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Design of the basic motion control system for water-jet-propelled unmanned surface vehicle

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Abstract: Design of the basic motion control strategy for the under-actuated Unmanned Surface Vehicle (USV) is undertaken. Firstly, the motion control system architecture of the water-jet propelled USV is introduced in detail. According to the characteristic of water-jet propulsion principle, the USV system is an under-actuated, time-varying and nonlinear coupled system. Secondly, simulating the coordination control function of the human cerebella, the human-simulate control strategy is proposed based on the coordination control of astern deflector rotating, nozzle rotating and engine rotation speed. So the full controlling of the surface vehicle in various sailing states is achieved, and its manoeuvrability and agility are improved. Then the software architecture for the control system is designed using this idea. Finally, the USV motion control simulation tests are undertaken in different sailing states. And the simulation validates the effectiveness of the human-simulate control strategy.

Key words: human-simulate; cerebella model; control strategy; unmanned surface vehicle; water-jet propulsion

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喷水推进无人艇的基础运动控制系统设计

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摘要: 针对欠驱动无人艇开展了其基础运动控制策略设计的研究. 首先详细地介绍了喷水推进无人艇的运动控制系统的构成, 并根据喷水推进器推进原理的特点, 可得出该无人艇系统是欠驱动的、快变的非线性耦合系统; 然后根据人类小脑的运动协调功能, 提出基于倒车斗、喷嘴转角和发动机转速协调控制的仿人智能控制策略, 实现了对无人艇的完全运动控制, 提高了其操纵性和灵活性; 并根据该思想设计了无人艇的基础运动控制系统的软件体系结构. 最后进行了无人艇在各种航行状态下的运动控制仿真试验, 仿真结果表明了该仿人智能运动控制策略的有效性.

关键词: 仿人智能; 小脑模型; 控制策略; 无人艇; 喷水推进

1 Introduction

The unmanned surface vehicle(USV) is an intelligent surface motion platform, which can navigate safely in port, riverine, harbour and coastal waterways in a variety of roles[1]. This surface vehicle has the potential, and in some cases the demonstrated ability, to reduce risk to manned forces, to provide the force multiplication necessary to accomplish various missions, and to perform tasks which manned vehicles cannot. For example, the protector USV, which has successfully served in the persian gulf and the mediterranean, is able to conduct a wide spectrum of critical missions, such as force protection, anti-terror, surveillance and reconnaissance, mine warfare and electronic warfare, while eliminating unnecessary risk to personnel and capital assets. So the USV will be highlighted for increasing special attention it receives around the world in the future.

In this paper, a water-jet-propelled USV will be introduced. According to the title, its basic motion control system will be designed using human-simulated intelligent control based on the cerebella model. The USV is controlled from a control center that can be located

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in a fixed shore facility, mobile shelter, or on board a ship. And in the future, it will operate autonomously. So the environment information and control command should be exchanged between the control center and the USV through the wireless communications system. When beyond visual range(BVR) or the remote control cannot be used, the USV must be able to detect the environment, target identifications, avoid obstacles, make autonomous path plans, auto drive and complete a variety of operational missions autonomously. So it must be capable of changing its position to avoid collision with other ships and complete various campaign missions safely due to the complexity of the real marine environment[2]. On the other hand, the USV is only equipped with water-jet propulsion to drive it, so it is an under-actuated, time-varying and nonlinear coupled system. How to design its motion control system based on the water-jet propulsion is the most important thing for the USV.

2 Architecture of the USV system

The USV is based on water-jet propulsion, the inflatable boat hull and unmanned system to provide high-speed, maneuverability and intelligence to meet the strenuous demands of multiple missions. The USV system is composed of two main parts: the control center and the USV. The USV is equipped with water-jet propulsion, marine diesel engine, nozzle pump(or autopilot pump), rudder sensor, astern deflector pump, astern deflector sensor, compass, radar, GPS, anemoscope & dogvane, lithium batteries, wireless system, embedded computer systems and so on. The equipment of the USV system is shown in Fig.1. The aim of this paper is to design the basic motion control system using the equipment.

