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New development thoughts on the bio-inspired intelligence based control for unmanned combat aerial vehicle

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Bio-inspired intelligence is in the spotlight in the field of international artificial intelligence, and unmanned combat aerial vehicle (UCAV) , owing to its potential to perform dangerous, repetitive tasks in remote and hazardous, is very promising for the technological leadership of the nation and essential for improving the security of society. On the basis of introduction of bio-inspired intelligence and UCAV, a series of new development thoughts on UCAV control are proposed, including artificial brain based high-level autonomous control for UCAV, swarm intelligence based cooperative control for multiple UCAVs, hybrid swarm intelligence and Bayesian network based situation assessment under complicated combating environments, bio-inspired hardware based high-level autonomous control for UCAV, and meta-heuristic intelligence based heterogeneous cooperative control for multiple UCAVs and unmanned combat ground vehicles (UCGVs). The exact realization of the proposed new development thoughts can enhance the effectiveness of combat, while provide a series of novel breakthroughs for the intelligence, integration and advancement of future UCAV systems.

bio-inspired intelligence, unmanned combat aerial vehicle (UCAV), artificial brain, autonomous control, bayesian network, bio-inspired hardware, heterogeneous cooperative control

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1 Introduction

One of the inevitable trends for the future information technology is intelligence, and the effective way to achieve intelligence is to simulate the various intelligent behaviors in nature. Many of the adaptive optimization phenomena in nature inspire us that many highly complex optimization problems can be perfectly solved with the self-evolution in organisms and ecological systems [1]. In recent years, some bio-inspired intelligent methods have emerged, which are definitely different from the classical mathematical programming principle. The typical BI methods include genetic algorithms (GAs), ant colony optimization (ACO), particle swarm optimization (PSO), artificial immune system (AIS), artificial bee colony (ABC), cultural evolution (CE), emotion computing (EC), and DNA computing. All the bio-inspired intelligent methods are trying to simulate the natural ecosystem mechanisms, which have greatly enriched the modern optimization techniques, and provided practical solutions for those complicated combinatorial optimization problems [2]. With the stealthy rise of bio-inspired intelligence era, which is characterized by the simulation of natural and biological mechanisms, a number of bio-inspired

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intelligence technologies have demonstrated strong vitality and potential for further development in solving the classic NP-C problems and practical applications.

Bio-inspired intelligence has the advantages of strong robustness, good distributed computing mechanism, and easy to combine with other methods. Although the rigorous theoretical analysis for most of the bio-inspired intelligent methods has not been conducted [3], and the current study in this field is still in the experimental and preliminary application stage, the bio-inspired intelligent methods have already found their applications in many typical fields. These methods can not only solve the one-dimensional static optimization problems, but also solve multi-dimensional dynamic optimization problems. There are also many breakthroughs in the hardware implementation of bio-inspired intelligent methods. All these make the bio-inspired intelligence show strong vitality and broad prospects for further development.

Unmanned combat aerial vehicle (UCAV) is a kind of unmanned combat aircraft, which is also a military equipment platform making full use of modern information technologies. Due to the ability to perform dangerous and repetitive tasks in remote and hazardous environments, UCAV is very promising for the technological leadership of one nation and essential for improving the security of the society. While recent technological advances have enabled the development of unmanned vehicular systems and recent implementations have proven the UCAV's benefits in both military and civilian applications, the full benefit of unmanned systems will be utilized when they can operate autonomously. Today, UCAVs can be used not only in communications, meteorology, disaster monitoring, agriculture, geology, transportation and many other civilian fields, but also has a wide application in intelligent monitoring and surveillance, artificial interference, bait, military communications, air defense suppression, fighter or cruise missile defense, air-to-air combat, and border patrols.

