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THE ADAPTABLE AMPHIBIOUS WHEEL-LEGGED ROBOT

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ABSTRACT

A new category of the large diameter adaptable amphibious wheel-legged robot is proposed in this paper. The proposed mechanism can achieve a greater ability to climb obstacles. The D-H coordinate system is used for kinematics analysis, and the constructed kinematics model is used to solve these joint variables for redundant robot. According to the control strategy which is based on foot trajectory and gait planning, the foot trajectory of the amphibious robot is planned, which is also optimized to meet the operation performance in the special environment, as well as the planning of the walk gait. Then the control system is distributed in closed space. Then related simulation is used to verify the usefulness of the planned foot trajectory and walk gait in the entire running cycle, and related circuit is designed to solve the commutation problem of Arduino and AX-12 servo. Finally, the foot trajectory of the single robot leg is captured by the three-dimensional motion capture system to verify the rationality of the foot trajectory and walk gait.

Keywords: Wheel-legged robot; kinematics; workspace; control system; foot trajectory; Walk gait
1. INTRODUCTION

With the demand of the adaptable amphibious robots in a non-structural environment, the wheel-legged robots are required to switch different operation mode according to different environments (Hu 2014). In order to realize both high speed running on flat areas and efficient movement on rough environment, there is much research of the wheel-legged robots have been done (Yoshino 2008). At present, there is a common problem in the amphibious wheel-legged robot. The leg-type operation mode and the wheel-type running mode of the wheel-legged can’t be guaranteed the high efficiency and stability of the operation at the same time (Hirose 1980). The direct cause is the structure design of the robots, such as, (a): previous leg mechanisms with the wheels at the end of the legs (Endo 2000), (b): the wheel modules on the body of the robots (Suwannasit 2004), (c): wheel-legged mechanisms have the wheel smaller than the leg mechanism as a whole (Tantichattanont 2007).

On one hand, there are many situations ignoring the running capacity in wheeled mode under the premise of the pursuit of operation performance in legged mode, especially on the aspect of the small wheel diameter structure of the robot in the wheeled mode (Ji 2013). The robot in wheeled mode can’t go through the obstacles when the obstacles reach a certain height or a certain width; on the other hand, the robot risks running capacity in legged mode to ensure high speed in wheeled mode (Hirose 1995), which greatly weakened the running capacity of the robot in the unstructured environment. Based on these situations, a new type of the adaptable wheel-legged robot is proposed to improve the performance of the wheel-mode running capacity under the premise of ensuring the leg-mode operation ability. As aging progresses, the elder are inconvenient to move, the adaptable amphibious wheel-legged robot can transport objects in the legged mode on rugged terrain and in a wheeled mode on a flat surface.

In this paper, according to a series of terrain situation that the robot may encounter, foot trajectory and operation gait should be planned in premise of ensuring the structure performance of the robot. Related polynomial interpolation and compound cycloid are taken into consideration, finally, the optimized quadratic polynomial interpolation and linear combination is chosen as the food trajectory when the robot is running on the rugged road. This trajectory reduces the number of acceleration and deceleration effectively, and improves the defects of the foot trajectory to ensure the operation efficiency of the robot. Then, it will produce a deflection torque because of the designed structure of the wheel-leg robot, and a walk gait is planned to solve this problem. Finally, the feasibility of control strategy which is based on foot trajectory and gait planning is verified by related simulation and experiment.
This new type of mechanism increases the wheel's obstacle-to-barrier performance and the ability to convert wheels and legs to each other. During the operation of the robot, the planned Walk gait can correct the robot's displacement deviation due to the deflection torque and ensure that the robot runs in a straight line. The optimized trajectory can improve the robot's ability to adjust in a non-institutional environment. With the deepening of research, the visual control and ultrasonic shielding can be applied to the robot in some unstructured environments, such as emergency rescue, anti-terrorism, military transport, field exploration, and especially underwater operations.

2. ROBOT STRUCTURE

Based on the present situation, the wheel-legged robot designed in this paper can ensure the high stability in the legged mode and guarantee the high speed running in the wheeled mode. The wheel-legged robot can also switch the different operation mode according to the different operation environment (Giesbrecht 2012). In this paper, the robot is driven by the AX-12 servo and digital servo, which can ensure the fastness of the signal transmission and the structure is simplified (Zhou 2018), which also enhances the operation performance of the robot in the unstructured environment and improves the effectiveness of the robot control.

2.1 STRUCTURE DESIGN OF THE WHEEL-LEGGED ROBOT

This designed wheel-legged structure of the amphibious robot is shown in Fig.1.

