Design and Implementation of Digital Twin System for Underwater Equipment

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Abstract. Due to the particularity, complexity and impalpability of the underwater equipment's working environment, in order to realize real-time monitoring and analysis of the underwater equipment movement status and accurately describe the movement characteristics, this paper introduces the underwater equipment digital twin system developed based on Unity3D and reinforcement learning technology. The system is used to simulate the underwater vehicle operation in dynamic and complex environmental scenarios. The results show realistic simulation, good user experience, multi-perspective and real-time.

Keywords: digital twinning, path planning, environmental awareness, DQN algorithm.

1 Introduction

Digital Twin has received high attention in the current academic and industrial circles due to its low-cost trial error and intelligent decision-making characteristics. At present, many world-famous enterprises regard digital twin as a new direction of digital business development and enterprise expansion. In 2002, Michael Grieves, a professor at the University of Michigan, proposed the ideal state of product life cycle management - "Build a virtual entity and subsystem in virtual space representing the physical device; and the connection is not one-way and static, but throughout the life cycle of the product." This is the first time that the digital twin concept has been mentioned by scientists. The original design idea of digital twin was to create an identical twin for the real-world objects, with a more comprehensive understanding of the organisms of the real world. In 2010, the US National Aeronautics and Space Administration (NASA) pioneered the application of digital twin technology to the development of its space mission, which is used for flight test simulation before launch of aircraft and real-time mirroring, potential risk diagnosis, simulation, and decision-making of parameter changes during formal flight of aircraft. NASA gives the definition of digital

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twin: digital twin refers to the process of integrating multidisciplinary and multiscale simulation by making full use of data such as physical models, sensors, operation history, as a mirror image of the physical entity in the virtual space, reflecting the full life cycle process of the corresponding physical entity.

In recent years, with the rapid development of cloud computing, Internet of Things, artificial intelligence and big data technology, digital twin technology has been applied to manufacturing, energy exploration and development, medical care, and other aspects. Gartnerc, the world's most authoritative IT research and consulting company, has ranked digital twin as one of the top ten strategic technology development trends for four consecutive years (2016-2019). As the application fields become more diverse, many new ideas and differences about the definition of digital twinning, the conceptual model and reference framework of digital twin technology have become a hot topic at home and abroad, for the role and function of digital twinning, the industry has reached a consensus, for example, a digital twin is a visual virtual reality created digitally, using historical data, real-time data, and algorithmic models. Simate, verify, predict, and optimize the whole life cycle process of actual twin objects. The core significance of the digital twin is to improve the production efficiency of the actual twin objects, help enterprises to achieve digital transformation, Integration, and optimization of its entire value chain, etc.

2 Research status

In 2016, ANSYS proposed creating digital twins to use ANSYSY Twin Builder and can quickly connect to the industrial Internet of Things platform, to assist users in troubleshooting, Determine the ideal maintenance plan, Reduce the costs due to unplanned downtime, Optimize the performance for each asset, and generate effective data to improve its next generation of products; Parametric Technology uses digital twin as a key link of smart connected products, dedicated to building a real-time connection between the virtual world and the real world, Record and track every movement and behavior of a smart product, and extends to the innovative design of the next generation of products, to realize the predictive maintenance of intelligent products, these services provide customers with efficient product after-sales service [1]. In 2018, German Siemens used the digital twin to help industry 4.0, the complete digital twin application model was published, realized the actual landing of the digital twin; Dassault has built a three-dimensional experimental platform using digital twin technology, interactively integrating the user feedback information knowledge base with the twin model, Continuous innovation, and iteration of physical products [2]. In 2021, Farsi [3] et al. proposed a new digital twin architecture, The architecture uses adaptive data structures and ontologies, automatically generate cost models from data information mined in the product lifecycle, The ability to estimate lifecycle costs at early stages, Improve the efficiency of product development. In 2021, St. Petersburg National Marine Technical University, Novikov [4] et al., proposed preliminary estimation methods for the creation of the parameters and structures of the products based on the digital twin, to identify the key challenge in the process is to jointly optimize the features and objects of all modules.

