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Research on Key Technologies for Water Intelligent Rescue Robots: Design and Implementation of Bionic Octopus Tentacle Rescue Mechanisms

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Abstract: In this study, a bionic octopus tentacle rescue mechanism is designed to address the bottleneck of the adaptability and grasping ability of traditional water rescue equipment (robotic arm and winch mechanism) in the complex water environment. Through the modular design of the robot structure (asymmetric buoyancy chamber, variable pitch propeller), the development of multi-joint flexible mechanical structure and the optimisation of the power system (vector control of permanent magnet synchronous motor), the stable operation and accurate grasping of the rescue equipment in turbulence and obstacle scenarios are realised. The experiment verifies the effectiveness of the bionic mechanism in complex environments and provides a new path for water rescue technology.

1. Introduction

More than 300,000 people lose their lives due to drowning every year, and the existing water rescue robots are facing two core challenges: the rigid structure of the traditional robotic arm is not stable enough in turbulence, and the winch mechanism is easy to be entangled by obstacles and cannot adaptively grasp [1-2]. This project focuses on the needs of complex water rescue, and proposes a flexible rescue mechanism design based on bionics [3], which improves the robot's anti-tipping performance through the layout of the asymmetric buoyancy chamber [4], optimises the propulsion efficiency by combining with the variable pitch propeller, and develops the multi-joint flexible tentacles to achieve the dynamic and accurate grasping [5]. The study aims to solve the bottlenecks of traditional equipment in environmental adaptability, grasping flexibility and multi-machine efficiency through technological breakthroughs in structural design, drive control and sensor fusion, and to promote the development of water rescue in the direction of intelligence and precision.

2. Structural design of rescue robots

2.1 Composite material system and structural layout

The main body of the water rescue robot is made of high-strength, seawater-resistant aluminium alloy. This material has a good strength-to-weight ratio, can withstand large impacts and loads, and at the same time in the long-term immersion in seawater can also effectively resist corrosion. The surface of the robot's casing is treated with a special anti-slip and wear-resistant treatment to ensure that the casing will not be easily damaged when used in a variety of complex water environments, thus affecting its performance. For some critical internal parts, such as the housing and connection parts of electronic components, engineering plastics with good sealing and insulating properties are used to further protect the internal circuits from flooding and short-circuiting. Stainless steel is used for structural parts that require more strength, such as the frame that carries the rescue equipment and power system, to ensure the ability of the entire robot to operate in harsh environments. The dimensions of the robot are designed to be about 1.2 metres in length, 0.8 metres in width and 0.4 metres in height, making it easy to carry and operate, while providing good stability in water.

The overall shape of the robot is streamlined to reduce resistance when travelling through water. The front part of the shell is designed as a rounded curved shape that gradually transitions smoothly to the rear. This shape not only helps to increase the speed of the robot, but also improves its stability in waves to some extent. At the bottom of the shell, multiple one-way drainage slots are designed to promptly drain any water that may enter the interior of the robot, preventing the buoyancy and manoeuvrability of the robot from being affected by the increased weight of the accumulated water.

The robot is equipped with a number of buoyancy chambers, mainly located at the bottom and sides of the robot. The outer shell of the buoyancy pods is made of high-density polyethylene (HDPE) and is filled with a buoyant material, such as closed-cell foam. These buoyancy compartments ensure that the robot is always buoyant enough to float stably in water, even if some of the buoyancy compartments are damaged or waterlogged. The total buoyancy of the buoyancy tanks is calculated to be able to carry the robot's own weight and the additional weight of at least one adult person in the water (approx. 100kg).

2.2 Propulsion system and motion control design

(1) FOC brushless motor propulsion

Two FOC brushless motors are mounted at the rear of the robot, symmetrically distributed on the left and right. The FOC brushless motors have high propulsion efficiency and good concealment, which can effectively prevent the entanglement of debris in the water. The shell of the thruster is made of corrosion-resistant titanium alloy, and the three-phase brushless motors are controlled by sinusoidal wave mode. In sinusoidal commutation, all three wires are continuously powered by sinusoidal currents spaced 120 degrees apart between each phase, which creates a rotating north-south magnetic field inside the motor. For optimal rotation of the rotor, the angular position of the rotor needs to be known in real time and a voltage is applied to the UVW wires of the motor accordingly, always keeping the rotating magnetic field 90 degrees apart from the stator magnetic field. This ensures stability and reliability at high rotational speeds.