The wheel-legged mechanism of the robot consists of the front wheel plate, the middle wheel plate and the end wheel plate. The three wheel plates are distributed on the different planes. The AX-12 servo and digital servo are chosen as the power source in this paper, they are built inside of the wheel plate, and then the wheel plate can be filled and sealed to ensure the power source and water are completely isolated, follow-up to achieve underwater operation, the wheel plate can be rotated back and forth around the axis of the servo. The front wheel plate is driven by Ax-12 servo, and the digital servo is chosen to drive the middle wheel plate and the end wheel plate. The robot can rotate continuously in wheel mode, in order to avoid the stuck phenomenon of the wire, this paper selects the slip ring (Wang 2016), and it can solve this problem and transmit signals to achieve normal communication.

The robot switches the legged mode into a large wheel diameter mode by the rotation of the three wheel-plate joints of the leg mechanism. The mode switching mechanism is easy to implement. Each wheel has an arc size of 60°. The middle wheel plate is rotated by 60° relative to the front wheel plate. Similarly, the end wheel plate is also rotated by 60° relative to the middle wheel plate. Finally, the three wheel plates form a circular wheel.
(Uchida 2000), this wheel-legged switching mechanism is easy to implement, as shown in Fig.2. Due to the large
diameter of the wheel, the wheel-legged robot can climb a certain height of obstacles and gully in wheeled mode,
enhancing the running ability of the robot in wheeled mode (Tadakuma 2010).

2.2 THE PROTOTYPE OF THE WHEEL-LEGGED ROBOT

The overall prototype of the adaptable amphibious wheel-legged robot can be shown in Fig.3. The topology has
12 degrees of freedom, that is to say, one leg has three active degrees of freedom. It can be seen that the three
wheel plates are distributed on the different plane and the axis of the servo aren’t the center of the wheel plate,
therefore, the wheel-legged robot has a large movement space and good operation performance because of the
structure character. The leg mechanism of the robot is connected by a rigid structure to ensure the robot has
sufficient rigidity (Phung 2010). This wheel-legged robot has a total of 12 power sources which consist of four
AX-12 servo and eight digital servo.

From the Fig.3(b), the axis of three wheel plates are parallel to each other, and then the leg of the robot only
can operation in a plane when the body of the robot is fixed, therefore, the wheel-legged robot belongs to the
redundant robot. The structural parameters of the adaptable amphibious wheel-legged robot are shown in Table
1. The parameters from the table 1 show the body size, overall size and weight of the robot.

The initial shape of the robot’s prototype in legged mode and wheeled mode are shown in Fig.4. This robot has
a large wheel diameter in the wheeled mode while it still has a large operating space in the legged mode. This
mechanism ensures both operational efficiency and obstacle performance. Active source of the middle plate and
the end wheel plate select digital servo in this paper, and digital servo can rotate among 0~180°, it can meet the
need of the robot in legged mode. Active source selects AX-12 servo in this paper. AX-12 servo can control more
accurate and possess two operating modes-free mode and lock mode. it is free to rotate between 0~300° in lock
mode exception 300°~360° area, it can meet the needs of legged mode running, it can also rotate 360° in free
mode and meet the wheel running needs of the robot in wheeled mode. The robot can run by driving AX-12
servo rotate continuously. These servos can also feedback position, temperature, load and voltage information.

3. **D-H KINEMATICS SYSTEM OF THE LEFT FRONT LEG**

In this paper, the D-H coordinate system is used for kinematics analysis about the adaptable wheel-legged
robot(Li 2017). As shown in Fig.5.
From Fig. 5, the running direction of the wheel-legged robot is defined as the $x$-axis, the axis direction is $z$-axis, and the $y$-axis direction is determined according to the right-hand rule. According to the D-H parameter method, the relevant D-H parameters of the robot’s left front leg are obtained. The adaptable amphibious wheel-legged robot maintains a steady state in the initial state of the body, so the reference coordinate system $\{o_1\}$ is located at the centre of the body. The size of the robot’s body is as follows: length $a$, width $b$, height $c$.