Each component in UCAV is a high-technologically complicated subsystem, and there is a strong dependence and coordination between the various components. Therefore, two prominent features of a typical UCAV are intensive high-technology and "system of systems". UCAV not only plays an active role in the civilian fields, but also can adapt to a long, large-depth combat, and even can act as the air combat weapon platform to support five-dimensional integration (land, sea, air, space, and electric) in future high-technological warfare. All these are due to that UCAV has the light weight, low-cost, zero-casualty, high mobility, and good adaptability. With the prominent role of the UCAV system in the future military combat, there are an increasing demand for various UCAV systems, and there are already many types of UCAV included in the "trump card" military equipment development programs in many developed and developing countries. Currently, many western countries have invested a lot in the development of advanced UCAV systems, and many UCAV research projects and technical validation reports have been launched. Air Force X-45A was jointly developed by the U.S. Defense Advanced Research Projects Agency (DARPA) and the Air Force, while Navy X-47A was jointly developed by DARPA and Navy.

On August 8, 2005, the United States (U.S.) Department of Defense (DoD) released of an "Unmanned Aircraft Systems Roadmap, 2005–2030", which offers a 213-page window into a major aspect of the U.S. military's evolution (Figure 1), and has received a great deal of coverage [4].

The purpose of this Roadmap is to stimulate the planning process for U.S. military unmanned aircraft system development over the period from 2005–2030. It was intended to assist DoD decision makers in developing a long-range strategy for unmanned aircraft system development and acquisition in future Quadrennial Defense Reviews (QDRs) and other planning efforts, as well as to guide industry in developing UA-related technology. Additionally, this document might help other U.S. government organizations leverage DoD investments in unmanned aircraft system technology to fulfill their needs and capabilities. On December 18, 2007, U.S. DoD released its new "Unmanned Systems Roadmap, 2007–2023" [5]. This was the first integrated report including unmanned aircraft systems, unmanned ground systems and unmanned maritime systems.

"Neuron" was an European UCAV demonstrator for the development, integration and validation of UCAV technologies and was not for military operational deployment. The main aim of the Neuron program was to sustain and develop European manufacturers' aeronautic and other technologies for next-generation combat aircraft and UCAVs. By summer 2005, a series of memorandums of understanding had been signed and industrial teaming arrangements been set up. By the end of 2005, the governments of France, Greece, Italy, Spain, Sweden and Switzerland had agreed to invest in the Neuron program. This began a 15-month feasibility phase. The French Defence Procurement Agency (DGA) awarded a contract for a 19-month project definition phase in June 2007. This was followed by production of a Neuron demonstrator with first flight in

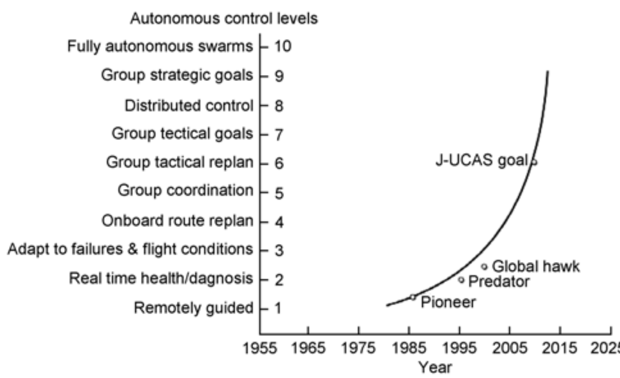

Figure 1 U.S. Unmanned Aircraft Systems Roadmap, 2005–2030 (edition 2005).

2011. Flight tests will begin in France followed by tests in Sweden then Italy. Russia is speeding up its investment in UCAV and R & D intensity, and trying to catch up with the United States in the high-altitude long-endurance strategic reconnaissance unmanned systems, multi-UCAVs, and the advanced rotary-wing unmanned aerial vehicles. Besides the military powers, many third world countries also engaged in the development of multi-UCAVs. However, there is a big gap in many technologies of UCAV between China and the western countries, and it is still relatively weak in the new ideas, new concepts, and new principles for the purpose of military applications.