(2) Steering gear

In conjunction with the thruster is an advanced steering unit. A rotatable deflector plate is mounted on the outer side of the FOC brushless motor thruster, which is connected to the robot's control system via an electric actuator. When steering is required, the control system drives the electric actuator to change the angle of the deflector plate according to preset commands or operator's operation, thus changing the direction of water flow and realising the steering of the robot. This steering method has high precision and response speed, and is able to flexibly manipulate the robot in complex water flow environments.

2.3 Integration of sensing and control systems

(1) Control compartment

There is a sealed control compartment inside the robot, which is located at the centre of the robot to ensure its stability and safety in the water. The control compartment adopts a double-layer sealed structure, with the outer layer made of stainless steel and the inner layer made of waterproof engineering plastic. Key equipment such as the main controller, communication module and power management system are installed in the control cabin. The main controller adopts a high-performance microprocessor, which is able to process information from various sensors in real time, and accurately control various execution parts of the robot according to the preset algorithms and the operator's instructions.

(2) Sensor system

A GPS positioning sensor is installed on the top of the robot, which is used to obtain real-time geographic location information of the robot and transmit it to the remote monitoring centre, so that the operator can accurately grasp the robot's position and action trajectory. There are and millimetre wave radar sensors installed at the front, sides and bottom of the robot for detecting the surrounding obstacles and the position of the person who has fallen into the water. The sensors can sense the distance and relative speed between the robot and the surrounding objects in real time, providing data support for obstacle avoidance and precise rescue. In addition, there is an attitude sensor installed inside the robot with built-in radar, gyroscope and accelerometer, which is used to monitor the robot's attitude changes in real time to ensure that the robot can remain stable under the action of waves and currents, and provide feedback information for the control system to adjust the robot's movements in time.

2.4 Energy supply and management programme

(1) Battery pack

The power supply system is the core of the robot's power, using a large-capacity lithium battery pack. The battery pack is installed in a specially designed waterproof, fireproof and explosion-proof chamber at the bottom of the robot. The battery compartment adopts a multi-layer protective structure, including fireproof insulation materials, waterproof sealing rubber ring and explosion-proof pressure relief valve. The Li-ion battery pack consists of multiple high energy density Li-ion battery cells with a total capacity of 15kWh, which is capable of providing the robot with at least 3 hours of continuous operation time to meet the basic needs of a rescue mission. The battery pack is equipped with an advanced battery management system, which can monitor the voltage, current, temperature and other parameters of the battery in real time, and realise the charging and discharging protection, equalisation management and fault diagnosis of the battery to ensure the safe and reliable operation of the battery.

(2) Charging interface and solar charging panel

A waterproof charging interface is set on one side of the robot, which can charge the battery pack through external power supply. At the same time, in order to increase the endurance of the robot, the top surface of the robot is covered with a layer of high-efficiency solar charging panels. The solar charging panel adopts flexible thin-film solar cell technology, which is lightweight, bendable and has high conversion efficiency. In sunny conditions, the solar charging panel can provide a certain amount of supplementary power to the battery pack, extending the robot's operating time.

2.5 Enhanced design for mechanical stability

(1) Centre of gravity and buoyancy balance

Through reasonable design of the robot's internal structure and component layout, it is ensured that the robot's centre of gravity is located below the buoyancy centre. In the design and distribution of the buoyancy compartment, precise calculations and simulations are made so that the robot can maintain a stable buoyancy balance under various loading conditions (including carrying a man overboard and rescue equipment). This gravity buoyancy layout design can effectively prevent the robot from capsizing in the water and improve its stability in waves and currents.

(2) Structural reinforcement and connection

High-strength bolts, rivets and welding are used between the various parts of the robot to ensure a solid connection. For the parts that are subject to large stresses, such as the connection part between the propeller and the robot body and the support structure of the stretcher lifting device, reinforcement and thickened connectors are used for reinforcement. At the same time, in the internal frame structure of the robot, a number of triangular support structures are designed, using the stability principle of triangles to enhance the structural strength of the entire robot, so that it can withstand the impact of various external forces that may be encountered in the rescue process.

(3) Waterproof and sealing design

In order to ensure the normal operation of the robot in the water, the waterproof and sealing design is crucial. In addition to the multi-layer sealing structure for key parts such as the control compartment and battery compartment mentioned earlier, other parts of the robot such as sensors, motors, valves, etc. are also designed to be waterproof and sealed. High-performance seals or sealing gaskets are installed at all connection parts and seams where water may enter. In addition, rigorous waterproofing tests, including immersion tests and high-pressure water spraying tests, are conducted during the design process of the robot to ensure that the robot will not fail due to flooding during long-term use.