Then the corresponding linked parameters of the left front leg can be defined in the established D-H coordinate system, as follows: $l_i$: Length of the vertical line between adjacent joint axes, that is, the distance from $z_{i-1}$ to $z_i$ along $x_i$; $d_i$: The distance between adjacent vertical lines, that is, the distance from $x_{i-1}$ to $x_i$ along $z_i$; $\theta_i$: The angle between adjacent vertical lines, that is, the rotation angle from $x_{i-1}$ to $x_i$ along $z_i$; $\alpha_i$: The angle between $z_{i-1}$ and $z_i$. It needs to transform by the translation coordinate transformation and the rotation coordinate transformation from coordinate system $\{o_1\}$ to the coordinate system $\{o_5\}$ for the robot model. From Fig. 5, there is a transform transformation and two rotation transformation from coordinate system $\{o_1\}$ to the coordinate system $\{o_5\}$, and the mount of the transform transformation is $[a/2, b/2, -c/2]$, and the two rotation transformations as shown in Fig. 6.

The D-H parameters of the left front leg from coordinate system $\{o_2\}$ to the coordinate system $\{o_5\}$ can be shown in Table 2 below. In this paper, the designed robot structure belongs to the redundant structure, and the leg of the robot leg can’t be outside, so there is no rotation around the $y$ axis when robot’s body is fixed, that is, $\theta_i = 0$, similarly, the coordinate points $o_1$ and $o_2$ are in the same vertical plane, that is, $d_i = 0$.

According to the established D-H coordinate system, the geometric relationships of the leg are acquired. The overall transformation matrix of the wheel-legged robot from coordinate system $\{o_5\}$ to the coordinate system $\{o_3\}$ is shown in the following equation 1.

$$
\begin{bmatrix}
-s_{2+3+4} & -c_{2+3+4} & 0 & \frac{a}{2} & -l_5 s_{2+3+4} + l_4 s_{2+3} + l_3 s_2 \\
0 & 0 & 1 & d_4 + d_3 + d_2 + \frac{b}{2} & 0 \\
-c_{2+3+4} & s_{2+3+4} & 0 & -l_5 c_{2+3+4} - l_4 c_{2+3} - l_3 c_2 - l_1 - \frac{c}{2} & 0 \\
0 & 0 & 0 & 1 & 0
\end{bmatrix}
$$

(1)

Where: $s_i = \sin \theta_i; c_i = \cos \theta_i; s_{i+j} = \sin(\theta_i + \theta_j); c_{i+j} = \cos(\theta_i + \theta_j); s_{i+j+k} = \sin(\theta_i + \theta_j + \theta_k); c_{i+j+k} = \cos(\theta_i + \theta_j + \theta_k)$. 

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We use Matlab to model the left front leg of the amphibious wheel-legged robot, as shown in Fig.7(a), and the correctness of the kinematics equation 1 is verified by calling the \texttt{fkine()} function, we don’t describe here in detail. The simulation workspace of the left front leg is carries out, as shown in Fig.7(b). Fig.7(b) shows that the wheel-legged robot has a larger foot-end workspace (Zhu 2010). According to the rotation range of the AX-12 servo and digital servo, where, \( \theta_1 = -150^\circ -150^\circ \), \( \theta_2 = -120^\circ -60^\circ \), \( \theta_3 = -120^\circ -60^\circ \).

The adaptable amphibious wheel-legged robot belongs to the redundant robot in the legged state, which needs to increase the joint constraints to get these variables. First, we will analysis the difference of the foot workspace by fixing \( \theta_2 \), \( \theta_3 \) and \( \theta_4 \) at a certain value respectively and obtain the best constraint scheme. As shown in Fig.8. Different color range represents different foot operation workspace of the robot in legged mode.

As shown in Fig.8(a) and Fig.8(b), the foot-end workspace distribution is good only in a small part when fixing \( \theta_2 \) at a certain value, but there is a great part of the region can’t reach. As shown in Fig.8(e) and Fig.8(f), the foot-end workspace is uniformly distributed in a full circle when fixing \( \theta_4 \) at a certain value, but there is a lack of thickness, it is possible to cause the robot to have poor ability to adjust the height of the body during the operation. When the variable \( \theta_2 \) is fixed, the workspace of the amphibious wheel-legged robot is largest in legged mode. As shown in Fig.8(c) and Fig.8(d). Therefore, when inverse kinematics calculation is carried out, the middle plate variable \( \theta_1 \) is fixed. The angles of the wheel plate are obtained by a series of operations, these variables are as follows. \( \theta_2 \), \( \theta_3 \) and \( \theta_4 \) are solved by inverse kinematics, as shown in Equation 2.

\[
\begin{align*}
\theta_2 &= \arccos\left( \frac{N}{W} \right) \\
\theta_3 &= \theta \\
\theta_4 &= \arccos\left( X / \sqrt{A^2 + B^2} \right) - \theta_3 - \alpha
\end{align*}
\]

