# A BCI-Based Motion Control System for Heterogeneous Robot Swarm

**Zhen Huo [1], Tao Deng[&,1], Zhiyan Dong[*,1,2], Lihua Zhang [1,2], Lan Niu[1]**

[1]Ji Hua Laboratory, Foshan 528200, China
[2]Academy for Engineering & Technology-AI and Robot Fudan University, Shanghai, China
[*]Corresponding author: Zhiyan Dong
[&]These authors contributed equally to this work and should be considered co-first authors.
huozhen@jihualab.ac.cn, dengtao@jihualab.ac.cn, dongzhiyan@fudan.edu.cn, lihuazhang@fudan.edu.cn, niulan@jihualab.ac.cn

**Abstract:** The study presents a method to construct a brain-computer interaction (BCI) motion control system that uses human brainwave signals to control the motion of different kinds of individuals in a heterogeneous robot swarm. Through establishing the BCI system based on Stable State Visual Evoked Potential (SSVEP), the virtual reality (VR) twin scene for monitoring the operating state and the external environment of robots and the heterogeneous robot swarm composed of unmanned drones and vehicles, the direct motion control of human brain wave signals on heterogeneous robot swarms is realized. The experimental results present that the subjects can apply the system to achieve motion control of a heterogeneous robot swarm in a simulated complex obstacle avoidance scenario with a 90% obstacle avoidance success rate. The system provides a new control method for traditional heterogeneous robot swarm motion systems, and also provides a new solution for how to deal with sophisticated and versatile application scenarios, which is significant for improving the system's perception capability, decision-making ability, and intelligence level.

**Keywords:** Brain-computer interface (BCI), Motion control, Heterogeneous robot swarm, Steady-State Visual Evoked Potential (SSVEP), Virtual reality (VR), Digital Twin

## 1 Introduction

Heterogeneous robot swarms are a research hotspot in the field of unmanned mobile platforms, which are widely adopted in search, exploration, rescue, pursuit, and other research fields. With the development of artificial intelligence technology and the advancement of sensor technology in recent years, the autonomous perception and decision-making capabilities of unmanned swarms have been greatly improved, and their applications have been extended to more complex scenarios, such as the fully autonomous micro-flying robot swarm proposed by Zhejiang University, which can realize the functions of swarm obstacle avoidance, formation, and tracking in the dense jungle environment in the wild [1].

However, limited by the control algorithm logic and sensor performance defects, the autonomous perception and decision-making capabilities of heterogeneous robot swarms cannot fully replace human thinking and judgment [2], and it is still difficult to meet the application requirements in more complex and variable environments. Although the traditional manual remote control function can realize the real-time correction of robots, it requires a high level of human operation, and the more types and numbers of robots and the more complicated the application environment, the higher the requirements for personnel, which is contrary to the research purpose of heterogeneous robot swarms. The current development of BCI technology has made it possible to control external devices through EEG signals [3-5]. Besides, operators can control a variety of robotic platforms simply through motor imagery or by receiving visual stimuli, without the need to master the relevant operational skills. In this way, the consciousness of the human brain can be incorporated into various robotic control systems and the operational stress of personnel can be reduced. Thus, it is meaningful to apply BCI technology to heterogeneous robot swarms to achieve direct control of robot swarms by the human brain, which improves the perceptual decision-making capability and intelligence of the system.

In particular, the BCI system in this work is constructed based on the SSVEP method, which has the characteristics of fast recognition speed and high recognition rate [6]. In contrast to other schemes that use SSVEP to achieve control of the human brain over external devices [7-9], this research allows subjects to receive stimulation from the stimulation module in the VR twin scene by wearing a VR head-mounted display (HMD) to improve immersion without interference from external factors, instead of using the commonly utilized 2D display screen as the stimulation source of EEG signals. In addition, to enable the subjects to better monitor the operation status of the heterogeneous robot swarm, a high-fidelity virtual scene with the same real environment as the heterogeneous robot swarm was constructed in the VR twin scene, and the digital twin for the moving process of the heterogeneous robot swarm was also realized. This allows the subject to make appropriate control decisions by observing the operation of each robot in real-time, thus eliminating the visual blindness and sight distance barriers associated with direct observation by the naked eye.