3. Design of rescue mechanism

3.1 Bionic octopus tentacle rescue organisation

(1) Multi-joint flexible mechanical structure

The tentacle part of the bionic octopus tentacle rescue mechanism is designed with multiple flexible joints, each of which is connected by high-strength but lightweight engineering plastics, which ensures the flexibility of the tentacles as well as their structural strength [6]. The inner part of the tentacle is embedded with steel wire rope, and the outer part is wrapped with corrosion and abrasion resistant flexible materials, such as Teflon, to adapt to complex water flow and obstacle environments. The end of the tentacle is fitted with a grasping head made of silicone, which has bumps and textures on its surface to enhance friction and prevent it from slipping when grasping, and the grasping head can be removed and replaced to cope with different body sizes and states of people falling into the water. The base of the rescue mechanism is made of aluminium alloy and is bolted to the platform of the rescue robot to ensure a firm connection. There are motors and transmission devices inside the base to transfer power to the tentacles and drive their movement, and the connection device adopts universal joints and flexible joints to allow the tentacles to move freely in multiple directions, which enhances the flexibility and adaptability of the rescue mechanism.

(2) Distributed drive and intelligent control

Each joint of the bionic octopus tentacle rescue mechanism is equipped with a micro-DC motor, and the motor with appropriate torque and speed is selected according to the joint movement requirements. The motors are installed close to the joints to reduce the transmission distance and inertia, and improve the response speed and control accuracy. The motor drive circuit adopts H-bridge driver chip, which can realise forward and reverse rotation and speed control of the motor. The circuit design focuses on efficiency and stability, and adopts a buck chopper circuit to supply power to the motor, ensuring stable operation of the motor under different loads. At the same time, the circuit is equipped with over-current, over-voltage and short-circuit protection functions to prevent motor damage. The motor drive signal is generated by the STM32 main control board, amplified by the amplifier circuit to drive the motor, and the amplifier circuit adopts a power amplifier to ensure the strength and stability of the drive signal. In order to prevent the motor current is too large to burn the main control board, the circuit added optocoupler isolation and continuity diodes and other protection devices. The power supply of the rescue mechanism is provided by the lithium battery pack of the robot, which provides a stable voltage for the motor drive circuit and control circuit through the voltage regulator chip and power management module. The power management module monitors the current and voltage in real time to prevent overload and undervoltage conditions from occurring, ensuring the safe operation of the rescue mechanism.

3.2 Performance advantages

(1) Extreme environmental adaptation breakthrough

Bionic octopus tentacle rescue mechanism through flexible joints and streamlined outer cladding design, theoretically can be in the 3m/s turbulent current and 1.5m wave height of the complex waters of stable operation, compared with the traditional robotic arm (resistance to flow speed $\leq$ 1.5m/s) to enhance the ability to withstand the environment by 100%. The friction coefficient of the Teflon cover is only 0.05, which can effectively avoid the entanglement of weeds, fishing nets and other debris, while the risk of entanglement increases by 67% in the same environment due to the high surface roughness of the traditional rigid robotic arm. In addition, the multi-joint redundancy design enables the mechanism to complete the gripping task through the remaining joints even when 30% of the joints fail, whereas the failure of a single joint of a traditional robotic arm leads to the overall failure.

(2) Dynamic and precise capture capability

Bionic octopus tentacle rescue mechanism has adaptive grasping ability, the tentacles can automatically adjust the grasping strength and angle according to the body type and posture of the person falling into the water. Based on the six-axis force sensor (accuracy $\pm$0.1N) and fuzzy PID control algorithm, the tentacle can complete the recognition of the posture of the person who fell into the water and adjust the grasping strength in 150ms, and the error of force control for different sizes of targets is less than 3%. Theoretically, the bionic suction cup texture of the end silicone gripping head can generate 2.8kPa adsorption force, which improves the gripping stability on slippery surfaces (e.g., life buoys) by 50% compared with the traditional gripping jaws.

4. Power and energy supply module

4.1 Mechanical system

The use of advanced permanent magnet synchronous motors as a power source brings superior performance in terms of high efficiency and high-power density to electric propulsion. Permanent magnet synchronous motors use permanent magnets to generate a magnetic field, which provides a higher energy conversion efficiency compared to conventional motors. At the same time, the high-power density makes the motors smaller and lighter, making them easy to mount on the robot without placing too much burden on the overall structure of the robot.

Through precise electronic control, the permanent magnet synchronous motor can achieve fast response and accurate speed regulation. Rescue needs vary under different sea conditions. For example, in a calm sea, a lower speed can be selected for detailed search; while in emergency situations, such as strong currents or bad weather, when it is necessary to quickly approach the rescued person, the motors are able to quickly respond to commands and provide a strong power output, so that the robot drives to the target at the fastest speed. The precise speed adjustment function also allows rescuers to flexibly adjust the robot's travelling speed according to the actual situation, ensuring the safety and efficiency of rescue operations.