In digital twin model establishment and standard establishment, represented by Beijing university of aeronautics and astronautics Tao Fei[5] digital twin research team put forward the digital twin five-dimensional model, from physical entities, virtual entity, said services, said twin data and the connection between the components of five dimensions of digital twin modeling, and the organization structure and application criteria of the five-dimensional model, put forward the six application criteria of digital twin driven. In 2019, Tao Fei within the UN digital twin related standard technical committee and application enterprises (including machine tools, satellite, engine and construction machinery and equipment industry) jointly established a set of digital twin standard architecture, and from the digital twin basic common standard, key technical standards, tools / platform standard, evaluation standards and industry application standard six levels has carried on the elaboration.

In terms of complex product manufacturing, The University of Cheng Ying [6] of Bei hang University and others established the basic framework for data-driven intelligent services in 2017. In 2019, Wuhan University of Science and Technology Xiang Feng [7] et al. proposed a new green manufacturing model of product life cycle, aiming to achieve the goals of small environmental impact, high resource utilization rate and maximum comprehensive benefits in the process of product life cycle manufacturing. In 2021, Hu Xiu-kun [8] and others of the Institute of Mechanical Manufacturing Technology of the Chinese Academy of Engineering Physics studied the operation mechanism of the digital twin assembly workshop.

In terms of equipment fault diagnosis and state evaluation, in 2021, China university of mining engineering college Yang Jun Feng [9] through Unity3D physical entity and virtual model of real-way real-time interaction, build digital twin model, using OPCUA protocol implements the physical entity, virtual simulation and service module between the data integration and fusion, completed the visual monitoring of equipment status and fault diagnosis.

3 Build a digital twin platform

The system is developed based on Unity3D to construct the sensing sensor model, the three-dimensional solid model of underwater equipment, the map environment model, the kinematics, and dynamics model of underwater equipment, etc. Since Unity3D development platform can identify 3ds and obj files, underwater equipment models can use 3Dmax for 3D physical model production. Unity3D built-in powerful terrain editor, can support all kinds of terrain creation and vegetation patch, facilitate environmental simulation, RAW map can directly generate 3D terrain; and has a rich library, various Marine creatures are very convenient; support automatic terrain LOD to build preset underwater scenarios for special requirements.

The system receives external sensor data, control instructions and communication with the Matlab algorithm module can be realized by using the network API (HLAPI) packaged in Unity and TCP / IP protocol-based Socket communication technology, its main function is to realize the network state management, including host, client, the server creation, state synchronization, remote process call and Internet service. There are two kinds of RPC technologies in Unity: client call server method (Command); server calls client method (ClientRPC) to realize the data transmission between dynamic simulation and visual simulation, use dynamic simulation results to drive the synchronous motion of underwater equipment and visual simulation, and show various real-time actions of underwater equipment through the simulation model in the system interaction interface. Through the viewpoint switching and data display, the motion state can be intuitively analyzed from different angles.

The underwater equipment kinematics and dynamic model establishment and simulation can be realized by Matlab, using its powerful data processing and convenient data visualization function, the data results intuitive image display processing, through the digital twin system, can be more intuitive image of the whole process of underwater equipment and real-time state, facilitate the underwater equipment movement performance and control algorithm for deeper analysis.

