Design and simulation analysis on underwater robots like reptiles

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Abstract. In order to clean up debris with a certain depth of water and a stepped section, an underwater mobile robot with four legs walking was designed. Used the engineering method to calculate the force of the robot roller cutter, and the step of one motion cycle is calculated by the geometric relationship of the robot travel mechanism. The hydrodynamics simulation was carried out using simulation analysis. The results show that the maximum horizontal displacement of a robot during a motion cycle is 0.45m; the buoyancy water tank is more buoyant than gravity when it is waterless; the local maximum stress and displacement of the drum cutter and the main frame meet the working requirements; the corresponding hydraulic cylinder provides more driving force than the hydraulic cylinder resistance. This four-foot dredging robot can provide reference for the underwater motion of the multi-foot underwater robot and its water resistance analysis.

1. Introduction
At the bottom of deep-water reservoirs, lakes, and urban rivers, the problem of sludge accumulation has been very serious [1]. This paper proposes a four-legged dredging robot that can work in terrain that is difficult to adapt to dredging vessels and crawler dredge vehicles [2]. Like the multi-footed underwater robot [3], the four-legged dredging robot moves forward with its four legs. Therefore, it is very important to analyse the movement gait and the underwater force of the dredging robot. The University of Toronto, Ontario, Canada, invented an automatic gait synthesis system for underwater walking robots [4]. South Korea’s Ocean Engineering Systems Research Department conducted hydrodynamic analysis of its multi-footed underwater robot and optimized the shape of the legs to reduce water resistance [5]. Jiman Luo analysed the fluid-solid coupling strength of dredging robots [6]. Yongjie Pang used computational fluid dynamics (CFD) to analyse the variation of water resistance of underwater robots with different flow rates and different shapes [7].

2. Overall scheme design

2.1. Structure and working principle of the robot
The four-legged dredging robot consists of a main frame, a dredging mechanism, a walking mechanism, a heave mechanism, a hydraulic module and an electronic module. The structure schematic diagram of the four-legged dredging robot is shown in ‘figure 1’. The robot receives voltage...
and control signals from the land with the aid of the umbilical cord cable [8]. The electronic module
controls the corresponding solenoid valves and various circuit components and the hydraulic module
is responsible for powering hydraulic and hydraulic motors. The dredging mechanism of the robot
includes a drum reamer that smashes the underwater sludge into a slurry and then the mud pump in the
dredging mechanism transports the sludge to the ground. The bottom of the dredging mechanism is
hinged to the main frame, and a hydraulic cylinder connected to the top of the dredging mechanism to
increase its working range.

![Figure 1: Structure diagram of four-legged dredging robot.](image)

2.2. Movement principle
The heave mechanism consists of four ballast tanks fixed at the four corners of the main frame. The
upward and downward movement of the robot is accomplished by adjusting the volume of water in the
ballast tank. The dredging robot's walking principle is complicated. The walking mechanism has four
legs and the movement state of each leg is controlled by two hydraulic cylinders connected to it. The
specific walking process is the synthesis of many periodic gaits. Each of the periodic gaits consists of
four motion steps, which can be seen in 'figure 2'.

![Figure 2: Motion diagram of walking mechanism.](image)

- In step a, the swing hydraulic cylinders connected to the legs and the main frame at both ends
working, the two swing hydraulic cylinders in front of the main frame are shortened, and the
remaining two swing hydraulic cylinders are elongated. This process moves the four feet of the
dredging robot forward.
- In step b, four leg hydraulic cylinder piston rods fixed to the legs and in parallel with the legs are
elongated to change the abdominal support state into leg support state.
- In step c, the swing cylinder piston rods are returned to the initial position, at which time the
centre of gravity of the dredging robot moves forward a distance.
- In step d, the piston rods of the outrigger hydraulic cylinder are shortened, and the leg support
state becomes abdominal support state. The robot returns to the initial state of motion.
2.3. Related calculations and selection of hydraulic components

2.3.1. Calculation of drum reamer. Using an empirical value algorithm to calculate the cutting resistance and power of the drum cutter of the four-legged dredging robot to select the matching hydraulic motor [9]:

\[
F_i = \frac{\tau \cdot t \cdot b}{\cos(\theta - \alpha - \delta) \cdot \sin \theta}
\]

(1)

\[
P = \sum_{i=1}^{n} P_i = \sum_{i=1}^{n} \frac{0.35 \times F_i \times n \times r}{716 \times 0.736}
\]

(2)

where, ‘\(\tau\)’ is the shear stress of the soil; ‘\(t\)’ is the cutting thickness; ‘\(\theta\)’ is the shear angle, ‘\(\alpha\)’ is the blade angle; ‘\(\delta\)’ is the surface friction angle; ‘\(b\)’ is the effective width of the blade ‘\(r\)’ is the radius of the cutter; ‘\(n\)’ is the rotation speed and ‘\(m\)’ is the number of blades for the cutter.