Where, \( W = (l_1 + 2l_1p_1 + 2l_4) ; A = 2l_1l_4 + 2l_1l_4 \cos \theta_3 ; B = 2l_1l_4 ; \alpha = \arcsin\left( \frac{B}{\sqrt{A^2 + B^2}} \right) ; \)

\[
\begin{align*}
M &= (a / 2 - b_2)^2 + (b / 2 + p_2)^2 + l_3^2 + (bl_1 + 2p_1l_1) - (l_2^2 + l_1^2 + l_4^2 + 2l_1l_3 \cos \theta_3) \\
N &= l_2^2 + l_3^2 + 2l_1l_4 \cos(\arcsin(M / \sqrt{A^2 + B^2}) - \theta_3 - \alpha) - [(a / 2 - b_2)^2 + (b / 2 + p_2)^2 + l_3^2 + l_1^2].
\end{align*}
\]

4. **CONTROL SYSTEM OF THE WHEEL-LEGGED ROBOT**
A good operation performance is required when the wheel-legged robot works in unstructured environment, and the key point is the control system (Sarkar 2010). This control system consists of hardware and software. Design of the hardware and software are completed in this paper (Zhu 2010). The control system of the wheel-legged robot shows in Fig.9.

The control system of the robot is composed of a central processing unit, two motion control system and a communication system (Ding 2017 and Khodayari 2015). This central processing unit is Arduino control board which is an ARM chip. The AX-12 servo and digital servo are chosen as power source which drive the wheel plate to rotate. The front wheel plate is driven by the AX-12 servo, and the middle wheel plate and the end wheel plate are driven by digital servo. Digital servo is directly driven by 16 road servo control panel which is commutating with Arduino by I^2C signal. AX-12 servo uses UART protocol communication. The UART is a universal serial data bus for half-duplex communication. But Arduino serial port uses a full-duplex protocol communication, which led to the fact that the Arduino can’t control the AX-12 servo directly. Based on this situation, this paper sets up an external half-duplex circuit to generate control signals which are used to drive the AX-12 servo. The circuit uses a 74LS241n receiver transceiver and a 10k ohm pull-up resistor to build an external circuit which is used to generate a half-duplex circuit to drive the AX-12 servo. The 74LS241n receiver transceiver consists of three-state-four-buffer driver and inverter. As a result, Arduino drives AX-12 servo successfully. This control system drives the robot to operate normally through the cooperation between the AX-12 servo and the digital servo.

5. THE OPTIMIZED FOOT TRAJECTORY OF THE WHEEL-LEGGED ROBOT

It will have a greater impact force between foot and ground when the wheel-legged robot is in the running process in legged mode, therefore, it’s necessity to plan the foot trajectory of the wheel-legged robot rationally. The trajectory can minimize the impact force when the robot lifted the legs and landed the ground, and the foot trajectory is also smooth and continuous, and the running speed and acceleration of each wheel plate are smooth...
and no singularity, which can prevent the wheel-legged mechanism from the impact of high speed effectively (Jiang 2018).

The foot trajectory of the wheel-legged robot on the larger fluctuating road surface has always been a difficult problem. Due to the complexity of the operating environment, which requires the robot’s foot have a certain swing height, better speed and acceleration properties. In view of the complexity of the robot operating environment, in order to ensure the stability of the robot’s operation efficiency when the robot operation in the gully low-lying road, we must ensure that the robot's operating rate, it’s necessity to try to avoid the change number of acceleration and deceleration, The foot trajectory analysis of wheel-legged robot shows Fig.10. Where, \( H_1 \) and \( H_2 \) are the maximum height of the swing phase, \( S \) is the length of swing phase.

The foot trajectory equation of the swing must ensure the uniformity of the running speed based on image fitting, as shown in Fig.10(a). Three kinds of foot trajectory are taken into consideration. The brown line (dotted line1) is expressed as the foot trajectory curve based on the on compound cycloid, and the middle distance of the curve is more abrupt. The actual height of the robot can’t reach (Tian 2010). The purple solid (solid line2) and the red line (solid line3) are expressed as the foot trajectory curve based on the on polynomial interpolated, and it can be seen that the high-order polynomial interpolation of the foot trajectory is more suitable for the operating environment, therefore, foot trajectory of swing chooses cubic polynomial interpolation in the z-axis under the premise of maintaining a certain height, if the foot trajectory still uses cubic polynomial interpolation in the x-axis, and this is closely linked with the offset distance of the robot’s gravity center, but the distance can’t reach such a length in the premise of maintaining stability, curve fitting results as shown in Fig.10(b) (purple solid), therefore, foot trajectory of swing chooses quadratic polynomial interpolated in the x-axis, curve fitting results as shown in Fig10(b) (red solid), which is more consistent with the foot trajectory of the robot, it also ensures the smoothness of the foot displacement, velocity and acceleration, follow-up will be verified by a series of simulation and experiment.