Cooperative control is one of the key technologies for multi-UCAVs, which mainly includes formation flying and reconfiguration, situation assessment, task allocation, trajectory planning and re-planning, communication, and information fusion [6]. Western countries have achieved a leading position in control technology and exact implementation, while there are still a lot of research gaps in multi-UCAVs cooperative control technology, especially in application of bio-inspired technologies for multi-UCAVs cooperative control. Therefore, it is necessary for us to focus on this emerging and challenging interdisciplinary field.

Currently, the key issue for UCAV control is high-intelligent autonomous control, which is puzzling the country's military scientific personnel. The current chip's processing speed is not fast enough, and the highly adaptive software has not developed [7]. In general, the intelligent autonomous control of UCAV is a daunting project. Only with the breakthroughs in fault-tolerant technology, conduct intelligence and adaptive reasoning systems (e.g. neural networks), can the intelligence of UCAV become an exact reality.

Artificial brain, swarm intelligence, and bio-inspired hardware have provided feasible ways for the high degree of intelligence of UCAV, and heterogeneous cooperative control for multiple UCAVs and unmanned combat ground vehicles (UCGVs) is also an newly emerging research area.

The dynamic, self-organization, coordination, strong robustness and other characteristics emerged in the process of bio-inspired intelligence can meet the requirements of UCAV under complicated battlefield environments. This paper mainly focuses the series of new development thoughts on UCAV control, including artificial brain based high-level autonomous control for UCAV, swarm intelligence based cooperative control for multi-UCAVs, hybrid swarm intelligence and Bayesian network based situation assessment under complicated combating environments, bio-inspired hardware based high-level autonomous control for UCAV, and meta-heuristic intelligence based heterogeneous cooperative control for multiple UCAVs and UCGVs. The exact realization of the proposed new development thoughts can enhance the effectiveness of combat, while provide series novel breakthroughs for the intelligence, integration and advancement of future UCAV systems.

2 New development thoughts

The scheme of the new development thoughts on the bio-inspired intelligence based control for UCAV is given in Figure 2.

2.1 Artificial brain based high-level autonomous control for UCAV

The concept of artificial brain in the field of autonomous control mainly refers to the hardware development of artificial brain similar to a human brain, which has the ability of cognition [8]. The idea of evolution is adopted in artificial brain, which has a pre-memory capacity by continuing learning. The artificial brain is "cognitive", "thinking", "decisive", and can actively response to external environments accordingly. The information processing process of an artificial brain can be illustrated by Figure 3.

Combined with artificial intelligence and control theory, an artificial brain can reproduce the decision-making proc-

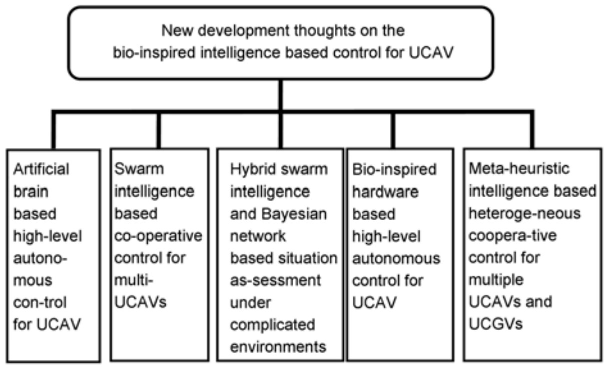

Figure 2 Scheme of the new development thoughts on the bio-inspired intelligence based control for UCAV.

