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Enhancing USV Navigation through Adaptive Obstacle Avoidance and Improved Q-Learning Path Planning

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Abstract: To achieve adaptive navigation for Unmanned Surface Vehicles (USVs) in specific environments, a model for automatic obstacle avoidance path planning based on an enhanced Q-Learning algorithm has been developed. This model accounts for the unique maneuvering characteristics of USVs, intensive learning processes, and spatial environmental factors. Enhancements to the Q-Learning algorithm include modifications to the Q-value update method, optimization of the reward path configuration during the USV's avoidance path planning, and overall improvements in algorithm learning efficiency. The action selection is tailored to the operational characteristics of USVs, and path optimization is conducted based on the USV's operational cycle. A simulation environment was created using the MATLAB GUI platform to test the model. Results from these simulations indicate that the USV, employing this intensive learning approach, can effectively plan superior obstacle avoidance routes that align with the vehicle's motion characteristics and successfully navigate around multiple obstacles.

Keywords:USV; obstacle avoidance; cycle motion characteristics; Reinforcement learning.

1. Introduction

In the 21st century, the ocean has gradually become a battlefield for all countries' comprehensive strength, and the research of unmanned boats has become a hot spot in the development of international science and technology. Western countries have begun research on surface unmanned boats earlier. The United States, Israel and other countries have made many research results in this field. The unmanned boats developed not only apply to the military, but also to civilian development. In recent years, China has carried out some research in the field of unmanned boats and achieved some results. However, in terms of key technology research and development, there is still a large gap with developed western countries. Automatic obstacle avoidance, as the core problem of unmanned boat research, represents the level of intelligence of unmanned boat to a certain extent.

Many scholars (Wu Bo, 2014, YAN Ru-jian, et al.,2010. CACCIA et al.,2008, Gao X., et al.,2011,Lee and Kim, 2016, Pehlivanoglu, 2012.) in the world have conducted in-depth research on the problem of automatic obstacle avoidance paths. For example, Chen Chao et al. (2013) proposed a heuristic search based on viewable A * algorithm to overcome the poor flexibility of traditional viewable methods and improve planning efficiency. Zhuang Jiayuan et al. (2011) proposed the Dijkstra algorithm for distance optimization based on electronic charts to improve the planning accuracy and reduce the memory occupation and operation time. The genetic algorithm proposed by J. Holland (1973) encodes chromosomes for individuals. It is controlled through several processes of selection, crossover, and random mutation. Setting fitness functions is more helpful to find the global optimal solution. Fan Yunsheng et al. (2017) proposed an improved genetic algorithm to generate an initial population for path search through random fast search to improve the

convergence efficiency and speed of path planning. Tan Baocheng et al. (2012) used the Euclidean distance between two points as an evaluation function in the A * algorithm. The forward search and backward search were performed alternately to reduce the path planning time. Chen Zhuo et al. (2019) proposed an unmanned boat path planning algorithm based on an evolutionary potential field model. A potential field path evaluation equation and a differential evolution algorithm were introduced into the potential field model, and a smoothing algorithm was used to optimize the potential field path twice. Zhang Chuang (2016) proposed a two-dimensional particle swarm trajectory planning algorithm based on fuzzy logic, which combined SVM models to simulate different environmental models.

This paper uses the Q-learning reinforcement learning method to solve the problem of obstacle avoidance path planning. This algorithm is an adaptive learning algorithm based on prior knowledge. It has been widely studied and applied in industrial development and expanded to the field of artificial intelligence, which can effectively Improved the intelligent decision-making level of industrial machinery and equipment.

2. Unmanned Swing Model

2.1. Unmanned Boat Plane Coordinate System

For the study of obstacle avoidance path of unmanned boat, only the motion model in the plane coordinate system of three degrees of freedom, that is, longitudinal, lateral and swaying, is needed.

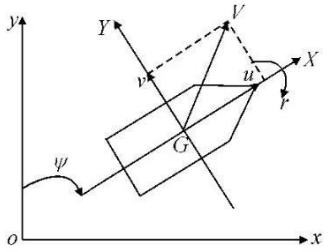


Figure 1. Three-degree-of-freedom plane coordinate system

The coordinate system of the ship's plane motion is shown in Figure 1. Among them, *xoy* represents the inertial coordinate system, *o* is the origin of the coordinates. The specified axis *x* points to the north direction and the axis *y* points to the east direction. The coordinate system *XGY* is the appendage coordinate system. The absolute motion of the ship and its surrounding fluid and the interaction force between the fluid and the hull are studied. The axis *X* points to the bow direction and the axis *Y* points to the starboard side of the ship. The center of gravity of the ship is represented by *G* , the origin of the attached coordinate system. The moving speed of a ship *V* is that the component on the *Y* axis is decomposed in the attached coordinate system, *v* is the ship's traverse speed, and the speed of axial direction *X* is the ship's forward speed *u* Indicates the angular velocity *r* and the heading angle.