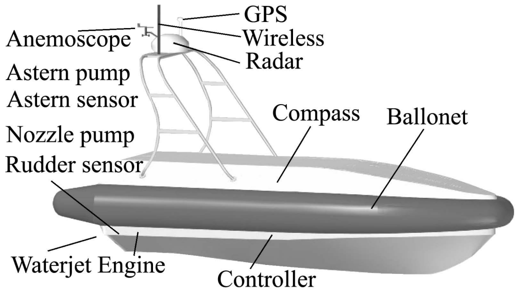


Fig. 1 The equipment of the USV system

3 The basic motion control strategy for the USV

As mentioned above, the vehicle is only equipped with the water-jet propulsion, marine engine, nozzle pump and astern deflector pump, which are used to propel and manipulate the USV. Although the astern deflector can be used to drive the USV astern sailing, it can only adjust the engine crankshaft speed and manipulate the angle of jet nozzle to control the vehicle speed and yaw, when the USV navigates in a high-speed state. So the vehicle belongs to the typical under-actuated system at the moment. If the roll, pitch, heave of the USV can not be ignored, in this situation, it is a six-degree freedom motion system. But the control inputs are still limited to these two variables, and the characteristic of under-actuated system is more obvious now.

Besides the under-actuated and strong-coupling characteristics, as it works in complex marine environment, the wind, wave and flow all have serious impact on the USV. The serious disturbance is not only random, but also uncertain. More importantly the USV is a small unmanned surface platform, so it is poor in homeostasis. And again, the USV must be capable of changing its position to avoid collision with other ships or submerged rocks. Therefore, the USV system is an under-actuated, fast changing, big disturbance and multiple-input multiple-output nonlinear coupled system[3]. And stability control of its own motion is highly demanding in disturbance of complex conditions. And how to coordinate and control the motion actuators, such as jet nozzle, astern deflector and marine engine, to achieve stable direction, and precise speed, and to complete the mission, is the key for designing the basic motion control system for the USV.

3.1 Design of the human-simulate control strategy for the USV based on the cerebella model

In the control of human body motion, the cerebella plays an important role, which has two main functions: one is to incessantly change the motion and correspond the parts of the body to maintain body balance when the motion mode and outside environment changing, the other is to calculate the space time mode of the body motion and learn it[4]. In here, the basic motion control coordination module was constructed based on the first function of the human cerebella. Firstly, the control experience, skill and instinct logic illation of human were checked, generalized and summarized from the lowest layer of the grade step intelligence control system; Secondly, the coordination control arithmetic was deduced, which is simple but practical and precise, and capable of real time running. Finally, the coordination control arithmetic was used in the basic motion control system of the USV[5]. The coordination control arithmetic and the elements of the USV sailing states are as follows:

$$Q = \{Q_L, Q_H\}. \tag{1}$$

Where: $Q_L = \{q_{LD}, q_{LS}\}$, $Q_H = \{q_{HD}, q_{HS}\}$.

Thereinto: $Q_L : u < \delta_L$, $Q_H : u \geqslant \delta_L$.

The symbol meaning of the formula (1) is as follows:

Q_L, Q_H: The basis element of the low-speed sailing states, the basis element of the high-speed sailing states.

u, δ_L: The practical speed of the USV, the low-speed threshold value of the USV.

The character model of the basic motion control of the USV:

$$\phi = \{\phi_D, \phi_S\}. \tag{2}$$

Where: $\phi_D = \{\phi_{LD}, \phi_{HD}\}$, $\phi_S = \{\phi_{LS}, \phi_{HS}\}$.

Thereinto:

$\phi_{LD} = q_{LD}$, $\phi_{LS} = q_{LS}$, $\phi_{HD} = q_{HD}$, $\phi_{HS} = q_{HS}$.

ϕ_D, ϕ_S: The direction control model, the speed control model.

The control model of the basic kinaesthesia intelligence of the USV:

$$\psi = \{\psi_D, \psi_S\}. \tag{3}$$

Where: $\psi_D = \{\psi_{LD}, \psi_{HD}\}$, $\psi_S = \{\psi_{LS}, \psi_{HS}\}$.