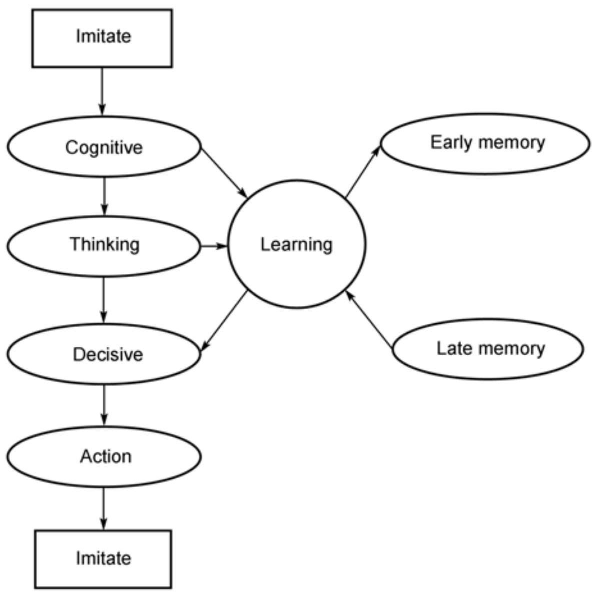

Figure 3 Information processing procedure of artificial brain.

ess of the real brain by using computer. Artificial brain based controller can enable UCAV to have higher intelligence. There are two implementation ways for the artificial brain: life-like modeling and social modeling. Artificial brain based controller has two major functions: control and learning. The former means the artificial brain based controller can control a variety of UCAV movements; the latter refers to learn the relevant specific knowledge from the outside environments. Of course, the artificial brain based controller must acquire some knowledge during the control of UCAV.

An artificial brain based UCAV adopts the theoretical aspects of artificial life and artificial tools in the controller implementation. The artificial tools mainly include "artificial brain", "artificial senses", "artificial organs", "artificial workers" and "artificial animals". The basic controller scheme of the artificial brain based UCAV can be illustrated by Figure 4.

(1) Artificial brain based intelligent controller: Computer software, hardware or light mechanical/electrical materials are adopted to develop a variety of simulated "natural brains" of the brain model, which can act as the key controller of future UCAV. As the artificial brain with high level intelligent thinking, the UCAV equipped with artificial brain based intelligent controller has strong autonomy.

(2) Artificial sense based feedback measuring device: Artificial senses is a novel type of sensors simulating human or animal sensing organs. Artificial sense based feedback measuring device is formed by a variety of intelligent sensors, which can make UCAV with the visual, auditory, and multi-sensory information integration, multi-mode data mining capabilities.

(3) Artificial organ based intelligent actuator: Artificial organ is a piece of equipment which can simulate the effects of human or animal organs, such as artificial arms, artificial legs, and artificial hearts. The UCAV equipped with the artificial organs can simulate control mechanism and regulation functions of the human body, hands and feet. In this way, the two-way regulation and coordinate control can be implemented.

2.2 Swarm intelligence based cooperative control for multi-UCAVs

Swarm intelligence derived from observation of a group of insects by some scientists. The IQ of the bees, ants and other insects is not high, and no one is commanded by others, but they are able to work together efficiently. They can build up a strong and beautiful nest, find food, and rear children. It is far beyond the individual's intelligence to rely on the capacity of a whole community. One major branch of swarm intelligence is evolutionary computation such as GAs, ACO, PSO, and ABC. If we apply the swarm intelligence to the future UCAV systems, the combating efficiency can be improved significantly, even the UCAVs are equipped with low performance sensors. However, this is unreachable for the general aircrafts. The general procedure of swarm intelligence is given in Figure 5 [1].

The main characteristics and advantages of swarm intelligence are as follows [1]:

(1) The cooperative individuals in each groups are distributed, and this makes the individuals are much easier to adapt the current working state;

(2) The robustness of the system can be guaranteed by the non-central control scheme, and the solution may not be affected by the failure of one individual or a certain number of individuals;

(3) The cooperation can be achieved by the indirect communication between individuals, which can guarantee the system with better scalability;

(4) As the communication overhead is still very small with the increase of individual number, and the capacity of each individual is very simple, the exact execution time for each individual is relatively short.

