Motion Planning and Simulation of Combined Land-Air Amphibious Robot

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Abstract. In order to carry out complex tasks such as disaster rescue and field investigation, this paper designs a land-air amphibious robot that combines the four-legged walking robot and the quadrotor. The robot can not only perform structural separation according to operational requirements in order to realize land and air multi-field investigations. At the same time, the quadrotor can fly freely on the quadruped walking robot body to perform combined operations, providing more possibilities for multi-purpose investigation. The foot trajectory of the four-legged walking robot adopts the Bezier curve, and the center of the robot body is planned to move in a straight line, which can ensure the fluency, stability, and flexibility of the walking motion of the robot. The results of simulation and verification show that the combined land-air amphibious robot has excellent sport characteristics and has popularization and application value.

1. Introduction

In order to successfully carry out a variety of investigation operations under complex terrain and respond flexibly to changing environmental conditions, a land-air amphibious robot combining the advantages of aircraft and foot robots has emerged. The HyTAQ Robot developed by Arash Kalantari[1] of Illinois Institute of Technology combines a quadrotor and a cage, four-rotor mode is used for air flight, and ground motion is used to roll the cage by adjusting the attitude of the aircraft. Koji Kawasaki[2] developed a MUWA, a universal land, sea and air robot consisting of four variable-pitch propellers and a peripheral ring. These robots are integrated with the ground robots and cannot be separated and work alone. Moreover, the ground robots do not have speed and acceleration sensors and cannot accurately control the movement and cannot adapt to a complicated ground environment.

For a combined land-air amphibious robot, the motion planning of the quadrupedal walking robot is particularly important to enhance the adaptability to the ground environment. Currently used methods for gait planning include Wang Lipeng[3] using composite cycloids as the swing-phase plantar trajectory. Using this kind of foot-end trajectory can make the impact of the foot end fall to zero.

2. Land and Air Amphibious Robot Configuration Scheme

The combined configuration scheme combines the functions of a quadrotor and a quadrupedal walking robot to achieve the flexibility of a quadrotor and the superior ground adaptability of a quadrupedal
walking robot. They can achieve structural separation and perform reconnaissance missions in the land and air space respectively. Simultaneously, four-legged walking robots can be used as ground stations.

Four-rotor aircraft can freely land and assemble on a four-legged walking robot body to perform combined operations. This can accurately control the four-legged walking robot overcomes the complicated and varied ground environment and can simultaneously conduct the detection of land and air. The three-dimensional model is shown in Figure 1. The four-rotor aircraft is a standard four-rotor UAV, and the rack is in the form of an X configuration. Taking into account the speed of the walking of the four-legged walking robot, the leg adopts a compound structure of the legs. In this paper, the three degree of freedom leg configuration is adopted, so that the method of adjusting the center of gravity of the robot by adjusting the position of the leg has more choice and is more adaptable to the environment.

3. The foot robot’s movement analysis model
The positive kinematics of the robot is a method which is on the basis of knowing the type of each joint of the robot, the size of the adjacent joints and the relative amount of the adjacent joints, and finally determines the posture of the robot end in a fixed coordinate system[4]. According to the configuration scheme of the robot, the D-H method was used to establish the leg 2 coordinate system for the whole robot model, as shown in Figure 2. According to the D-H parameter table, the transformation matrix of the foot-end with respect to the fuselage is obtained, and the coordinates of the foot-end trajectory point are further obtained. This is the solution of forward kinematics.

4. Ground robot motion planning
4.1 Gait Planning Analysis
Motion planning is a key technology to ensure robot motion stability. In order to ensure the stability and fluency of their movements, robots can be required to be simple. Slow and stable walking under the terrain. Therefore, the static gait is selected. The preliminary selected gait is the walk gait. The foot trajectory used is the Bezier curve.

Figure 1. 3D model of robot
Figure 2. Robot kinematics model
Figure 3. A sequence diagram of a robot
In the Walk gait plan, the triangle formed by the fulcrum of the three legs of the robot is called the supporting triangle. The central projection method (COP) is used as the stability criterion of the robot. The minimum value of the distance from the center projection point to the triangle edge is called the stability margin. The greater the stability margin, the more stable the robot[5]. When a step is at any moment in the movement and the stability margin of the robot is not zero, it is considered that the step is stable and feasible. For quadruped robots, there are six non-singular static gait steps[6]. Among these six steps, 1-4-2-3 is the best stability margin[7]. Thus, as shown in Figure 3, the order of the steps of 1-4-2-3 is adopted.

4.2 Bessel curve-based planning analysis

The Bessel curve initially determines four points according to the known curve parametric equations, and then connects polygons end to end, and then approximates the polygons by the Bezier formula to obtain the Bezier curve [8]. Its equation is shown in equation (1). In the actual planning, interpolation is used, that is a series of points are selected on the Bezier curve. By controlling the legs of the robot to reach these points, the desired planning is achieved.

\[ B(t) = \sum_{i=0}^{n} \binom{n}{i} P_i (1-t)^{n-i} t^i \]

Control the two points to coincide and produce zero speed; the three points of the control point coincide, resulting in zero acceleration[9] is the characteristic of the Bessel curve derived equation. In this paper, the commutation point is added to the trajectory so that when the foot end moves according to the trajectory curve, the impact on the body is reduced as much as possible. The coordinates of 12 interpolation points are selected from the zero point as shown in Table 1. They can satisfy the zero-direction velocity component of the four-legged walking robot when the feet are connected to the ground, and the foot acceleration is as smooth as possible to ensure the height of the legs.

