}j. \tag{5}$$

5 Qualitative Evaluation of Self-learning Characteristic

Limited by application scenarios, system maturity, security problems, test cost and other aspects, it is difficult to implement multiple intelligence characteristics evaluation for a real unmanned swarm at this stage. According to the existing basic conditions, this paper mainly takes the test and evaluation of the self-learning characteristic of unmanned swarms based on simulation platform to verify the feasibility of the proposed scheme.

5.1 Mathematical Description of Self-learning Characteristic

Learning is an important characteristic of whether a UAV has intelligence [39]. Simon [40] argues that if a system can improve its performance by executing a process, it has the learning characteristic. This view focuses on traditional machine learning completed by a single agent. Unmanned swarm mainly adopts interactive learning among multiple agents and its mathematical description is as follows:

Let ε^t be the local environment or object state of an agent at time t, and ξ represents the sensor information input of the agent. τ represents the function that each agent can complete. The response of the unmanned swarm to ε^t is a cooperative control action U. U is composed of the constraint μ generated by the environment and the control functions achieving the performance standard υ of the control task of unmanned swarms. Then unmanned swarm behaviors can be expressed by the following formula [41].

$$\forall\ \varepsilon^t,\ \exists\,\gamma^t \in \tau, \text{enable } U \equiv \{\gamma^t\}, E(A) \Rightarrow \upsilon. \tag{6}$$

In the above formula, $\{\gamma^t\}$ represents swarm behavior oriented by the target at time t. A represents the unmanned swarm under test, and $E(A)$ represents the performance evaluation results of unmanned swarm A.

Self-learning characteristic of unmanned swarms aims at a given task, which needs continuous experience from the interaction between agents and environment or object, and these experiences are constantly updated. It can be described as follows.

$$\eta^t = \varepsilon^{t-1} \oplus \eta^{t-1}, \text{ results in } \eta^t | \Delta\eta^t \approx 0,\ E(A) = r. \quad \textbf{(7)}$$

In the above formula, η^t is the collective experience at time t, $\oplus$ is the computational update mechanism, and ε^{t-1} corresponds to the environment or object state perceived at time *t*-1.

Given unmanned swarm *A* composed of a group of agents that can perceive and change the environment or object ε^t and the desired control target, unmanned swarm *A* can gradually obtain the cooperative control action *U* on the basis of a series of changes of η^t through the cooperative learning mechanism $\oplus$. After action *U* is executed, the control target is adjusted to the expected value *υ* by unmanned swarm *A*.

5.2 Test Implementation Based on Simulation Platform

The evaluation objects of the intelligence characteristics of unmanned swarms include real systems and simulation systems. Compared with the evaluation based on real systems, the evaluation based on simulation systems has the advantages of faster speed, lower cost and no security risk, and it is more suitable for the evaluation of the learning characteristic. As shown in Fig. 7, we mainly take simulation UAV swarm *A* [42] designed by our lab based on ROS and Gazebo platform as the evaluation objects. Simulation swarm A performs area coverage tasks based on the Virtual Linkage (VL) cooperative formation method and avoids obstacles based on Deep Deterministic Policy Gradient (DDPG) reinforcement learning algorithm.

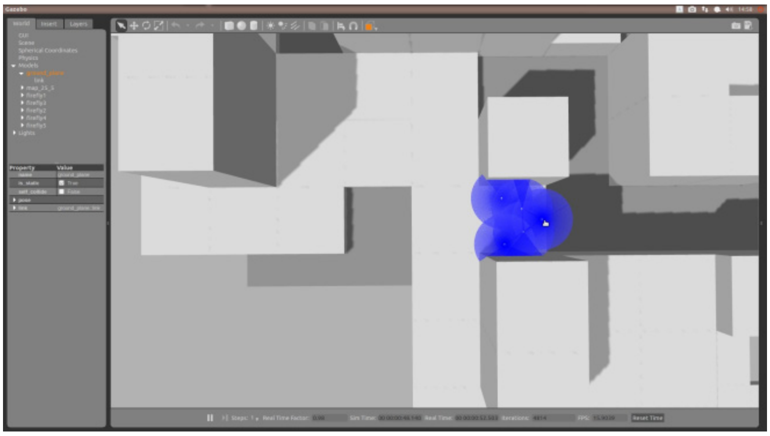

Fig. 7. Simulation UAV swarm A based on Gazebo

The first task of intelligence characteristics evaluation is to determine test content and test method, and then the test can be implemented, and the test results will be fed back to the upper layer of the evaluation system. The test project mainly includes test effect and test algorithm. The commonly used test methods are the white box method, black box method, grey box method, experience method and comprehensive test method. The test results are obtained by sharing method, manual test method, man-machine combination test method, automatic test method, simulation method and a mixture of the above methods. Aiming at self-learning characteristic of unmanned swarms, the main test method is the grey box method, and the test results are obtained by the simulation method.