Based on the above, this article proposes a heterogeneous robot swarm motion control system based on BCI technology, which adds a new EEG signal control mode to the traditional control method, realizing direct motion control of the heterogeneous robot swarm by human brainwave signals, while reducing the operator's operation level requirements and operating stress. The experimental results indicate that the subjects achieved a high success rate in controlling the motion of the heterogeneous robot swarm in intricate obstacle avoidance scenarios, and verified the feasibility of relying on human brain consciousness to help the robots in the swarm to avoid dangers they cannot predict, which is essential for improving the intelligence level of the heterogeneous robot swarm and its ability to cope with complicated and changing environments.

## 2 Methods

### 2.1 System description

As shown in Figure 1, the system consists of a BCI system and a heterogeneous robot swarm system, which are connected wirelessly via UDP and TCP/IP protocols to achieve real-time interaction of data. The hardware part of the BCI system consists of a 128-channel EEG cap, VR HMD, and TDT electrophysiological workstation. The heterogeneous robot swarm system consists of an unmanned aircraft and an unmanned vehicle. As the controlled object, both of them can perform autonomous co-movement and also receive direct control by brain-controlled commands. During the movement, the position and attitude information obtained by the positional sensors can be transmitted back to the twin system in real-time as the source of the drive data of the twin system.

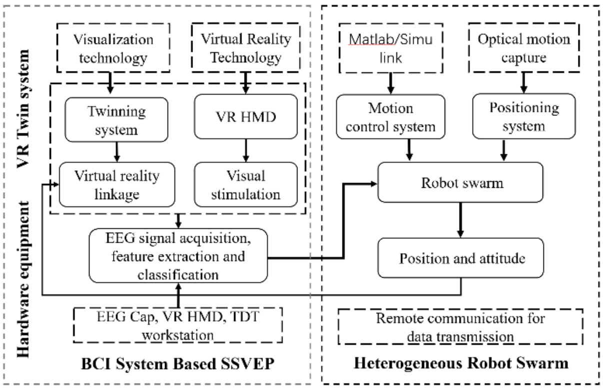



**Figure 1** System architecture

Figure 2 shows the operation process of the control system. The user wears a VR head-mounted display to observe the unmanned aircraft or unmanned vehicle in the VR twin scene and receives stimulation from the visual stimulation module to generate EEG signals, which are collected by the EEG cap and TDT physiological workstation. These EEG signals are classified and identified by relevant algorithms to generate brain-controlled motion commands, which are then sent to the heterogeneous robot swarm system, and the unmanned aircraft or unmanned vehicle makes corresponding action responses according to the kinds of brain-controlled commands received, while their motion results and states are fed back in the twin scenes in real- time to assist users in making the next control strategy. So far the complete process of a brain-controlled heterogeneous robot swarm is realized.

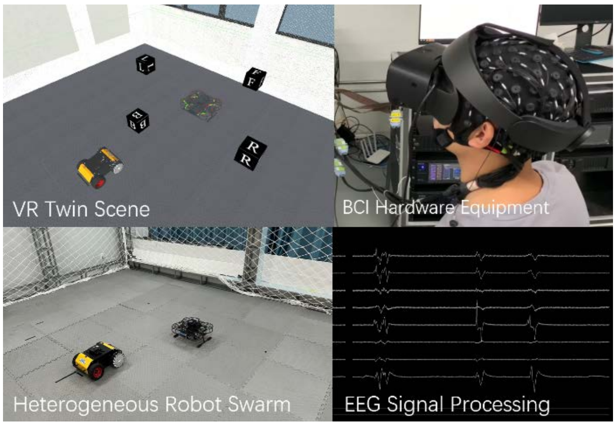



**Figure 2** System prototype demonstration

### 2.2 BCI system

#### 2.2.1 VR twin scene

The traditional visual stimulation scenes adopted in the SSVEP method are mostly two-dimensional image scenes, and the stimulation modules are usually marker patterns with different flicker frequencies. This stimulation method has the characteristics of a simple style and single function, but its open stimulation scene also increases the influence of external environmental factors on the subject. At the same time, testers often also need to visually observe the real-time state of the controlled object or with the help of video acquisition equipment, which has a certain impact on the testers' concentration and thus affects the stability of the EEG signal features and the recognition efficiency of the processing program.