2.2. Analysis of Cycle Motion Characteristics

The force of the ship when studying the obstacle avoidance path of the unmanned boat is analyzed by using the MMG model. Unlike the motion trajectory of a car, the direction of movement of the ship cannot be turned directly at 90 degrees, so it will produce a loop, that is, the arc trajectory of the ship under the action of the car and the rudder. The MMG model (Lu Mengmeng et al, 2016) decomposes the force of an unmanned boat into one-way forces acting on the hull, propeller, and rudder. This model is more versatile in a clear physical sense. According to the nature of force generation, the fluid forces and moments on the unmanned boat can be divided into inertial and viscous fluid forces and moments.

According to the simulation of the MMG model, it can be obtained that the trajectory of the fixed-speed rotation of the ship at different rudder angles in still water is approximately circular, as shown in Figure 2.

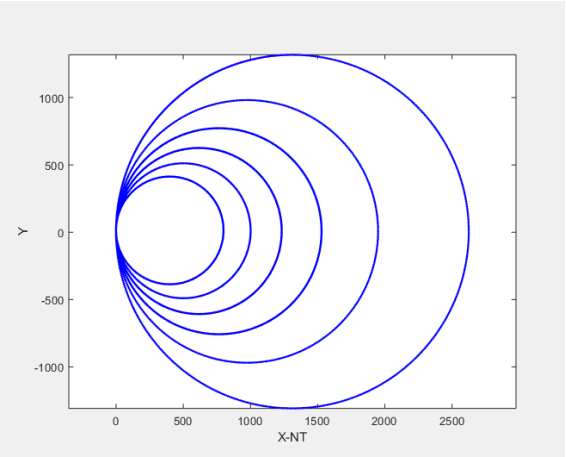


Figure 2. The trajectory of the MMG model cycle

3. Reinforcement Learning Principles and Models

3.1. Markov Decision

Most reinforcement learning algorithms can be performed within the framework of a Markov decision process. Markov's (Yan Zheping et al., 2018 and Kober, 2013) state transition processis a tuple S, P, A, R, y , which is the state set S , the state transition probability matrix P , the action set A , the return function R and the discountfactor y.

$$P_{ss'} = P[S_{t+1} = s' \mid S_t = s] = P[S_t = s, A_t = a]$$

Assume that there are n states. Then the state transition probability set can be defined by amatrix as:

$$P = \begin{bmatrix} P_{11} \cdots P_{1n} \\ \vdots \quad\quad \vdots \\ P_{n1} \cdots P_{nn} \end{bmatrix}$$

The goal of reinforcement learning is to give a Markov decision process to find the optimal strategy π* so that it can maximizes the cumulative return expectation under this decision, thatis:

$$\pi^* = \arg\max q_\pi(a, s)$$

3.2. Improved Q-learning Algorithm

The Q-learning algorithm (Li Guangchuang et al., 2019) is applied to reinforcement learning problem solving without the need for an environmental state transformation model. It is not amodel-based reinforcement learning problem solving method. For its control problem solving, it combines dynamic programming and Monte Carlo method for value iteration, that is, updating the strategy by updating the value function, generating new states and instant rewards through the strategy, and then updating the value function. Continuing until the valuefunction and strategy converge.

At this time, the selected action will not be executed, but will only participate in the update of the value function. In the whole algorithm, the values in the Q-table are constantly updated, and continuously updated until the end point is reached. Then based on the updated value to determine what action to take in a certain state is best. When solving the obstacle avoidance path of the unmanned boat, every Q-table update is a process of finding the optimal action, so as to obtain the control of the unmanned boat.

It can be known from the update formula of Q-table that the update of the value Q is based on the judgment error back for learning passed between the real value and the predicted value. Inorder to improve the update efficiency, an update method *Sarsa*(*lambda*) is introduced. Refer to Chen

Shenglei et al., 2008, the updated formula for the improved Q value is:

$$\delta = R + \gamma * Q(S', A') - Q(S, A)$$
$$E(S, A) = E(S, A) + 1$$
$$Q(s, a) = Q(s, a) + \alpha * \delta * E(s, a)$$
$$E(s, a) = r * lambda * E(s, a)$$

When *lambda* =0, the method is the Sarsa strategy algorithm. The strength of all step updates remains the same as the largest. E means a matrix similar to Q-table's structure, initialize E to 0 matrix. When agent takes action A and transfers from state S to S' then E(S,A) change from 0 to 1. When *lambda* □(0,1) , it means the update strength of all steps are different, the larger lambda is the larger update intensity is. Lambda can be understood as the decay value coefficient of the step, that is, the action closer to the end point is more important. When it is larger, the algorithm converges faster, but the optimization capability is insufficient. When it is smaller, it improves the obstacle avoidance path optimization capability but the convergence speed decreases.