In addition, the permanent magnet synchronous motor has good reliability and durability. In the marine environment, faced with harsh conditions such as salt spray, humidity, and wave impacts, the motors need to have strong corrosion and impact resistance. The permanent magnet synchronous motor adopts high-quality materials and advanced manufacturing process, which can operate stably in the harsh marine environment, reduce the probability of failure, and provide reliable power guarantee for rescue operations.

(1) Adequate control algorithm for permanent magnet synchronous motors

Vector control is a control method based on magnetic field orientation, and its core idea is to decompose the stator current of the motor into two components, the excitation current and the torque current. By controlling these two components separately, independent control of the motor magnetic field and torque can be achieved, thus achieving the purpose of decoupling. This decoupling control results in a significant improvement in the dynamic and steady state performance of the motor. In terms of dynamic performance, due to the ability to independently control the magnetic field and torque, the motor can quickly respond to changes in speed commands and achieve rapid acceleration and deceleration. For example, in ocean rescue missions, when it is necessary to urgently approach the rescued person, the motor can quickly provide a strong torque to enable the rescue robot to accelerate rapidly. At the same time, when facing complex changes in sea conditions, the motor can also quickly adjust the output torque to maintain a stable operating state.

In terms of steady state performance, precise magnetic field and torque control can make the motor maintain a stable speed and output power under different load conditions. This is very important for marine rescue robots because during the rescue process, the robot may face different load conditions, such as current resistance, wind and wave impacts, and so on. With vector control, the motor can automatically adjust the output torque according to the load changes, ensuring that the robot always travels at a stable speed and improving the accuracy and reliability of the rescue.

(2) Implementation steps of vector control

Step 1: Coordinate transformation

Clarke transform: Firstly, the three-phase stator currents are transformed to the two-phase stationary coordinate system by the Clarke transform, which is a linear transformation that converts the three-phase current signals into two orthogonal current components, i.e., α-axis current and β-axis current. This process removes the coupling between the three-phase currents in preparation for the subsequent Park transform.

Park transform: Next, the α-axis currents and β-axis currents obtained from the Clarke transform are transformed to the rotating coordinate system by the Park transform, which is a rotational transform that converts the current components in the stationary coordinate system to the excitation currents and torque currents in the rotating coordinate system. In the rotating coordinate system, the excitation current is mainly used to generate the magnetic field of the motor and the torque current is used to generate the torque of the motor. In this way, decoupled control of stator current is achieved.

Step 2: Speed adjustment

Speed command and feedback: The given speed command represents the desired operating speed of the motor, while the actual speed feedback is obtained through a speed sensor mounted on the motor shaft. The speed sensor monitors the motor's speed in real time and feeds it back to the control system.

PI controller regulation: Based on the given speed command and actual speed feedback, a proportional-integral (PI) controller is used to regulate the excitation and torque currents. The PI controller is a commonly used feedback controller, which, through the action of both proportional and integral links, enables the output of the system to quickly track the given values and eliminates the steady state error. During the speed regulation process, the PI controller calculates the required excitation current and torque current adjustments according to the speed error, and then adds them to the current excitation and torque currents to realise the precise control of the speed.

Step 3: Current regulation

Separate control: The excitation current and torque current are regulated separately by PI controller. The function of the excitation current PI controller is to make the excitation current track the given value to keep the magnetic field of the motor stable. The function of torque current PI controller is to make the torque current track the given value to achieve precise control of motor torque.

Tracking the given value: By adjusting the parameters of the PI controller, the excitation current and torque current can track the given value quickly and accurately. In practical application, it is necessary to reasonably adjust the proportional and integral coefficients of the PI controller according to the characteristics of the motor and the control requirements in order to achieve the best control effect.

Step 4: Inverse coordinate transformation

Park inverse transformation: the voltage command in the rotating coordinate system is converted to the two-phase stationary coordinate system by Park inverse transformation, which is the inverse process of Park transformation, and it converts the voltage component in the rotating coordinate system to the α-axis voltage and β-axis voltage in the stationary coordinate system.

Clarke inversion: the α-axis voltage and β-axis voltage obtained by Park inversion are then converted to three-phase stationary coordinate system by Clarke inversion, which is the inverse process of Clarke transformation, and it converts the voltage components in two-phase stationary coordinate system to three-phase voltage control signals.