Therefore, to solve this problem, we built a VR twin visual stimulation scene with a digital twin function based on Unity3D software, which is a virtual mapping of a heterogeneous robot swarm system. As shown in Figure 3, the scenario consists of virtual entities of robot, the external static environment, and the EEG signal visual stimulation module. We modeled the scene accurately based on the real test environment and the robot swarm entities, while the virtual entity can remotely receive the position pose information from the physical robot to update the position and pose in the twin scene in real-time. The EEG visual stimulation module consists of seven cubes, which are labeled as "F", "B", "L", "R ", "J", "C", and "Q", and they are flashed at the flashing frequency of 5Hz, 6Hz, 7Hz, 8Hz, 8.9Hz, 10Hz, 13.3Hz. The four cubes "F", "B", "L", and "R" around the drone stimulate the subject to generate corresponding "forward", "backward", "left", and "right" brain control commands. Each command will control the robot to move 1m in the specified direction. The "J", "C", and "Q" cubes stimulated the subjects to choose to control the unmanned aircraft, the unmanned vehicle, or the swarm of robots. By looking at these seven cubes as needed during the experiment, subjects could control any of the robots to reach any target location in the scene.

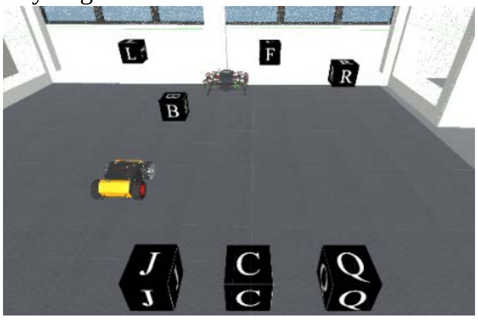



**Figure 3** VR twin Scene

### 2.2.2 Hardware equipment

The EEG cap and TDT electrophysiology workstation applied in this study have a hardware base of 128 channels, but in the actual test, we mainly use 8 channels related to visual stimulation for the experiment, which are O1, O2, PO3, PO4, PO7, PO8, POz, Oz. The EEG signal acquisition frequency is 305HZ, and the sampling period is 9s. During each sampling cycle, the visual stimulus module flickered for 5s, and the free 4s were adopted for the categorical transmission of EEG signals and the action response of the heterogeneous robot swarm while giving the experimenter sufficient rest time to maintain a better test state.

As for the classification processing method of EEG signals, this exploration adopts the canonical correlation analysis (CCA) algorithm, which is often utilized in EEG signal processing, with good robustness, high accuracy, and low arithmetic power requirements [10]. The classification process of the EEG signal and the invocation of the CCA algorithm is implemented by the Matlab program, and the processing flow is shown in Figure 4. The raw EEG signals collected by the EEG hat are pre-processed such as amplification and filtering and then input to the CCA algorithm. Then the CCA algorithm performs feature extraction and classification on the input signals and calculates the correlation coefficient between the input signals and the reference signal corresponding to each visual stimulus frequency to derive the final identified target frequency, and finally sends the control command corresponding to the frequency to the heterogeneous robot swarm system.

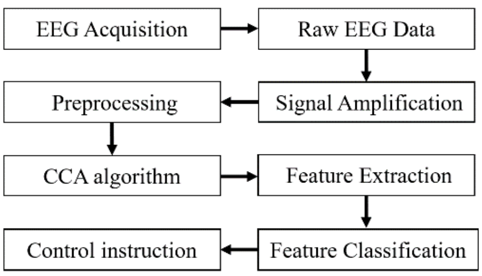



**Figure 4** EEG signal processing flow

## 2.3 Heterogeneous robot swarm system

The heterogeneous robot swarm system consists of one quadrotor unmanned aircraft and one quad-wheeled unmanned vehicle. The unmanned aircraft and the unmanned vehicle are built based on hardware such as Raspberry Pi and have stable and reliable motion performance. The integrated positioning system can monitor the position and attitude data of the aircraft or vehicle in real-time. The positioning accuracy can reach 0.1mm and the update frequency can reach 250Hz, which is an important hardware foundation for the digital twin function of the system.