4. Environment Model Simulation

In this paper, deep reinforcement learning technology is applied to obstacle avoidance path planning for unmanned boats. First, the unmanned boat space environment must be modeled. Based on the MATLAB GUI platform, a two-dimensional simulation environment is constructed, and the environment model is designed as a 40 × 40 two-dimensional map. In the two- dimensional coordinate system, the unmanned boat is regarded as a particle, and each pair of integer coordinate points corresponds to a state of the unmanned boat. Each state can be mapped by an element in the environmental state set S. In the simulation environment model, each state coordinate has a mark, which is 1 or 0, respectively. 0 represents the navigable area, which is displayed as a white area in the environment model; 1 represents the obstacle area, and is displayed as a black area in the environment model.

In the experimental simulation of the specific ship type and navigation environment, the working space was modeled by the cell decomposition method (Su Jintao, 2015), and a large enough sea area including the starting point and the end point of the unmanned boat was divided into rectangular units of equal area. In the working space of the boat, the full rudder rotation diameter at the rated speed is selected as the side length of the unit rectangle divided by the two-dimensional map according to the unmanned boat's maneuvering motion characteristics. Obstacles are inflated. The size of the inflated area can be determined according to the safety area of the ship and the division of rectangular units, so that the unmanned boat can meet real-time requirements and safety requirements during operation. This article simulates the starting ship, the end point, and various irregular obstacles that may be encountered during the voyage in the environmental model. The starting point and the end point are particle-sized, and the obstacles are treated as inflated. The location information of these obstacles is unknown. See Figure 3 for details of the MATLAB GUI simulation environment model.

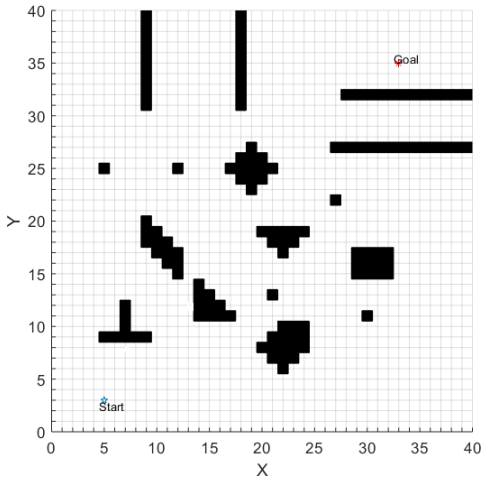


Figure 3. Environmental space simulation

5. Trajectory Optimization of Obstacle Avoidance Path

The movement process of the unmanned boat is a continuous state change process, and the obstacle avoidance path planning algorithm of reinforcement learning discretizes the continuous process in steps. The discrete point trajectory map is calculated and the discrete points are connected. Polyline trajectory diagram, such as the line segment OBDE shown in Figure 4. In the above, the action selection direction is selected at 45-degree intervals, so the corners of the obtained path trajectory are 90 degrees or 145 degrees. According to the maneuvering characteristics of the ship, the unmanned boat's motion trajectory should be a smooth curve, and the obstacle avoidance path trajectory should be optimized according to the ship's cycle motion trajectory map based on the MMG model in Chapter 2.2.

The optimized route is shown as arc OACE in Figure 4(). When the unmanned boat is sailing in the OBC section, a certain rudder angle (δ) is output at point A, which is the length of the half of the rectangular unit in front of point B. Under the action of the rudder, the unmanned boat determines the radius of the half-rectangular unit Speed rotation. It can be seen from the simulation diagram that the unmanned boat turns the trajectory arc AC under the control of the rudder angle δ at point A, and quickly returns to the rudder at the position of point C. When the unmanned boat is sailing in the CDE section, it also starts to make feasible turning trajectory that meets the limited parameters at the long position C of the half of the rectangular unit before reaching point D. The second steering at the anti-rudder angle makes the unmanned boat sail along the plan The line arc CE reaches the rudder at point E. At this time, the radius of the turning circle is (1/tan22.5∘) side lengths of rectangular units.