The above-mentioned advantages have made swarm intelligence one of the most important research directions in the field of intelligent information processing. Swarm intelligence can be applied to combinatorial optimization problems, knowledge discovery, communication networks, and robotics. The Pentagon is funding a project called "Swarm Strategy", which mainly involves the utilization of swarm intelligence to command and coordinate groups of UAVs and UGVs under complicated environments.

The future orientations of the swarm intelligence based cooperative control can be generalized as follows:

(1) Multi-UCAVs cooperative control based on distributed multi-agents;

(2) Multi-UCAVs cooperative path planning and replanning based on swarm intelligence;

(3) Multi-UCAVs cooperative formation control and reconfiguration based on swarm intelligence;

(4) Multi-UCAVs situation assessment and cooperative task assignment based on swarm intelligence;

(5) Multi-UCAVs cooperative target attacking based on

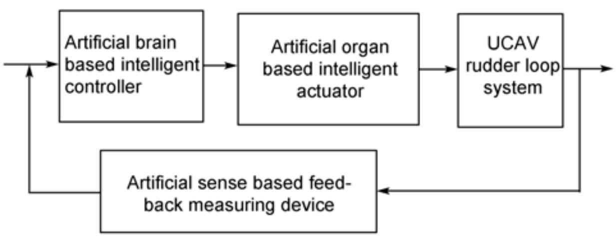

Figure 4 Basic controller scheme of the artificial brain based UCAV.

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Initialization
While (Does not satisfy the termination criteria) do
    Social collaboration;
    Self-adaptation;
    Competition
End
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Figure 5 General procedure of swarm intelligence.

swarm intelligence.

2.3 Hybrid swarm intelligence and Bayesian network based situation assessment under complicated combating environments

Due to the uncertainties of input data and knowledge for complicated combat situation assessment, it is necessary to make reasoning from the incomplete, uncertain and imprecise data. Therefore, how to represent and reason becomes one of the key issues in situation assessment under complicated combating environments.

Bayesian network is a knowledge representation tool that encodes probabilistic relationships among variables of interest. This representation has two components: (a) a graphical structure, or more precisely a directed acyclic graph, and (b) a set of parameters, which together specify a joint probability distribution over the random variables. Over the last decade, the Bayesian network has become an increasingly important area for research and application in the entire field of artificial intelligence. Bayesian network has now become a popular representation for encoding uncertain expert knowledge in expert systems [9]. More recently, researchers have developed methods for learning Bayesian networks from data. The techniques that have been developed are new and still evolving, but they have been shown to be remarkably effective for some data-analysis problems.

Bayesian network is an NP-hard problem, and swarm intelligence is a type of efficient methods for solving NP-hard problems. Therefore, Bayesian network can be integrated with swarm intelligence for solving the UCAV situation assessment problem under complicated combating environments.

All the intelligent individuals construct the network by using incremental construction solution. This process can be illustrated with Figure 6 [10]. Let G_0 denote the initial state, and G_h the current state with h arcs. The intelligent individual's incremental construction of the solution starts from the empty graph G_0 and proceeds by adding an arc $x_i \leftarrow x_j$ to the current state G_h, i.e., $G_{h+1} = G_h \cup \{x_i \leftarrow x_j\}$. The final solution will be the state G_h, in which the ant decides to stop the construction phase.