Thereinto:

$$\psi_{LD} : A_J = \frac{2.0}{1.0 + e^{(-k_{J1}x_J - k_{J2}y_J)}} - 1.0,$$

$$A_D = A_{D0} + K_{DI} \cdot [\frac{2.0}{1.0 + e^{(-k_{D1}x_D - k_{D2}y_D)}} - 1.0],$$

$$\psi_{HD} : A_J = \frac{2.0}{1.0 + e^{(-k_{J1}x_J - k_{J2}y_J)}} - 1.0,$$

$$\psi_{LS} : A_E = 1000,$$

$$A_D = A_{D0} + K_{DI} \cdot [\frac{2.0}{1.0 + e^{(-k_{D1}x_D - k_{D2}y_D)}} - 1.0],$$

$$\psi_{HS} : A_E = A_{E0} + K_{EI} \cdot [\frac{2.0}{1.0 + e^{(-k_{E1}x_E - k_{E2}y_E)}} - 1.0].$$

The meanings of these unreferenced symbols above are as follows:

ψ_{LD}, ψ_{HD}: The low-speed direction control mode, the high-speed direction control mode;

ψ_{LS}, ψ_{HS}: The low-speed control mode, the high-speed control mode;

A_J: The Output of the nozzle controller;

x_J, y_J: The error of the currently course, the rate of error change;

k_{J1}, k_{J2}: The S pane control parameter k_1, k_2 of the nozzle controller [6];

A_D: The output of the astern deflector controller;

x_D, y_D: The error of the currently sailing speed, the rate of error change;

k_{D1}, k_{D2}: The S pane control parameter k_1, k_2 of the astern deflector controller;

A_{D0}, K_{DI}: The previous output of the astern deflector controller, the integral coefficient of the astern deflector controller;

A_E: The output of the engine controller;

x_E, y_E: The error of the currently sailing speed, the rate of error change;

k_{E1}, k_{E2}: The S pane control parameter k_1, k_2 of the engine controller;

A_{E0}, K_{EI}: The previous output of the engine controller, the integral coefficient of the engine controller.

The logic illation rule of the basic motion control model of the USV:

$$\Omega = \{\Omega_D, \Omega_S\}. \tag{4}$$

Where: $\Omega_D = \{\omega_{LD}, \omega_{HD}\}, \Omega_S = \{\omega_{LS}, \omega_{HS}\}$.

Thereinto:

ω_{LD} : if ϕ_{LD} then ψ_{LD},

ω_{HD} : if ϕ_{HD} then ψ_{HD},

ω_{LS} : if ϕ_{LS} then ψ_{LS},

ω_{HS} : if ϕ_{HS} then ψ_{HS}.

4 Design of the software architecture for the basic motion control system

According to the logic illation rule of the basic motion control model in formula (4), the motion control software architecture for the USV will be designed using this method. As a core of the whole USV software system, the basic motion control module gets motion control information from wireless equipment, and decodes the messages, and decompounds the commands into different control character models by the dictate apprehend module. So the vehicle speed is compared with the low-speed threshold value; therefore, the basis element of the USV sailing state is ascertained, low-speed sailing state or high-speed sailing state. Then the character model is ascertained, direction control model or speed control model. At this time, the USV gets the basic kinaesthesia intelligence. If the basic motion control system gets a motion command, it will be inferred by the logic illation rule, as showed in formula (4). Subsequently, the USV carries out different control calculations by different motion controllers, such as nozzle controller, astern deflector controller and engine controller. Finally, the USV'S motion actuators are driven by these controllers to produce the needed thrust and moment[7]. At the same time, the marine environment information, USV'S pose information and USV'S state information are acquired by the sensor data acquisition module, and are also fed back to the basic motion controllers, which provides the needed decision-making information for the basic motion control system[8,9]. As showed in Fig.2.