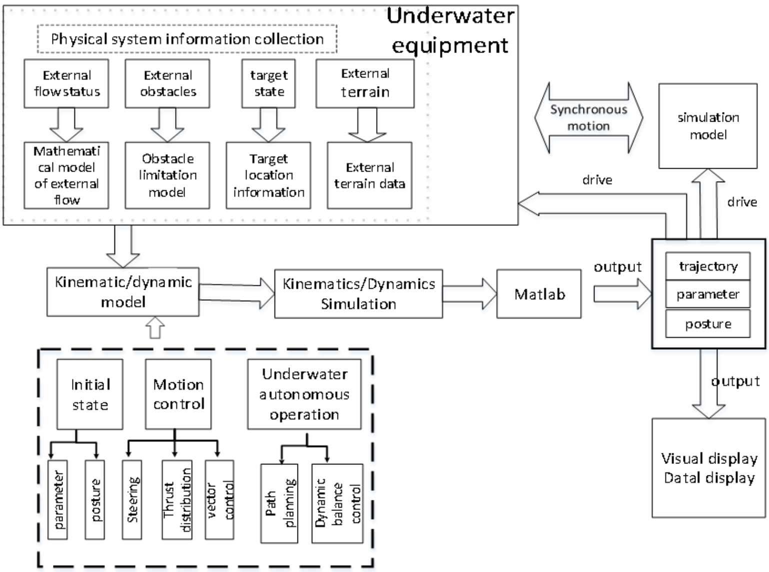

Fig. 1. Working principle of the digital twin system

4 Path planning based on the DQN algorithm of fully connected neural networks

We adopt the DQN technique in the path planning of the underwater equipment, and the DQN adopts the dual network, where one network produces the current Q value, and the other network generates the estimate of Q [10].

(1) The structure of the neural network is shown in Fig.2. The network structure consists of two fully connected layer neural networks. Fc1 takes the leakyReLU func-

tion as the activation function, and the number of nodes is the lattice number of the grid graph, which represents the number of states in the state space. Fc2 has four nodes corresponding to four action spaces, up and down, not using the activation function.

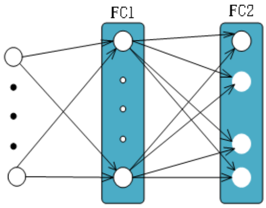

Fig. 2. A fully connected neural network used for the DQN

(2) The reason for using LeakyReLU is that although the common sigmod function is smooth, there are gradient explosion or gradient disappearance problems, which leads to the problem of network parameters update is not obvious after many iterations. Function is defined as follows:

$$f(x) = \begin{cases} x, & \text{if } x \geq 0 \\ \alpha x, & \text{if } x < 0 \end{cases} \tag{1}$$

It is easy to derive its derivative, but when x equals 0, we set the derivative value to 1, which can be expressed as:

$$f'(x) = \begin{cases} 1, & \text{if } x \geq 0 \\ \alpha, & \text{if } x < 0 \end{cases} \tag{2}$$

(3) The loss function adopts the mean variance function (Mean Squared Error, MSE), such as formula (3), where y represents the output of the neural network, t represents the supervised data, K is the data dimension, and the loss function calculates the formula such as formula (4)

$$\mathrm{E} = \frac{1}{2}\sum_{i=1}^{K}(y_i - t_i)^2 \tag{3}$$

$$E = \frac{1}{2N}\sum_{j=1}^{N}\sum_{i=1}^{K}(y_{ij} - t_{ij})^2 \tag{4}$$

(4) The optimizer adopts Adam. Compared with the traditional SGD (stochastic gradient descent), Adam has small oscillation, fast convergence and good real-time performance. Adam mimics RMSProp by preserving the exponential decay average v_t of the past gradient square, while borrowing from Momentum holding the exponential decay average m_t of the past gradient, with the gradient g_t of the loss function against the weights in Eq. The calculation formula is shown in the formula (5).

$$m_t = \beta_1 m_{t-1} + (1-\beta_1) g_t$$
$$\upsilon_t = \beta_2 \upsilon_{t-1} + (1-\beta_2) g_t^2 \tag{5}$$

m_t And v_t are initialized as zero vector,to prevent bias towards zero at decay rate hours, actual deviation corrected moment estimates such as formula (6).

$$\overline{m_t} = \frac{m_t}{1-\beta_1^t}$$
$$\overline{v_t} = \frac{v_t}{1-\beta_2^t} \tag{6}$$

After the moment estimation is obtained, the network parameter can be updated, θ as the network parameter, α as the learning rate, and ε (recommended as 10^{-8}) as the smoothing factor introduced to prevent the zero-removal problem (7):

$$\theta_{t+1} \sim \theta_t - \frac{\alpha}{\sqrt{\overline{v_t}} + \varepsilon} \overline{m_t} \tag{7}$$