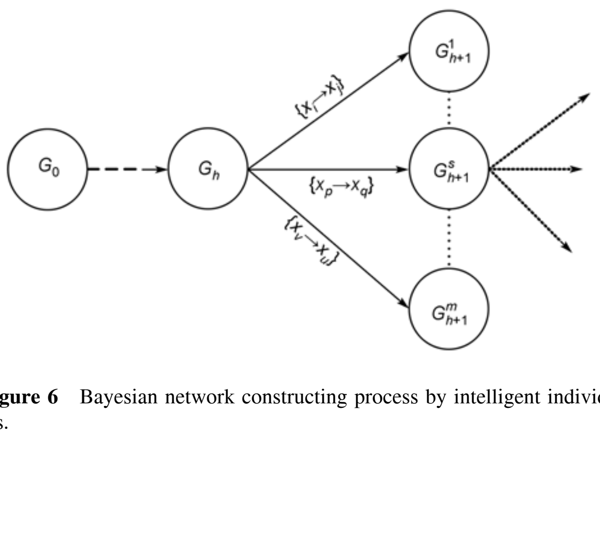

Figure 6 Bayesian network constructing process by intelligent individuals.

The above-mentioned procedure makes effective use of the heuristic information in the problem domain, and is very suitable to solve large-scale Bayesian network learning problems. This procedure can provide an effective approach for UCAV situation assessment under complicated combating environments.

2.4 Bio-inspired hardware based high-level autonomous control for UCAV

Bio-inspired hardware (BHW) is also named "evolvable hardware (EHW)" [3], which refers to hardware that can change its architecture and behavior dynamically and autonomously by interacting with its environment, and bio-inspired hardware has been proposed as a new method for designing systems for complex real-world applications. At present, almost all bio-inspired hardware uses an evolutionary algorithm (EA) as the main adaptive mechanism. In early 1960s, Neumann, the father of the computer, firstly proposed the great concept of developing a general-purpose machine [11], which has the capacity of self-reproduction and self-repairing. However, it was Garis who made the first move to investigate the design of evolving circuits. In his paper [12], Garis suggested the establishment of a new field of research called evolvable hardware (bio-inspired hardware).

In view of this emerging field it is expected to have a great impact on space exploration and defense applications, the National Aeronautics and Space Administration (NASA) and Department of Defense (DoD) of USA have shown great interest in this field [13]. The first NASA/DoD workshop on evolvable hardware was held in California on July 19–21, 1999, and the same workshops are held each year now. The aim of NASA/DoD is to develop a series of bio-inspired hardware for space shuttles, spacecrafts, space probes, satellites, strategic aircrafts, and nuclear submarines.

Each candidate circuit for UCAV can either be simulated or physically implemented in a reconfigurable device. Typical reconfigurable devices are field-programmable gate arrays (FPGA) (for digital designs) or field-programmable analog arrays (for analog designs). In its most fundamental form a bio-inspired algorithm manipulates a population of individuals where each individual describes how to construct a candidate circuit. Each circuit is assigned a fitness, which indicates how well a candidate circuit satisfies the design specification. The bio-inspired algorithm uses stochastic operators to evolve new circuit configurations from existing ones. Over time the evolutionary algorithm will evolve a circuit configuration that exhibits desirable behavior. This definition can also be illustrated with the following simple equation [14].

BHW = Bio-inspired Algorithms+ FPGA

The bio-inspired hardware based high-level autonomous control architecture for UCAV is illustrated in Figure 7 [15].

Generally, the bio-inspired hardware for UCAV consists of three main modules: population, generator and evaluation. The population module manages all communication between the queue and the generator module. At the end of the current iteration, the population module receives the best solution from the evaluation module, which is then inserted into the queue. The evaluation results of the solutions (from the solution module) are collected in a comparison block, which chooses the best solution of the current iteration. The advantages of this bio-inspired hardware include fast processing speed [16], self-repairing, self-organization and self-adaptation.

2.5 Meta-heuristic inspired heterogeneous cooperative control for multiple UCAVs and UCGVs

Meta-heuristic intelligence mainly refers to a class of general heuristic methods for solving a very general class of computational problems by combining user-given black-box procedures, usually heuristics themselves, in the hope of obtaining a more efficient or more robust procedure. These methods seldom rely on the optimization mechanism of the definite problems. Meta-heuristic intelligence has become one of the active interdisciplinary areas recently.