**Figure 5** Heterogeneous robot swarm system

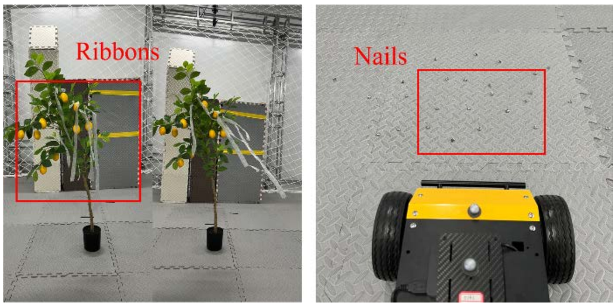
The motion control system of the swarm system mainly consists of the master program running on the Raspberry Pi ground station and the sub-control programs running on the robots, both of which are built by the Simulink module and run in each robot platform after code compilation and deployment. The master program is responsible for the status monitoring, data interaction, and instruction issuance for the whole system, and the sub-control program is responsible for the hardware response execution of the unmanned aircraft or vehicle. This motion control system can realize automatic control, manual control, and EEG signal control for the robot swarm in single mode or swarm mode. In the automatic control mode, the unmanned vehicle can follow the movement of the unmanned aircraft, while in the EEG control mode, the unmanned aircraft or the unmanned vehicle can receive EEG control signals and make corresponding action responses.

# 3 Experimental background and results

## 3.1 Experimental background

To verify the feasibility of guiding the heterogeneous robot swarm to avoid hazards through EEG signals under complicated conditions, the following experimental conditions were assumed in this study: in the process of movement, the heterogeneous robot swarm encounters an obstacle that cannot be monitored by its sensors, in this case, the subjects control the heterogeneous robot swarm to perform evasive motion through EEG signals to avoid colliding with the obstacle. In this study, we simulated such a scenario in a laboratory environment by placing obstacles in the test site and requiring the subjects to control the movement of the heterogeneous robot swarm to avoid obstacles and reach the specified location according to the specified route.

We set up two kinds of obstacles, one is a transparent ribbon obstacle for unmanned aircraft and the other is a scattered nail obstacle for unmanned cars. In Figure 6(a), some transparent ribbons are hung on the tree branches. They are stationary under windless conditions. When the UAV approaches, these ribbons float due to the wind generated by the paddles, which can easily get entangled in the paddles and damage the unmanned aircraft. In Figure 6(b), some nails were randomly placed on the ground, which made it impossible for unmanned vehicles with pneumatic tires to pass. Both of these obstacles are not easily detected by the robot's sensors, so in this case, we want to use the perceptual capabilities and control awareness of the human brain to guide the robots to avoid danger.

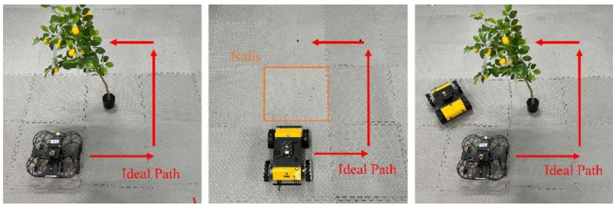



**(a)** **(b)**

**Figure 6 (a)** transparent ribbon obstacle **(b)** scattered nail obstacle

Figure 7 shows that the experiment is divided into three parts in total. The first part is the obstacle avoidance control experiment of the unmanned aircraft, in which the subject needs to control the unmanned aircraft to avoid obstacles and move to the specified position. The stimulus frequencies and corresponding control commands applied in the experiment are shown in Table- **I**. At the beginning of the experiment, subjects were first stimulated by stimulus module "J" to correctly select the unmanned aircraft control mode, and then stimulated by four stimulus modules "F", "B", "L", and "R" to control the movement of the unmanned aircraft. In the second part of the experiment, the subjects were required to control the unmanned vehicle to avoid obstacles and move to the designated position. Similarly, the subject first receives stimulus module "C" to correctly select the control mode of the unmanned vehicle, and then further controls the movement of the unmanned vehicle. In the third part of the experiment, a robot swarm was controlled to avoid obstacles. The subject first receives the stimulus module "Q" to correctly select the swarm control mode, and then further controls their movement. In this part of the experiment, the subject only needs to control the movement of the unmanned aircraft, and the unmanned vehicle will automatically follow the movement of the unmanned aircraft.