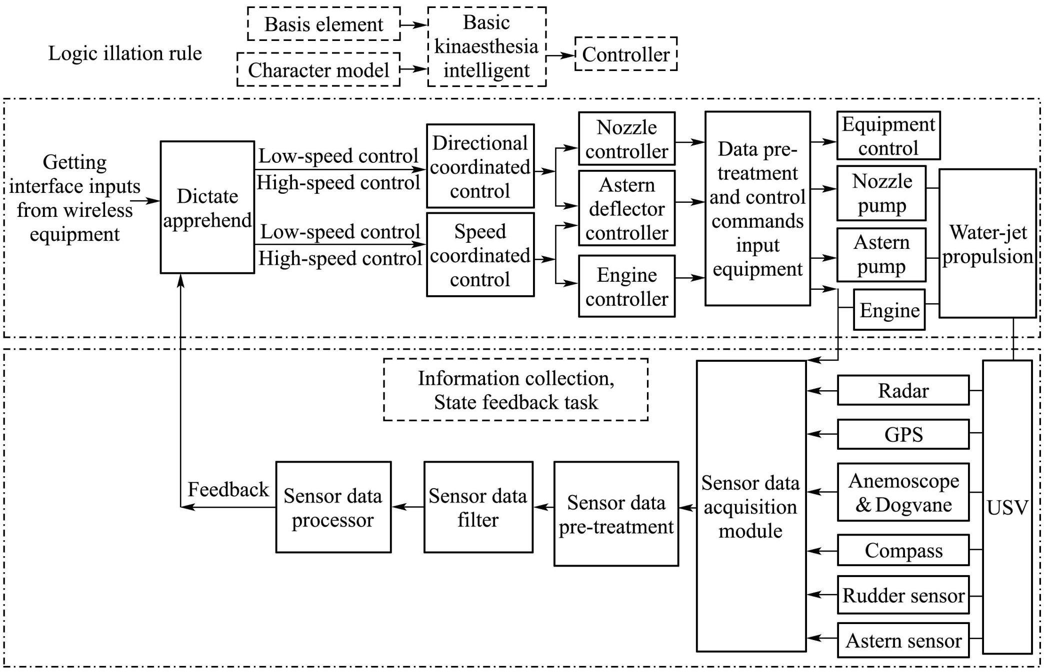


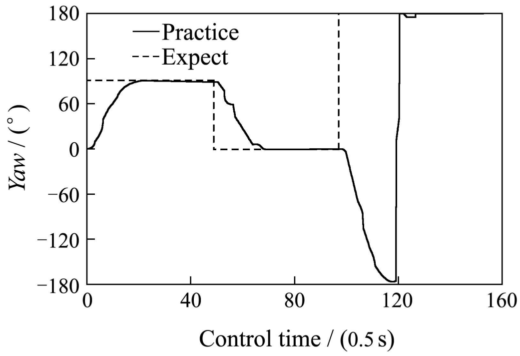
Fig. 2 Software architecture of the basic motion control system

5 Simulation

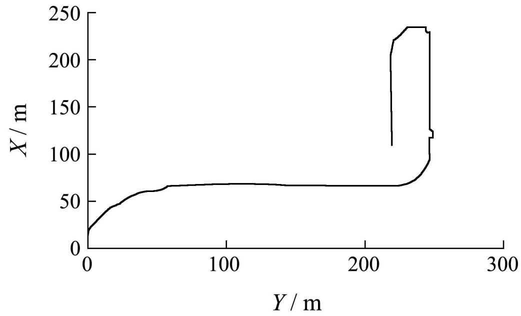
Now, the design work for the basic motion control system is nearly completed. The following work is to validate the reliability and feasibility of this system. As the USV hull is under construction, the simulation work of the USV is done to validate the correctness of the design. Then the simulation of the directional and speed motion control for the USV is done on the basic of USV kinematic simulation. According to the character model of the basic motion control, various control modes were particularized and their simulation trials are described as follows:

5.1 The low-speed directional control based on the coordinate control of the astern deflector rotation and nozzle rotation