The use of multiple UCAVs in concert with UCGVs affords a number of synergies [17]. First, UCAVs with cameras and other sensors can obtain views of the environment that are complementary to views that can be obtained by cameras on UCGVs. Second, UCAVs can avoid obstacles while keeping UCGVs in their field of view, providing a global perspective and monitoring the positions of UCGVs while keeping track of the goal target. This is especially advantageous in two and a half dimensions where UCAVs can obtain global maps and the coordination of UCAVs and UCGVs can enable efficient solutions to the mapping problem. Third, if UCAVs can see the UCGVs and the UCGVs can see UCAVs, the resulting three-dimensional sensor network can be used to solve the simultaneous localization and mapping problem, while being robust against failures in sensors like global position system (GPS) or errors in dead reckoning. In addition to this, the use of UCAVs and UCGVs working in cooperation has received a lot of attention for defense applications because of the obvious tactical advantages in such military operations as scouting and reconnaissance.

Hettiarachchi and Spears demonstrated a novel use of a generalized Lennard-Jones (LJ) force law in Physicomimetics, combined with offline evolutionary learning, for the control of swarms of UGVs moving through obstacle fields towards a goal [18]. The work by Chaimowicz presented a hierarchical architecture in which a few UAVs were used to command, control and monitor swarms of UGVs [19]. The use of UAVs in concert with UGVs affords a number of synergies. A popular flocking control algorithm was applied to a heterogeneous swarm of robots by McCook, who was working at the United States Naval Academy [20]. The flocking controller contains separation, cohesion and velocity matching terms and has been shown to converge properly in the case of homogeneous swarms (Figure 8).

The dynamics, self-organization, distributed parallelism, cooperation and robustness embedded in the emergence of meta-heuristic intelligence have proven that meta-heuristic intelligence can be adopted in the heterogeneous cooperative control for multiple UCAVs and UCGVs. The future orientations in this issue can be generalized as follows:

(1) Meta-heuristic inspired heterogeneous flocking control for multiple UCAVs and UCGVs;

(2) Meta-heuristic inspired heterogeneous visual guidance for multiple UCAVs and UCGVs;

(3) Meta-heuristic inspired heterogeneous pursuit-evasion techniques for multiple UCAVs and UCGVs;

(4) Meta-heuristic inspired heterogeneous task link techniques for multiple UCAVs and UCGVs.

6 Concluding remarks

In recent years, bio-inspired intelligence technology has been developing with an amazingly rapid speed, and the

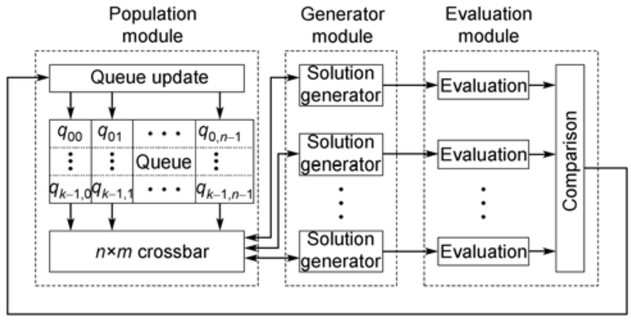

Figure 7 The bio-inspired hardware based high-level autonomous control architecture.

Figure 8 Artistic concept of real-life autonomous convoy operation with the heterogeneous UCAVs and UCGVs.

design and implementation of UCAV control have remained a fixed pattern. Today, when we are engaging in developing high-performance UCAV systems, we usually feel that the traditional design and implementation technologies can hardly meet the strict requirements of UCAV. At present, due to the inherent technical idea of the fetters, there are very few intelligence elements in the newly-developed UCAV.

This paper attempts to provide insightful sources for the researchers and scholars interested in UCAV technologies. We believe that the exact realization of the proposed new development thoughts can enhance the effectiveness of combat, which can definitely provide a series of novel breakthroughs for the intelligence, integration and advancement of future UCAV systems.

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