During operation of the robot swing phase, the support phase of robot need to adjust the pose position when the support phase and the swing phase are not in the same horizontal plane, as shown in Fig.11, which will
cause the movement of support phase, since movement of support phase is small in the inclined road surface, so the support phase are small displacement movement in $x$-axis and $z$-axis direction. If the polynomial is used for the foot trajectory, it is inconsistent with actual length and height. Therefore, linear equations are selected as foot trajectory equations of the support phase, as shown in Fig.11 (the red arrow), and it is more suitable for the foot trajectory of the wheel-legged robot in this paper. In summary, the adaptable amphibious wheel-legged robot uses a foot trajectory based on polynomial interpolation and linear combination in legged mode, as shown in Equation 3.

$$
\begin{align*}
    x_{\text{swing}}(t) &= a_i + b_i t + c_i t^2 + d_i t^3 + e_i t^4 \\
    z_{\text{swing}}(t) &= a_i + b_i t + c_i t^2 + d_i t^3 \\
    x_{\text{stand}}(t) &= k_i t + e_i \\
    z_{\text{stand}}(t) &= k_i t + e_i
\end{align*}
$$

Where $a_i, b_i, c_i, d_i, e_i (i=1,2)$ are unknown constant in the equation, $x_{\text{swing}}(t)$ and $z_{\text{swing}}(t)$ are the trajectory equations of the swing phase in $x$-axis and $z$-axis, $x_{\text{stand}}(t)$ and $z_{\text{stand}}(t)$ are the trajectory equations of the support phases of the robot in $x$-axis and $z$-axis direction.

The trajectory equation of the wheel-legged robot satisfies the relevant constraints in $x$-axis direction.

$$
\begin{align*}
    x_{\text{swing}}(0) &= 0, \quad x_{\text{swing}}(T/2) = s_i, \quad x_{\text{swing}}(T) = T, \\
    x_{\text{stand}}(0) &= s_i, \quad x_{\text{stand}}(T) = T
\end{align*}
$$

Then the equations 4 are obtained as follows.

$$
\begin{align*}
    x_{\text{swing}}(t) &= \frac{2h}{T} t^2 + \frac{64H_0}{T^2} t^3 + \frac{-256H_0}{T^3} t^4 + \frac{64H_0}{T^4} t^5 \\
    x_{\text{stand}}(t) &= s_i + \frac{e_i}{T} (0 \leq t < \frac{T}{2})
\end{align*}
$$

The trajectory equation of the wheel-legged robot satisfies the relevant constraints in $z$-axis direction.

$$
\begin{align*}
    z_{\text{swing}}(0) &= 0, \quad z_{\text{swing}}(T/4) = H_o, \quad z_{\text{swing}}(T/2) = 0, \quad z_{\text{swing}}(T) = 0, \\
    z_{\text{stand}}(0) &= s_o, \quad z_{\text{stand}}(T) = 0
\end{align*}
$$

Then the equations 5 are obtained as follows.

$$
\begin{align*}
    z_{\text{swing}}(t) &= \frac{2s_o}{T} t^2 + \frac{12(s_o - s_i)}{T} t^3 + \frac{16(s_o - s_i)}{T} t^4 \\
    z_{\text{stand}}(t) &= \frac{2h}{T} t^2 - h_o
\end{align*}
$$
In this paper, the foot height $H_o$ is 45mm, the step length $s_o$ is 160mm, $h_o$ is 2mm, $s_1$ is 5mm. Fig.12(a) and Fig.12(b) show the foot trajectory displacement curves based on the polynomial interpolation and the linear combination in x-axis and z-axis direction, Fig.12(c) shows composite curve of foot trajectory. Fig.12 (d) and Fig.12(e) show the velocity curves of foot trajectory in x-axis and z-axis direction. These curves of the foot trajectory are as the following.

It is useful to choose the foot trajectory based on polynomial interpolation and linear combination to plan the running route when the robot is running on a large undulating road such as rugged, gully and so on. This foot trajectory ensures the uniformity of the robot operation and avoids the slow running speed which caused by the acceleration and deceleration, and this scheme also takes into account the movement of the support phase in the pose adjustment process.