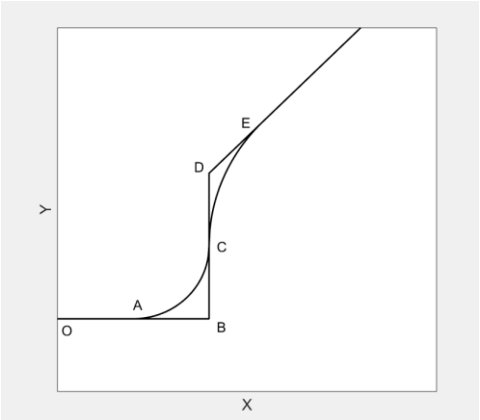


Figure 4. Schematic diagram of route trajectory optimization

6. Experimental Simulation Results and Analysis

Some model parameter settings in the experiment: learning rate alpha = 0.3; discount factor gamma = 0.95; lambda = 0.5; exploration rate epsilon = 0.5; set the maximum number of trials trials = 5000; maximum iterations per attempt (maxiter) = 2000; convergence target (convgoal) The standard deviation of the number of steps to reach the end point is taken as 0.25; the step deviation of the convergence process is calculated according to the number of iterations (avgtrials) is 10; the initial position of the unmanned boat (6, 4) and the end point (33, 35) are set. Once the unmanned boat collides with an obstacle during the experimental iteration process, it will return to the previous step and re-select the action according to the action selection strategy.

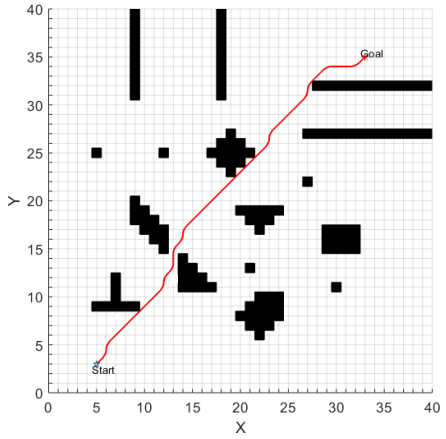


Figure 5. Unmanned obstacle avoidance path

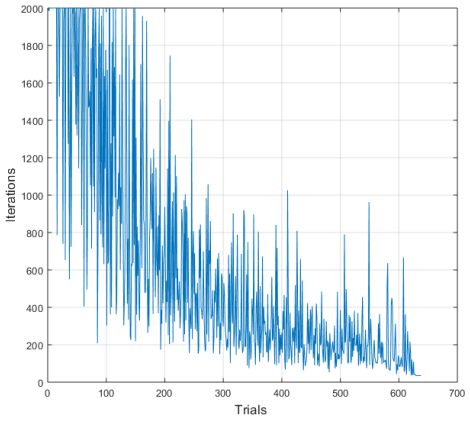


Figure 6. Number of trial and error search iterations

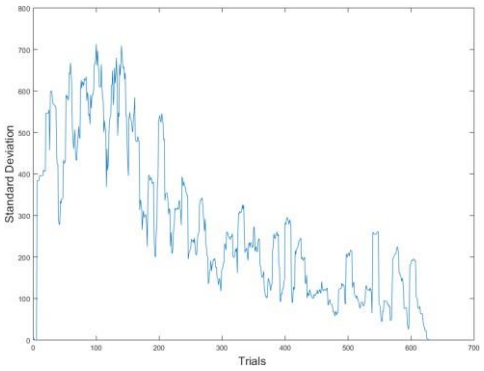


Figure 7. Convergence target change

The results of the obstacle avoidance path planning of the unmanned boat are shown in Figure. 5. After learning the reinforcement learning model, the unmanned boat successfully avoided each obstacle and reached the end point. The number of steps of the unmanned boat was 35, which was close to Optimal.

In combination with Figure 6 and Figure 7, in the initial iteration, the unmanned boat can not judge the safe area and obstacle area in the simulation environment, so that it often gets into trouble. At the same time, the search path is random, and it is often unable to find within the specified iteration number After the effective path is obtained, the value of the objective function changes greatly. After 150 iterations, the system gradually plans an effective path. During the process, the collision obstacles still occur many times and the number of planned path steps fluctuates greatly. The overall value of the objective function shows a downward trend; After 400 to 600 iterations, the collision phenomenon gradually eases and the number of planned path steps fluctuates. The objective function is still decreasing, but it has not reachedthe set requirements. Until 600 iterations, the probability of random search is gradually approaching the minimum. After the 638th iteration, the requirements of the objective function were reached, and the reinforcement learning system planned the obstacle avoidance path thatfinally reached the end point.

7. Conclusions and Prospects

The obstacle avoidance path planning model given by this article can comprehensively describe and solve the problem of obstacle avoidance path planning for specific environments. Simulation was performed on the MATLAB GUI platform. In the early stage of interaction with the environment, the unmanned boat knew too little about the state of the environment, and there were collisions and large steps in path planning. As the number of iterations increases, the unmanned boat system accumulates learning experience, gradually adapts to the environment, and finally successfully plans the path and reaches the end. However, to really apply reinforcement learning to unmanned boats, the reinforcement learning algorithm still needs a lot of improvements. Although the improved algorithm has accelerated the calculation efficiency, its convergence speed is still slow, the number of iterations is large, and it takes a lot of time. In the actual voyage, the ship's behavior has complex continuity, and this article is simply divided into 8 Action, this is also the future direction of the unmanned boat reinforcement learning algorithm needs detailed research to improve.

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