Motor control: The final three-phase voltage control signal is input into the motor drive circuit to control the three-phase stator windings of the motor and realise the precise control of the motor.

4.2 Energy supply systems

(1) Lithium-ion battery pack

The rescue robot adopts a 110Ah high-performance lithium-ion battery pack as the main power supply, which has high energy density and can store more energy than other types of batteries in the same volume. It can provide sufficient power support for rescue robots with limited space, ensuring that they do not need to return to the base frequently for recharging when performing long rescue missions, which greatly improves rescue efficiency. At the same time, the lighter weight of lithium-ion batteries helps to reduce the overall weight of the robot, improve its mobility and flexibility in the water, and reduce the resistance of the water, so that it can move more quickly to the target location. And for rescue robots that need to carry other complex equipment and sensors, reducing weight reduces the burden on the energy system and extends endurance. In addition, lithium-ion batteries have a relatively long cycle life and can withstand multiple charge/discharge cycles without significant performance degradation, which allows the rescue robot to frequently use the lithium-ion battery pack over a long period of time without having to replace the batteries frequently, reducing maintenance costs and time costs. At the same time, it also ensures that the robot can always maintain a stable energy supply in long-term rescue operations, improving the reliability of the rescue.

(2) Solar power supply

The rescue robot first uses high-efficiency polycrystalline silicon solar panels to power the lithium battery pack. Polycrystalline silicon solar panels have a high conversion efficiency, can be in the sunny marine environment will be more solar energy into electricity, for the robot to provide continuous energy supplement. Moreover, it is stable and can withstand the effects of salt spray, humidity and temperature changes in the marine environment without being easily damaged or degraded. In terms of installation location, solar panels can be installed on the top of the robot, the top of the installation can be directly facing the sun to receive the most sunlight, and the installation of adjustable angle of the bracket to improve the efficiency of solar energy collection.

5. Project realisation and validation

5.1 Rescue robot prototype construction

Currently, the team members have completed the preliminary model of the rescue robot and finished building the hull structure, propulsion system, and control compartment of the robot. The preliminary model of the rescue robot is shown in Figure 1.

Figure 1 Preliminary model drawing of the rescue robot

The model adopts asymmetric buoyancy module design, and optimises the distribution of components through CFD simulation, so that the centre of gravity is lower than the centre of buoyancy, and the measured capsize resistance is increased by 30%, and the angle of transverse inclination is ≤8° under Class 3 sea state (wave height 0.6-1.0m). The propulsion system draws on the technology of racing boats to design a variable pitch propeller, which is optimised by hydrodynamic simulation and testing to increase speed by 20% and reduce energy consumption by 15%. The bionic tentacle base adopts industrial-grade high-precision joints (±0.1 ° control precision), combined with hollow nano-reinforced structure, which improves strength by 40% and reduces weight by 10%. The three-layer composite coating technology (anti-corrosion inner layer, wear-resistant middle layer and hydrophobic outer layer) adopted for the outer shell has been tested to reduce the corrosion rate by 80%, surface wear by 60% and the probability of biological attachment by 90%, thus strengthening the long-term operational reliability.

5.2 Rescue organisation performance test

The team members have completed the modelling and printing of the single claw of the bionic octopus claw rescue mechanism and the physical drawing is shown in Figure 2.

Figure 2 Rescue mechanism single claw model drawing

The single claw model is 3D printed by FDM process, with a joint range of motion of 270 °, and a measured end grasping force of 4.8N, which can stably grasp simulated falling objects with a diameter of 10-25cm (e.g., life buoys, dummy arms). In the water tank test with a current speed of 1.5m/s, the tracking error of the tentacle on the moving target is <3cm, and the successful grasping rate reaches 91%. Together with the overall test of the robot, under the wave height of 0.8m, the bionic tentacle took 1.2s from recognition to grasping, 85% higher than that of the winch mechanism (8s), which verifies its ability to work efficiently in complex environments.

6. Conclusions

In this study, a water intelligent rescue robot and a bionic octopus tentacle rescue mechanism adapted to the complex water environment are developed through the principle of bionics and modular design. The asymmetric buoyancy chamber and variable pitch propeller enhance the stability and propulsion efficiency of the robot, and the multi-joint flexible structure combined with vector control breaks through the limitations of traditional robotic arm grasping and realises dynamic target adaptive grasping. The prototype has excellent stability and efficiency in simulated turbulence, and the performance of the bionic tentacle is better than that of traditional solutions. In the future, it will optimise the multi-robot collaborative algorithm, deepen the AI autonomous decision-making to promote the automation of the whole process, provide more efficient and safe technical support for water rescue, and help upgrade China's special rescue equipment.

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