6. SIMULATION OF THE FOOT TRAJECTORY

At first, the wheel-legged robot model is constructed in Adams (Gao 2010). The planned walk gait process is shown in Fig.13 below. The robot has deflection torque due to the designed mechanism, therefore, In order to ensure that the robot runs in straight line, legs is running diagonally. During the complete gait cycle, the order of the robot's operating legs is as follows: the right hind leg, the left front leg, the left hind leg and the right front leg. The running process can be divided into six parts: initialization, center of gravity adjustment, raising the right hind leg, raising the left front leg, raising the left hind leg and raising the right front leg, and finally adjusting the center of gravity into the next running cycle.

The amphibious wheel-legged robot is running based on the planned foot trajectory and walk gait in two gait cycles, where, $T=10$s, as shown in Fig.14. The curve tui1.Velocity represents the running gait curve of the left front leg in two gait cycles. Both curves are smooth curves, and it can be confirmed that the robot in accordance with the planned foot trajectory and walk gait can guarantee a stable operation.

The following Fig.15 shows the centre displacement of the robot in the two running cycles. The curve Center_Position.X shows the operation displacement curve of the robot in the x-axis direction. The curve Center_Position.Z shows the displacement change curve in the z-axis direction.

A deflection torque will be generated when the robot runs, and it will cause a certain displacement deflection of the robot’s body, which will affect the running direction of the robot, therefore, displacement deflection will be revised constantly when the robot runs in planned walk gait, as shown in Fig.15(blue dotted line), The
revised process will cause small amount of movement in the opposite direction, as shown in Fig.15 (red solid line), so as to ensure the stability of the robot.

The body centre change of the robot in z-axis is shown in Fig.16. First of all, the body centre will down when the body lean forward, and then the position adjustment will cause height change of the body, there are four significant changes in one cycle, and finally, the robot body leans back to the initial state.

In order to get the planned foot trajectory, the three wheel plates need to be operated at the same time. This article takes the right hind leg as an example. Fig.17 shows the wheel plate angle curve of the robot’s left front leg in two gait cycles.

Curve Joint1 (red solid line), Joint2 (blue dotted line) and Joint3 (red dotted line) correspond to angle change curve of the end wheel plate, the middle wheel plate and the front wheel. As shows in following curves, these curves are smooth curves, which show the stability of the wheel plate transformation. Similarly, according to the operation order of leg, the rotation curves of the left front leg, the left hind leg and the right front leg are respectively shown in the following Fig.18, Fig.19 and Fig.20. The end wheel curve is shown by the red solid line in the figure, the curves of the middle wheel and the front wheel shown in blue dotted line and dashed red line. These wheel plate angle curves are also smooth.

At last but not least, the adequate power is also a significant factor, which can guarantee the normal operation of the amphibious robot. This article takes the right hind leg as an example. Fig.21 shows the required power of the end wheel plate in the entire walk gait running cycle. The required power of the end wheel plate is within the range of \([-600 \text{N/mm}, +600 \text{N/mm}]\), but the servo is within the range of \([-1790 \text{N/mm}, +1790 \text{N/mm}]\), therefore, the digital servo meets the functional requirements of the left front leg’s end wheel plate.

As shown in following curves, Fig.22 shows the required power of the front wheel plate and the middle wheel plate in the entire walk gait running cycle. The required power of the front wheel plate and the middle wheel plate is within the range of \([-1500 \text{N/mm}, +1500 \text{N/mm}]\), so the digital servo and AX-12 servo also meet the functional requirements, therefore, the wheel-legged robot can achieve normal operation by adopting the planned walk gait and the optimized foot trajectory.
Fig.23 shows the foot-end impact curve of the wheel-legged robot during the entire walk gait cycle. The red solid line, the blue dashed line, the red dashed line and the black dashed line correspond to the stress curves of the right hind leg, the left front leg, the left hind leg and the right hind leg respectively. The foot-end impact of the robot is within the range of [0, +50 N·mm], the impact value is relatively small and reducing the impact both foot and ground greatly.

According to a series of simulation which is based on the planned walk gait and the optimized foot trajectory, the wheel-legged robot can operate normally and stably, we verify the effectiveness of the foot trajectory by analyzing the leg speed, impact and power demand of the robot.