In the table1, \( S \) and \( h \) represent the step length and step height. According to the robot design scheme, the walking speed in the actual plan is \( \nu=0.05 \text{m/s} \), the phase difference between each leg and the first swing leg \( [b_1,b_2,b_3,b_4]=[0.25,0.75,0,0.5] \), the length of each leg segment is \( L_1, L_2 \), and \( L_3 \).

The foot-end trajectory equations obtained for each leg are shown in equations (2) to (5), and the airframe trajectory is shown in equation (6). The resulting Bezier curve and each interpolation point are shown in Figure 4.

\[ y_{c1} = \sum_{i=0}^{11} \binom{11}{i} y_i (1-t_1)^{11-i} t_1 \]

\[ x_{c1} = -a \cos \frac{\pi}{4} - n \]

\[ y_{c2} = \frac{S}{4} + \frac{S}{4} + \sum_{i=0}^{11} \binom{11}{i} y_i (1-t_2)^{11-i} t_2 \]

\[ x_{c2} = a \cos \frac{\pi}{4} + n \]
\[
\begin{align*}
 y_3 &= \frac{s_3}{4} \cdot \frac{s_3}{4} + 2m + a \sin \frac{\pi}{4} + \sum_{i=0}^{11} \left(1 - t_i\right)^{i-i} t_i' \\
 z_3 &= \sum_{i=0}^{11} \left(1 - t_i\right)^{i-i} t_i' \\
 x_3 &= a \cos \frac{\pi}{4} + n \\
 y_4 &= \frac{s_4}{4} \cdot \frac{s_4}{4} + 2m + a \sin \frac{\pi}{4} + \sum_{i=0}^{11} \left(1 - t_i\right)^{i-i} t_i' \\
 z_4 &= \sum_{i=0}^{11} \left(1 - t_i\right)^{i-i} t_i' \\
 x_4 &= -a \cos \frac{\pi}{4} - n \\
 y_b &= m + a \sin \frac{\pi}{4} + \frac{1}{4} s + vt \\
 z_b &= H \\
 x_b &= 0
\end{align*}
\]

5. Virtual Prototyping and Simulation

The virtual prototype technology is a method of using the virtual prototype established in the computer instead of the physical prototype to design and test the product. In order to verify the correctness of the robot gait obtained through Bezier curve programming, the robot virtual prototype model is established by ADAMS software, and simulation analysis is carried out.

First create a model in Solidworks and import it into ADAMS[10]. Define the quality information for each part, then add 12 connectors and motion, as shown in Figure 5. In order to facilitate the analysis and planning effect, add the Maker point to the foot of each leg of the robot. Through the measure, you can see the real-time changes of the values such as the displacement speed of the relevant point.
By analyzing the displacement data of the foot-end trajectory, the effect of the planning can be evaluated. The displacements of the center of mass of the robot in the three directions of X, Y, Z in the first 10 cycles are measured, as shown in Figures 6 to 8. Through analysis, it is found that the displacement curve of the robot in the Y direction is relatively smooth, and the speed is gradually increasing, which is consistent with the gradual increase of the step length in the first three cycles of the previous plan. After 4s, it is a diagonal line with constant slope, the corresponding motion is a uniform linear motion, and the fluctuation is very small, indicating that the fuselage follows a straight line and the amount of deflection occurring during the advancement is very small. The maximum X-direction offset of the robot is 2.5mm, indicating that the robot has better stability. The offset of the center-of-mass equilibrium position in the Z direction is about 0.5 mm, mainly because the first three cycles are gradual adjustment phases, and the center of mass does not reach the predetermined position. After stabilization, the change of the center of mass is regular and the equilibrium position is fixed, indicating that the robot maintains linear motion. The ability is better.

Through simulation analysis, it is found that the movement of robot motion planning based on the foot-end trajectory can reach the expected requirements in the virtual environment. The actual movement performance of the robot and the planning are consistent, indicating that this planning method is scientific.
6. Summary
In this paper, a land-air amphibious robot combining a quadrotor and a four-legged walking robot is designed. The robot can not only perform structural separation according to operational requirements in order to realize land and air multi-field investigation, but also the quadrotor is free. Rising and landing on a four-legged walking robot body to perform combined operations provides more possibilities for multi-purpose detection. The separable structural design not only greatly enhances the environmental adaptability of the land-air amphibious robot, but also lays a solid foundation for the future diversified design. The four-legged walking robot's leg has selected a three-degree-of-freedom configuration. The foot trajectory adopts the Bezier curve. The robot body's center of mass is planned to move in a straight line, which can ensure the fluency, stability, and flexibility of the walking robot. The results of simulation and verification show that the combined land-air amphibious robot has excellent sport characteristics and has popularization and application value.

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