In each experiment, if the robot arrives at the specified location without colliding with the obstacle and the number of controls does not exceed 15, we consider the obstacle avoidance guidance to be successful. Otherwise, it is considered a failure, and the experiment will be aborted if any one of the conditions occurs




**(a)** **(b)** **(c)**

**Figure 7 (a)** aircraft experiment **(b)** vehicle experiment**(c)** swarm experiment

**Table I** Stimulation frequency and instruction description

| Stimulation Module | Blinking frequency/Hz | Control commands |
|---|---|---|
| F | 5 | Move forward 1m |
| B | 6 | Move backward 1m |
| L | 7 | Move to the left 1m |
| R | 8 | Move to the right 1m |
| J | 8.9 | Control unmanned aircraft |
| C | 10 | Control unmanned vehicle |
| Q | 13.3 | Control swarm |

## 3.2 Experimental results

In this research, 10 healthy volunteers with normal vision were selected to participate in the experiment. Each volunteer performed three parts of the experiment in turn, and each part of the experiment was conducted three times. In each experiment, the volunteers first performed a round of recognition tests for each brain-controlled command and then performed a robot obstacle avoidance test. To avoid the effect of visual fatigue on the experimental results, the volunteers were given a 3-minute rest period after each experiment. The accuracy rate of brain-controlled commands and the success rate of obstacle avoidance were recorded for each experiment, as shown in Table **II-IV.**

**Table II** Experimental results of the unmanned aircraft

| Subjects | Accuracy | | | Success |
|---|---|---|---|---|
| | 1 | 2 | 3 | rate |
| 1 | 10/11 | 11/11 | 11/12 | 3/3 |
| 2 | 12/13 | 11/12 | 13/13 | 3/3 |
| 3 | 11/12 | 11/13 | 13/14 | 3/3 |
| 4 | 12/14 | 13/15 | 9/11 | 2/3 |
| 5 | 11/11 | 13/13 | 12/13 | 3/3 |
| 6 | 12/13 | 10/11 | 12/12 | 3/3 |
| 7 | 14/15 | 14/14 | 12/12 | 3/3 |
| 8 | 11/13 | 10/13 | 10/14 | 2/3 |
| 9 | 11/11 | 12/13 | 12/14 | 2/3 |
| 10 | 12/12 | 11/12 | 11/11 | 3/3 |
| Mean | 0.931 | 0.915 | 0.916 | 0.900 |

**Table III** Experimental results of the unmanned vehicle

| Subjects | Accuracy | | | Success |
|---|---|---|---|---|
| | 1 | 2 | 3 | rate |
| 1 | 11/12 | 13/13 | 12/13 | 3/3 |
| 2 | 13/15 | 9/11 | 12/14 | 3/3 |
| 3 | 10/11 | 12/12 | 12/13 | 3/3 |
| 4 | 10/13 | 10/14 | 11/13 | 3/3 |
| 5 | 11/12 | 11/11 | 12/12 | 3/3 |
| 6 | 10/12 | 10/14 | 11/15 | 1/3 |
| 7 | 11/11 | 13/14 | 10/11 | 3/3 |
| 8 | 13/14 | 15/15 | 12/12 | 3/3 |
| 9 | 14/15 | 11/13 | 12/13 | 3/3 |
| 10 | 14/14 | 13/14 | 11/12 | 3/3 |
| Mean | 0.907 | 0.895 | 0.903 | 0.933 |