7. EXPERIENCE

We use the space three-dimensional motion capture system of American Motion Analysis Company to capture the foot trajectory curve of the adaptable amphibious wheel-legged robot. The accuracy of the space capture system is close to 0.1mm. As shown in Fig.24 below, the robot is surrounded by six CCD high-speed cameras whose frequency of image acquisition is about 20 frames per second. The camera is connected with PC by CAN bus, the Mark point is placed at the foot end of the left front leg. This robot operation according the planned walk gait and the optimized foot trajectory, and then the spatial trajectories of the left front foot are collected by the Cortex3.0 software.

Through real-time cooperation with the rotation of the three wheel plates of the wheel-legged robot to ensure that the foot end of the end wheel plate runs to the well-known point, In order to be more effective to capture the actual foot trajectory of the robot, the reflective point is placed at the foot end position of the robot as the mark point, and the foot trajectory of the robot are simultaneously captured by the 6 CCD high speed cameras. Where, the height of lifting left front leg $H=45mm$. This article takes the left front leg as an example. The foot trajectory movement process of the adaptable amphibious wheel-legged robot is shown in Fig.25.

The real motion trajectory of the robot is collected by the space three-dimensional motion capture system in the whole running gait. According to the foot trajectory of the robot, it can be seen that trajectory is not a smooth curve from Fig.26 (Blue solid line), reasons are as the following. Firstly, the full-duplex conversion half-duplex control circuit is designed to solve the problem that Arduino board can’t directly drive the AX-12 servo with half-duplex communication, then, the designed circuit wiring will produce larger impedance which
can lead to control the current is weakened; it will cause the control signal instability and the jitter phenomenon of the servo. Besides, in order to reduce the overall load and material of the wheel board whose material selects hard aluminium during the early robot design, this will cause slight deformation of the wheel plate for a long time running. Last but not the least, the foot target mark point is closer to wheel plate colour of the robot, and this will cause the CCD high-speed camera to have an impact on the capture of the foot end point. These reasons caused the fact that the actual foot trajectory of the robot is not a smooth curve.

The blue solid line is expressed as the foot trajectory curve based on the quadratic polynomial interpolation and linear combination. In summary, the proposed foot trajectory is more suitable for the trajectory of the wheel-legged robot. In this paper, the foot trajectory is still needs to be optimized. On one hand, we reduce the impedance and enhance control signal by improving circuit wiring, on the other hand, we use the Cortex 3.0 software to analyse the data of the foot mark points which show the data at the spatial position, these data are continually optimized, and then they are used to generate the actual foot trajectory of the robot finally. The actual foot trajectory (blue solid line) and planned target foot trajectory (blue solid line) are shown in Fig.27.

According to Fig.27, although it can be seen that the actual foot trajectory curve of the robot has a deviation from the planned foot trajectory in $x$-axis direction and $z$-axis direction, the overall movement curve is match with the planned foot trajectory curve. At last but not least, Walk gait of the wheel-legged robot in legged mode based on optimized foot trajectory is shows Fig.28, which shows that the control strategy based on the foot trajectory is feasible and reasonable.

8. CONCLUSION

In this paper, a new type of large diameter adaptable amphibious wheel-legged robot is designed according to the robot's operation performance requirements, which enhances the performance of the wheel-legged robot. The $D-H$ coordinate system is used for kinematics analysis, and the constructed kinematics model is used to solve these joint variables for redundant robot. Based on the planned walk gait and the optimized foot trajectory, the wheel-legged robot can achieve a greater ability to climb obstacles in the unstructured environment, and then the control system of the robot is built, this paper sets up an external half-duplex circuit to generate control signals which are used to drive the AX-12 servo. Finally, the superiority and correctness of the foot trajectory and walk
gait are verified by related simulation and experiment.

In future, we can improve the structural design of the adaptable amphibious wheel-legged robot, such as enhancing the overall sealing of the structure so that the robot can have a better adaptability in underwater environment, it’s also necessity to improve the robot structure size and enhance the operation performance of the robot. Then the deviation of the actual foot trajectory and the theoretical foot trajectory should be optimized continuously, the wheel-leg robot can ensure the high barrier and stability in the legged mode, guarantee the high speed running in the wheeled mode much better.