The cutting resistance of the blade of the drum reamer can be broken down into forces in three different directions. ‘\(F_a\)’ is the axial force along the axis of the reamer. ‘\(F_n\)’ is the normal force in the direction perpendicular to the reaming axis. ‘\(F_t\)’ is the circular force along the circumferential direction of the reamer shaft. ‘\(F_a\)’, ‘\(F_n\)’ and ‘\(F_t\)’ can be calculated using the following formula:

\[
F_a = \frac{C_a M}{R}, \quad F_n = \frac{C_n M}{R}, \quad F_t = \frac{C_t M}{R}
\]

(3)

\[
M = \frac{9549 P}{1000 N}
\]

(4)

where, ‘\(C_a\)’ is the axial force coefficient of the cutter; ‘\(C_n\)’ is the normal force coefficient of the cutter; ‘\(C_t\)’ is the circumferential force coefficient of the cutter; ‘\(N\)’ is the rotating speed of the cutter and ‘\(M\)’ is the torque of the cutter.

2.3.2. Selection of hydraulic components. Combine the actual requirements and related calculations to select the hydraulic actuators and mud pump of the dredging robot. ‘Table 1’ shows the parameters of each hydraulic cylinder of the walking mechanism. ‘Table 2’ and ‘Table 3’ show the operating parameters of the hydraulic motor and mud pump of the dredging mechanism respectively.

| Table 1. Parameters of hydraulic cylinders |
|-------------------------------------------|
| Inner diameter of the hydraulic cylinder (mm) | Diameter of the piston rod (mm) | Piston rod stroke (mm) |
|-------------------------------------------|
| **Outrigger hydraulic cylinder**          | 100                                  | 50                               | 800                                   |
| **Swing hydraulic cylinder**              | 100                                  | 50                               | 600                                   |
| **Pitch hydraulic cylinder A**            | 100                                  | 50                               | 700                                   |
| **Pitch hydraulic cylinder B**            | 80                                   | 40                               | 500                                   |

| Table 2. Working parameters of hydraulic motor |
|-----------------------------------------------|
| Displacement (mL/r) | Rated pressure (MPa) | Range of rated speed (r/min) | Rated torque (N-m) |
|---------------------|----------------------|-----------------------------|-------------------|
| 397                 | 25                   | 15-630                      | 1483              |

| Table 3. Working parameters of mud pump      |
|----------------------------------------------|
| Flow (m³/h) | Lift (m) | Rated speed (r/min) | Rated power (kW) |
|-----------|---------|---------------------|-----------------|
| 80        | 36      | 2900                | 18.5            |
2.3.3. Step calculation of the walking mechanism. Establishing a mathematical model of the walking mechanism is the first step, as showed in ‘figure 3’. Then the horizontal displacement of the front and rear legs when the piston rod of the hydraulic cylinder is in the maximum extension state and the minimum contraction state should be calculated.

‘A’ is the distance between the hinge of the main frame and the leg to the hinge of the pivot and the swing hydraulic cylinder in the direction of the leg and ‘B’ is the distance of vertical to the leg direction. ‘C’ is the distance from the end of the leg to the hinge of the main frame and the leg. ‘D’ is the distance from the centre of the frame to the hinge of the main frame and the leg. ‘E’ is the maximum variation of the piston rod of the leg hydraulic cylinder. ‘L’ is the length of the swing hydraulic cylinder.

Figure 3. Mathematical model of the walking mechanism.

Before the leg step is sought, the angle of rotation of the leg is required, that is, change value of the angle ‘α’ in ‘figure 3’. The maximum displacement of the swing cylinder piston rod elongation and recovery is 300mm. When the piston rods of the two swing hydraulic cylinders move to the maximum and minimum positions respectively, the angle ‘α’ changes to ‘αₙ₁’ and ‘αₙ₂’. The horizontal distances ‘S₁’ and ‘S₂’ that the front and rear legs move forward are calculated by the following formula:

\[
\alpha = \cos \frac{A^2 + B^2 + D^2 - L^2}{2\sqrt{A^2 + B^2} \cdot D}
\]

\[
S_1 = (C + E) \cdot \sin(\alpha - \alpha_n)
\]

\[
S_2 = (C + E) \cdot \sin(\alpha_n - \alpha)
\]

It is calculated that the horizontal distances ‘S₁’ and ‘S₂’ are 0.55m and 0.45m respectively. To keep the dredging robot running continuously, the maximum step distance for each robot is 0.45m.