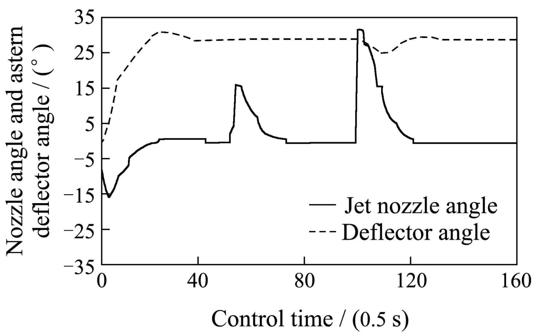
According to the logic illation rule of the USV'S basic motion control model in formula (4), when the USV is in low-speed mode, the engine crankshaft standby speed is still too fast. And now it is required to coordinated control the astern deflector and nozzle to achieve the control of the USV bow in low-speed. At this time the astern deflector controller is needed to control the reversing degree of the astern deflector. The astern deflector controller and astern deflector sensor form the closed-loop control, so the control of the astern deflector is achieved, which is according to the ψ_{LD} control model as showed in formula (3). The precision and stability control of bow was achieved by using the coordination motion of astern deflector and nozzle in low-speed mode. Its low-speed directional control simulation trial results were showed in Fig.3. The control parameters are as follows: where the low-speed threshold value of the USV was $\delta_L = 4$ m/s, and the engine crankshaft speed was $n = 1000$ r/min, and $k_{J1} = 2$, $k_{J2} = 5$, $K_{DI} = 0.1$, $k_{D1} = 3$, $k_{D2} = 2.5$, $u = 2.0$ m/s. The effect of low-speed directional control was showed in Fig.3(a). The practice pathway of the USV in this control process is showed in Fig.3(b). And Fig.3(c) displayed the practice jet nozzle angle and astern deflector angle with the control time.



(a) The curve of low-speed directional control



(b) The curve of practice pathway from the low-speed directional control

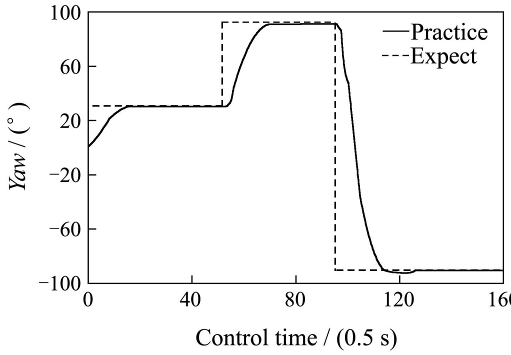


(c) The curve of practice jet angle and astern deflector angle

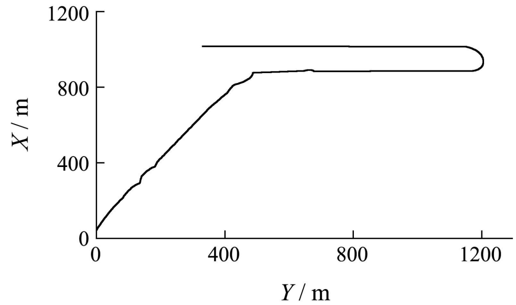
Fig. 3 Analysis of the USV low-speed directional control

5.2 High-speed directional control

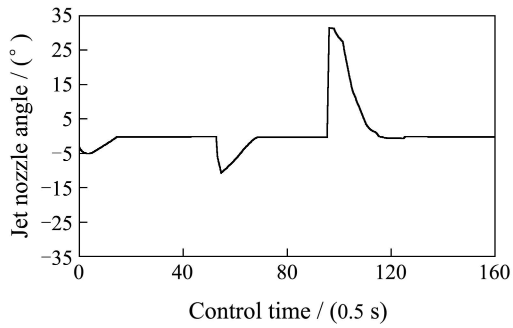
On the other hand, when the USV is in high-speed mode (Namely, the engine crankshaft speed is greater than the standby speed), only control the nozzle rotation angle can be better control of the turning of the USV, so the ψ_{HD} control mode is adopted to control the bow of the USV hull in high-speed sailing state. In this mode, the improved S panel control method was used to design the nozzle controller, which was combined with the rudder sensor to form the control-loop. And the nozzle pump was driven by the controller to steer the nozzle in real-time. The directional control simulation trial in high-speed mode was done based on the above analysis. Its control parameters were as follows: where the engine crankshaft speed was n = 3600 (r/min), and $k_{\mathrm{J1}} = 2$, $k_{\mathrm{J2}} = 5$. The process of the high-speed directional control was showed in Fig.4(a). The practice pathway of the USV in this control process was showed in Fig.4(b). And Fig.4(c) displayed the practice jet angle with the control time.