Acknowledgement

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References


Table 1. Parameter of the amphibious wheel-legged robot

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<th>Parameter</th>
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<td>Body Height</td>
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<td>Robot Weight</td>
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Table 2. The parameters of the left front leg from \( \{O_1\} \) to \( \{O_2\} \)

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<th>Distance ( d_i )</th>
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Fig. 1 Leg structure of the wheel-legged robot: (a) wheel plate connection diagram; (b) rotation diagram of the wheel plate

Fig. 2 Wheel structure of the wheel-legged robot: (a) Main view in wheeled mode; (b) Front view in wheeled mode

Fig. 3 The overall pattern of the wheel-legged robot: (a) Assembly side view of the wheel-legged robot; (b) The overall view of the wheel-legged robot

Fig. 4 The overall prototype of the amphibious wheel-legged robot: (a) Leg mode of the robot; (b) Wheel mode of the robot

Fig. 5 Kinematics system of the amphibious wheel-legged robot

Fig. 6 Rotation transformations from coordinate system \( \{o_o\} \) to coordinate system \( \{o_1\} \)

Fig. 7 Model and simulation workspace of the left front leg: (a) Model of the leg in Matlab; (b) foot-end simulation workspace of the leg in Matlab

Fig. 8 The foot workspace of the left front leg: (a) Negative point cloud of the front wheel plate. Where, \( \theta_2 = -25^\circ, -50^\circ, -75^\circ, -100^\circ, -125^\circ \) and \(-150^\circ\); (b) Positive point cloud of the front wheel plate, where, \( \theta_2 = 25^\circ, 50^\circ, 75^\circ, 100^\circ, 125^\circ \) and \(150^\circ\); (c) Negative point cloud of the middle wheel plate, where, \( \theta_3 = -10^\circ, -20^\circ, -30^\circ, -40^\circ, -50^\circ \) and \(60^\circ\); (d) Positive point cloud of the middle wheel plate, where, \( \theta_3 = 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ \) and \(60^\circ\); (e) Negative point cloud of the end wheel plate, where, \( \theta_4 = -10^\circ, -20^\circ, -30^\circ, -40^\circ, -50^\circ \) and \(60^\circ\); (f) Positive point cloud of the end wheel plate, where, \( \theta_4 = 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ \) and \(60^\circ\).

Fig. 9 the hardware control diagram of the wheel-legged robot

Fig. 10 Foot trajectory analysis of the wheel-legged robot: (a) Foot-end trajectory fitting analysis diagram; (b) Three kinds of foot trajectory diagram. Dotted line1: compound cycloid in x-axis and z-axis; solid line 2: cubic polynomial interpolation in the x-axis and z-axis; solid line 3: quadratic polynomial interpolation in the x-axis and cubic polynomial interpolation in the z-axis.

Fig. 11 Foot trajectory analysis of wheel-legged robot

Fig. 12 Foot trajectory of the wheel-legged robot: (a) displacement curve of foot trajectory in x-axis direction; (b) displacement curve of foot trajectory in z-axis direction; (c) composite curve of foot trajectory; (d) velocity curve of foot trajectory in x-axis direction; (e) velocity curve of foot trajectory in z-axis.

Fig. 13 Walk gait of the wheel-legged robot in legged mode: (a) initialization; (b) centre of gravity adjustment; (c) raising the right hind leg; (d) landing the right hind leg; (e) raising the left front leg; (f) landing the left front leg; (g) raising the left hind
leg; (h) landing the left hind leg; (i) raising the right front leg; (j) landing the right front leg; (k) centre of gravity adjustment.

Fig.14 Foot trajectory and speed curve of amphibious robot

Fig.15 Centre position of the wheel-legged robot in legged mode

Fig.16 The body centre change of the wheel-legged robot

Fig.17 The wheel plate angle curve of the right hind leg

Fig.18 The wheel plate angle curve of the left front leg

Fig.19 The wheel plate angle curve of the left hind leg

Fig.20 The wheel plate angle curve of the right front leg

Fig.21 The required power curve of the end wheel plate

Fig.22 The required power curve of the front and middle wheel plates

Fig.23 the foot-end impact curve of the wheel-legged robot

Fig.24 Foot trajectory experiment of the wheel-legged robot

Fig.25 Foot trajectory movement process of the wheel-legged robot

Fig.26 Foot trajectory comparison curve of wheel-legged robot

Fig.27 The optimized foot trajectory curve of the wheel-legged robot

Fig.28 Walk gait of the wheel-legged robot in legged mode: (a) initialization; (b) centre of gravity adjustment; (c) raising the right hind leg; (d) landing the right hind leg; (e) raising the left front leg; (f) landing the left front leg; (g) raising the left hind leg; (h) landing the left hind leg; (i) raising the right front leg; (j) landing the right front leg.
End Wheel Plate
Middle Wheel Plate
Front Wheel Plate
Slipring
AX-12 Servo
Digital Servo
Left front leg of the wheel-legged robot

(a)  
(b)
full-duplex protocol to half-duplex circuit