**Table IV** Experimental results of the robot swarm

| Subjects | Accuracy | | | Success |
|---|---|---|---|---|
| | 1 | 2 | 3 | rate |
| 1 | 12/13 | 10/12 | 13/14 | 2/3 |
| 2 | 10/11 | 13/13 | 11/12 | 3/3 |
| 3 | 14/14 | 12/13 | 14/15 | 3/3 |
| 4 | 10/12 | 11/13 | 11/14 | 2/3 |
| 5 | 11/11 | 11/12 | 10/11 | 3/3 |
| 6 | 9/12 | 12/14 | 13/15 | 1/3 |
| 7 | 11/13 | 13/14 | 11/12 | 3/3 |
| 8 | 13/13 | 12/13 | 11/11 | 3/3 |
| 9 | 14/14 | 12/12 | 14/15 | 3/3 |
| 10 | 12/13 | 12/14 | 11/11 | 3/3 |
| Mean | 0.918 | 0.908 | 0.919 | 0.867 |

The BCI system designed in this paper has a high level of recognition of EEG signals with a rate of over 90%. The statistical results of the accuracy rate demonstrates that the results are universal, which indicates that the system is universally applicable to different individuals, and the user does not need a lot of training and individual matching to use the system and control the robot movement. The high recognition rate ensures the success rate of obstacle avoidance targets. The process of obstacle avoidance guidance for the robot swarm is shown in Figure 8. Although some subjects sent wrong EEG signals, which led to the collision of the robot with the obstacle and the failure of the experiment, the majority of the subjects successfully guided the robot to complete the obstacle avoidance target with a success rate of 90%, thus verifying the feasibility of controlling and guiding a heterogeneous robot swarm by EEG signals under intricate conditions. Overall, the system achieves the design goals.

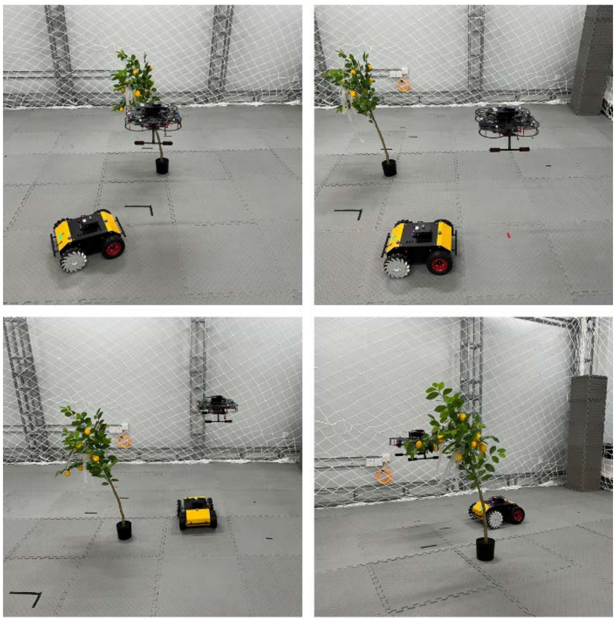


**Figure 8** Obstacle avoidance guidance of robot swarm

## 4 Discussion

The purpose of this research is to demonstrate that the motion control of a heterogeneous robot swarm system can be achieved through human brain consciousness, thus improving the system's perception capability, decision-making ability, and intelligence level. From the experimental results, by wearing VR HMD devices, users can observe the operation status of a heterogeneous robot swarm in twin scenes in real-time, and control the motion of robots in the groups through EEG signals to guide each robot to avoid hazards, which makes up for the deficiencies of the robot's algorithm level and sensor performance, and improves the system's ability to cope with complicated and changing environments.

Furthermore, controlling robot motion through human brain consciousness makes up for the lack of robot autonomy while also reducing the system's requirement for personnel operation level, fundamentally freeing human hands. The construction of a VR twin environment, while improving the immersion of manipulators, also provides a new way for manipulators to monitor heterogeneous robot group systems, alleviating the disadvantage of manipulators' naked-eye observation and eliminating visual blindness and distance barriers to a certain extent. The VR twin system proposed in this work is built based on 3D software, which can map static scenes better, but relies on high-performance sensors for dynamic targets. Nonetheless, from the complexity of the real environment, it is not feasible to rely on software and sensors alone, so using an all-around camera system and VR technology to construct a high-fidelity twin environment is one feasible research direction in the future.