(5) Because the activation function of ReLU series was used, we adopted the normal distribution recommended by KaimingHe et al. with mean and standard deviations like formula (8), where the negative half axis coefficient of the LeakyReLU function α is the input data dimension of this layer n_l and the network parameter θ_l.

$$\theta_l \sim \mathrm{N}\left(0, \sqrt{\frac{2}{(1+\alpha^2)\ n_l}}\right) \tag{8}$$

After the neural grid training in the form of a five-component empirical data storage pool (s,α,r,s',G), the path planning algorithm of the fully connected neural network is finally obtained.

5 Underwater equipment simulation experiment

The system takes the underwater back transformation vehicle as the experimental model and conducts the underwater autonomous path finding and the effect based on DQN obstacle avoidance algorithm test experiment.

First, on the Unity3D development platform, when the dynamic addition of underwater simulation environment and obstacles is completed, the return vehicle model made by 3Dmax is added to Unity3D, adding the corresponding collision detection attributes, route planning of DQN obstacle avoidance algorithm through Matlab simulation software, generating motion curve and various motion parameters, driving the model in the twin system through the generated data, and the generated data can be recorded and stored in running state data in the database, with online or offline data analysis function through the data management module. We implemented the DQN algorithm using python combined with TensorFlow and NumPy based on the fully connected neural network. We used the grid map dynamically collected by the navigator as the input of each local planning, so that the navigator is close to the target coordinates when considering the dynamic obstacle avoidance. Each algorithm takes the results of one thousand runs and is compared with algorithms such as traditional A * and artificial potential fields. The success rate (obstacle avoidance), the probability of successfully reaching the target point, and the average running time are shown in the following table:

Table 1. Performance indicators of various path planning

method	Path planning success rate, (%)	Reach target point probability (%)
A* algorithm	44.2	100
Artificial potential field method	78.3	86.2
The method of this paper	86.7	89.4

Through analysis and comparison, the A * algorithm can reach the target point, but the obstacle avoidance success rate is only about 44%, which is difficult to accept in complex environment; the probability reaches 80%, but the operation of the algorithm, although the average running time and navigation efficiency reach an acceptable level. Through this digital twin system, the motion characteristics of the vehicle and the motion state parameters of the vehicle can be observed synchronously, thus realizing the visual analysis of the motion state of the simulation model, to continuously improve the design and development of underwater equipment.

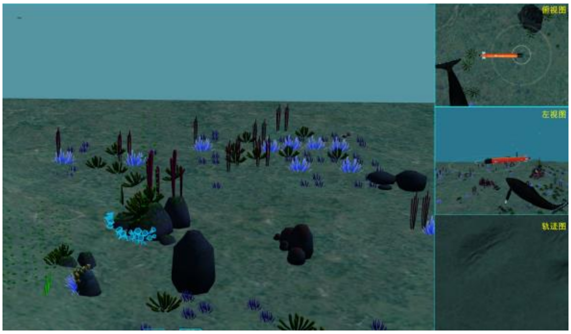

Fig. 3. Underwater View Simulation

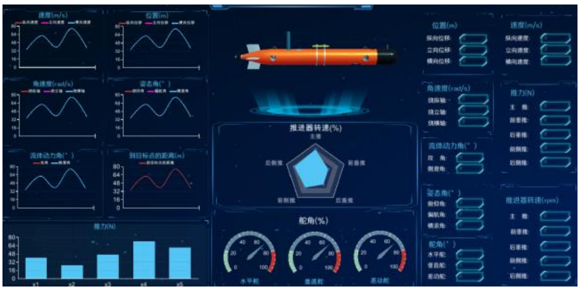

Fig. 4. System data display

6 Conclusion

Through the underwater equipment digital twin system, we can clearly feel that the digital twin system can play an important role in the future development of underwater equipment. Not only the cost of research and development and production cycle of underwater equipment can be reduced, but also the performance of underwater equipment can be accelerated in the areas of intelligence, multi-task, multi-water operation and other aspects.

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