(a) The curve of directional control



(b) The curve of practice pathway from the directional control



(c) The curve of practice jet angle

Fig. 4 Analysis of the USV directional control

5.3 High-speed control

When the USV needs high-speed sailing(namely, the engine crankshaft speed is greater than the standby speed), only controling the engine crankshaft speed can be better for control of the speed of the USV, so the ψ_{HS} control mode is adopted to control the USV speed based on the control model logic illation. And in this mode, the improved S panel integral control method was used to design the engine controller, which was combined with the engine crankshaft speed feedback to form the control-loop. And the water-jet pump was driven by the controller to control the jet flux in real-time. The speed control simulation trial in high-speed mode was done based on the above analysis. Its control parameters were as follows: $K_{\mathrm{EI}} = 0.1$, $k_{\mathrm{E1}} = 2$, $k_{\mathrm{E2}} = 2.5$. The 6 m/s speed control was processed, then the expect speed was changed to 10 m/s and follow to 4 m/s as showed in Fig.5(a). The practice engine output at crankshaft and propeller power in this control process were showed in Fig.5(b). And Fig. 5(c) displayed the practice engine running parameters with the control time.

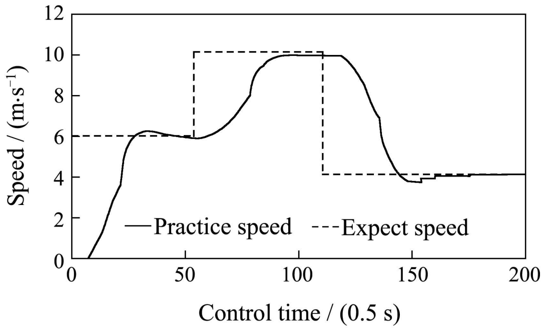


Fig. 5(a) The curve of speed control

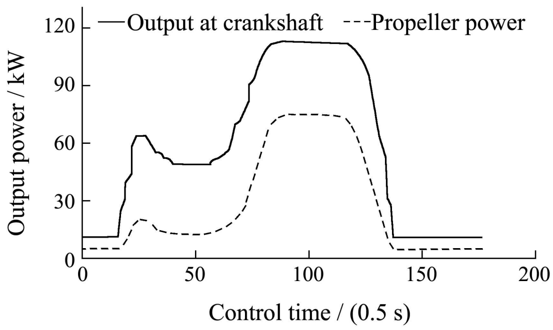


Fig. 5(b) The curve of practice engine rotation

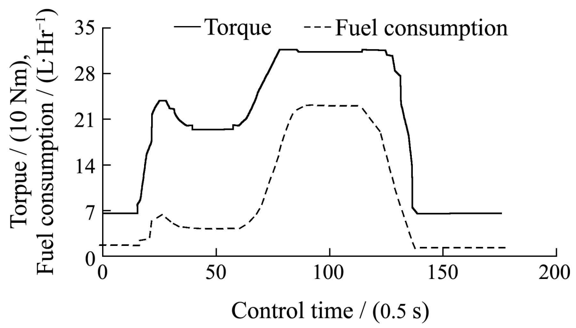


Fig. 5(c) The curve of practice output at crankshaft

6 Conclusions

The architecture of the USV's basic motion control system is presented in terms of the hardware in this paper. And the motion coordination control strategy for the USV was proposed based on the human cerebella model. Then the reliability and feasibility of the system architecture verified by simulation trial is given. It showed that the human-simulated coordination control strategy based on cerebella model is applicable for engineering.

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