The EEG signal recognition rate of this system reached over 90%, and the success rate of obstacle avoidance guidance also reached 90%, which is a result that can be called excellent. On the other hand, the EEG command output rate of the present system is low. This is mainly due to the long EEG acquisition time and the 4-s rest period reserved for the subjects to reduce the test injury. While the recognition rate of the EEG recognition algorithm we use is quite fast, just a few tens of milliseconds. Therefore, there is still much room for improvement in the output rate of brain-controlled commands. In the future, we can improve the accuracy rate and output rate by improving the EEG signal classification algorithm and optimizing the BCI operation process.

Finally, due to the experimental site conditions and robot sensor level limitations, this paper only investigates the brain-controlled robot scheme in a single obstacle avoidance scenario. In the real environment, the dynamic environment faced by robots is often more complex. However, this study lays the foundation for research on how to adopt human brain consciousness to improve the robot's autonomous perception and decision-making capabilities under sophisticated and variable conditions. In the future, we will further improve the depth and practicality of the application of human brain consciousness in heterogeneous robot swarms from the actual needs of robots.

## 5 Conclusions

In this study, a heterogeneous robot swarm motion control system based on BCI technology is constructed to realize the motion control of a heterogeneous robot swarm through human brain consciousness, which liberates human hands. Besides, the construction of a VR twin scene improves the immersion of the traditional SSVEP stimulation paradigm while lowering the pressure on personnel to monitor the operation process of the complex robotic swarm system. The experimental results note that the system can realize the motion control of heterogeneous robot swarms in complex obstacle avoidance scenarios by EEG signals, and the success rate of obstacle avoidance reaches 90%, which verifies the feasibility of using human brain consciousness to help the robots in the swarms to avoid dangers that they cannot predict themselves, and has certain practical application significance. Overall, the system provides a new control method for the traditional heterogeneous robot swarm motion system and also provides a new solution for how to deal with intricate and changing application scenarios, which is of great significance for improving the system's perception capability, decision-making ability, and intelligence level.

## Acknowledgements

This work is supported by Guang Dong Basic and Applied Basic Research Foundation (No. 2019A1515110352).

## References

[1] Chao Xu, Fei Gao, Xin Zhou et al. Swarm of micro flying robots in the wild. Science Robotics. 2022:7-66.

[2] Duan Haibin, Qiu Huaxin, Chen Lin et al. Prospects on unmanned aerial vehicle autonomous swarm technology. Science & Technology Review, 2018,36(21): 90-98.

[3] A. Nourmohammadi, M. Jafari, T. O. Zander. A Survey on Unmanned Aerial Vehicle Remote Control Using Brain-Computer Interface. IEEE Transactions on Human-Machine Systems, 2018, 48(4):337-348.

[4] C. Vishal, M. Vikas, M. Vikas et al. Brain-Bot: An Unmanned Ground Vehicle (UGV) Using Raspberry Pi and Brain Computer Interface (BCI) Technology. Advances in Computing and Data Sciences. 2017

[5] M. Prasath, R. Naveen, G. Sivaraj et al. Mind-Controlled Unmanned Aerial Vehicle (UAV) Using Brain-Computer Interface (BCI). Unmanned Aerial Vehicles for Internet of Things (IoT).2021.

[6] Zhang Yangsong, Xu Peng, Cheng Kaiwen et al. Multivariate synchronization index for frequency recognition of SSVEP-based brain-computer interface. Journal of Neuroscience Methods, 2014, 221:32-40.

[7] A. Chiuzbaian, J. Jakobsen and S. Puthusserypady. Mind Controlled Drone: An Innovative Multiclass SSVEP based Brain Computer Interface. 2019 7th International Winter Conference on Brain-Computer Interface (BCI). 2019.

[8] C. J. Perera, I. Naotunna, C. Sadaruwan et al. SSVEP based BMI for a meal assistance robot. 2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC).2016.

[9] K. S. Mistry, P. Pelayo, D. G. Anil et al. An SSVEP based brain computer interface system to control electric wheelchairs. 2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC). 2018.

[10] Lin Ke, Gao Shangkai, Gao Xiaorong. Boosting the information transfer rate of an SSVEP-BCI system using maximal-phase-locking value and minimal-distance spatial filter banks. Tsinghua Science and Technology, 2019, 24(3):262-270.