3. Water resistance simulation analysis

3.1. Establishment of simulation model

3.1.1. Selection of turbulence model. The motion state of the surrounding water flow when the four-legged dredging robot is working can be regarded as turbulent motion [10]. The turbulence model is chosen as the standard k-ε model because the dredging robot’s working environment is subject to less eddy currents and wall constraints and most cases are isotropic uniform turbulence. The turbulent kinetic energy ‘k’ and the dissipation rate ‘ε’ of the standard k-ε model is calculated by the following formula [11]:

\[
\frac{\partial \left( \rho k \right)}{\partial t} + \frac{\partial}{\partial x_j} (\rho ku_j) = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} + G_k + G_s - \rho \varepsilon - Y_k
\]
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu}{\sigma_k} \right) \frac{\partial u_i}{\partial x_j} \right] + C_{ti} \frac{\varepsilon}{k} (G_k + C_{sg} G_b) - C_{2\varepsilon} - \rho \frac{\varepsilon^2}{k}
\]

where, ‘\(u\)’ is the average velocity. \(G_k\) and \(G_b\) are the turbulent pulsating kinetic energy caused by the average velocity gradient and buoyancy effects respectively. ‘\(Y_{t\delta}\)’ is the influence of the turbulent expansion on the total dissipation rate. ‘\(\sigma_k\)’ and ‘\(\sigma_{\varepsilon}\)’ are the turbulent Prandtl numbers of ‘\(k\)’ and ‘\(\varepsilon\)’ respectively. ‘\(\mu\)’ is the viscosity coefficient. ‘\(C_{ig}\)’ is the model constant.

### 3.1.2. Establishment of a computational model

The structure of the robot is quite complicated, and the calculation of simulation is too large when the model is directly used for simulation. Therefore, a simplified three-dimensional model of the four-legged dredging robot is established[12], as showed in ‘figure 4’. In order to simulate the actual working environment, the calculated water area adopts a rectangular parallelepiped. According to the length × width × height (L × B × H) of the robot, the distance between the entrance and exit to the centre of the robot is set to 5L. The distance between the two sides of the calculated water area to the centre of the robot is 3B, and the distance from the robot to the upper surface is 4H. The dredging robot calculation model is shown in ‘figure 5’.

**Figure 4.** Simplified three-dimensional model of dredging robot.

**Figure 5.** Water resistance calculation model of dredging robot

### 3.2. Simulation analysis

After the calculation model is meshed and the initial conditions are set in Fluent software, the calculation model is simulated. ‘Figure 6’ is a water flow diagram of the calculation area. It can be seen from the figure that the water flow impact mainly acts on the front surface part of the dredging robot, and the water flow is distributed on the front surface of the dredging mechanism and the front surface of the buoyancy tank. ‘Figure 7’ is a surface pressure cloud diagram of the simplified dredging robot model under the impact of water flow. It can be seen from the figure that the front surface of the dredging mechanism of the robot, the buoyancy tank and the four legs are subjected to a large positive pressure. There is a large negative pressure on the side of the entire robot, and the rest is relatively gentle. [13]. According to the simulation results of Fluent software, the total water resistance of the dredging robot is about 3700N. Swing hydraulic cylinders have a maximum thrust and maximum tensile force of 11775N and 8831N under the working pressure of 2MPa. Obviously, the combined force of the swing hydraulic cylinder in the horizontal direction is greater than the water resistance of the robot, and the resultant force of the outrigger hydraulic cylinder in the vertical direction is also greater than the weight of the robot.
4. Conclusion

The four-legged dredging robot not only has the functions of other dredging equipment, but also can walk with a special movement principle and achieve heave movement underwater. The power and driving force of the selected hydraulic motor is greater than the calculated force and power of the drum reamer. Similarly, the selected swing hydraulic cylinder and outrigger hydraulic cylinder can overcome the horizontal and vertical resistance of the robot. Using the length of the piston rod of the hydraulic cylinder and other related dimensions, the horizontal displacement of a four-legged dredging robot during walking is about 0.45m.

Because the front surface of the robot is severely impacted by the water flow, the front surface of the robot is stressed. In order to ensure that the dredging robot can work for a long time, the surface of the robot perpendicular to the direction of the water flow and the side of the leg need to be strengthened. If necessary, the model of the dredging robot should be optimized to reduce water resistance. Gait design of the walking mechanism is the key to the robot movement. The gait analysis of the walking mechanism is the key to the robot movement. To accurately control the walking of the robot, it is necessary to study its motion gait and related algorithms more deeply.

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