Before testing, this paper assumes that simulation UAV swarm *A* have self-learning characteristic. Then two identical test tasks are designed for evaluating the self-learning characteristic of simulation UAV swarm *A*. The design of the test task requires learning to be completed successfully. During the two designed tests, UAV swarm *A* is given a certain learning time under the guidance of users. Then record the performance standard *E(A)* for simulation UAV swarm *A* to complete the task under the first test and the second test respectively. Here we mainly take the time *t1* and *t2* as *E(A)* to record performance under the two identical test scenarios. The test results show that UAV swarm *A* cannot complete the given task in the first test, that is, it would collide obstacles in a very short time, but can avoid obstacles and complete the task successfully after inserted learning. The qualitative evaluation conclusion is that the simulation UAV swarm *A* has the self-learning characteristic, the intelligence in the Co-Orient unit and the intelligence in unmanned swarm.

5.3 Evaluation Process Based on Multi-layer Generalized Operators

When and only when the self-learning characteristic is evaluated, the generalized output of the test layer is YIII4, the generalized input is XIII4={t1, t2}, KIII4(·) represents the generalized operator for qualitatively evaluating the self-learning characteristic, then YIII4=KIII4(·)XIII4. Although the self-learning characteristic of unmanned swarm not only reflects the improvement of performance, but also includes the growth of knowledge and ability. But from the final results, all of them can be expressed by a unified rule. In this paper, we initially define KIII4(·) as the qualitative evaluation rule of self-learning characteristic as follow.

If $t2 < t1$, then the unmanned swarm under test has self-learning characteristic;

Else the unmanned swarm under test has no self-learning characteristic.

End if

The rule can not only judge whether the unmanned swarm under test has self-learning characteristic in exactly identical scenarios, but also can judge whether the unmanned swarm under test has the self-learning characteristic from an incompetent scenario to a competent scenario. In the incompetent scenario, the value of $t2$ will be equivalent to positive infinity.

According to the multi-layer generalized operator model, KII2(·) represents the generalized operator for qualitatively evaluating the intelligence in the Co-Orient unit and KI(·) represents the generalized operator for qualitatively evaluating the intelligence in unmanned swarms. According vertical relation operators between different layers, the generalized outputs in the coordination layer and the organization layer are shown in formula 8 and formula 9 respectively.

$$Y\text{II}2=K\text{II}2(\cdot)\{\ R\text{II}3(\cdot)K\text{III}3(\cdot)X\text{III}3,\ R\text{II}4(\cdot)K\text{III}4(\cdot)X\text{III}4\}. \quad \textbf{(8)}$$

$$Y1=K\text{I}(\cdot)\{\ R\text{I}1(\cdot)Y\text{II}1,\ R\text{I}2(\cdot)Y\text{II}2,\ R\text{I}3(\cdot)Y\text{II}3,\ R\text{I}4(\cdot)Y\text{II}4\}. \quad \textbf{(9)}$$

In order to facilitate reasoning, various complex relationships between the intelligence characteristics in the same layer or between different layers are simplified. All the horizontal relation operators are temporarily ignored and all vertical relation operators are set as composition relations with the same weight. KI(·) and KIIi(·) are set as or operations. Then, YII2 and Y1 can be obtained easily.

6 Conclusion

This paper clarifies the concept of the intelligence characteristics of unmanned swarms, presents a comprehensive description model based on Co-OODA loop to organize and integrate various discrete intelligence characteristics of unmanned swarms from the aspect of engineering realization, and proposes an qualitative evaluation scheme based on multi-layer generalized operators to infer the presence of intelligence characteristics with different granularity. It is conducive for researchers and users to understand the intelligence of unmanned swarms more comprehensively and systematically, deepen the intellectualization research of unmanned swarms continuously, and judge the intelligence development levels of unmanned swarms more reasonably. Due to the limitations of the existing basic conditions, this paper temporarily ignores many subtle influencing factors and simplifies various complex relations between the intelligence characteristics in the same layer or between different layers. On the basis of the qualitative evaluation scheme proposed in this paper, researchers can further study the detailed logical relations between specific intelligence characteristics, implement the qualitative evaluation of one or a group of intelligence characteristics in some relatively mature unmanned swarms, set the intelligence level classification standards based on Co-OODA loop, pick some intelligent evaluation methods for evaluating the intelligence levels, and study scientific quantitative methods for evaluating the intelligence of unmanned swarms.

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