A Novel Terrain Adaptive Landing Gear Robot

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Abstract. In order to expand the landing areas and application range of vertical take-off and landing (VTOL) aircrafts, this article proposes a new type of landing gear robot. The robot is mainly composed of a base and three limbs with planar parallel mechanisms. The control system collects depth data through a depth camera, and fuses attitude angle and velocities to establish terrain data of the landing area. According to the terrain data and the robot kinematics model, the driving variables are calculated and used to drive the robot to achieve the adaptive landing.

1. Introduction  
Vertical take-off and landing (VTOL) aircrafts such as helicopter, rotor UAV, planetary probe benefit from their vertical power output, which greatly reduces the levels for the take-off and landing environment, and are widely used in fields such as investigation, search and rescue, logistics and so on. However, VTOL aircrafts can only take off and land on flat terrain. When performing the tasks such as investigation, search and rescue and polar scientific research, the terrain is usually complex and unstructured. In order to further expand the mission capability of VTOL aircrafts, that is to achieve the taking-off and landing operations on complex terrain, it is necessary to expand adaptive landing gear system on the aircraft.

The two key factors to realize adaptive landing [1-3] include adjustable landing gear and terrain detection. Most of the existing adjustable landing devices use leg-type mechanisms. Leg mechanisms can be divided into series mechanisms [1, 4] and parallel mechanisms [5]. The series mechanism has a simple structure, but more degrees of freedom are required to achieve the expected motion. Parallel mechanisms can achieve expected motion with less degrees of freedom through multiple connecting rods parallel and dimensions optimization. The existing terrain detection system adopts different control strategies according to the different sensors. These sensors are mainly divided into three types, contact sensing [6, 7], visual sensing [8, 9] and attitude sensor [10].

This article mainly introduces a new type of adaptive landing gear robot. It uses a parallel mechanism as an adjustable landing device, and scans the terrain through depth camera, so as to realize the function of adaptive terrain landing.

2. A novel landing gear robot  
A novel landing gear robot proposed in this article is mainly applied to the amphibious robot of our research team, as shown in Figure 1. The amphibious robot is mainly made up of a drone and a landing gear robot. The landing gear robot is mainly made up of three motion chains and one base.

The base is the foundation structure component t, and can be connected and fixed with the drone through bolts. The base is mainly integrated with electronic components and structural parts. The
structural parts are mainly made of photosensitive resin and carbon fibre board. The electronic components integrate host computer, drive board and sensors of the system, show in Figure 2. Figure 3 shows the geometric structure of the robot. The coordinate system of the base is shown in Figure 3(a). The centre points of the three motion axes connected with the three limbs are points \( A_i \) \((i=1, 2, 3)\).

![Figure 1](image1.png)

Figure 1. Prototype and 3D model of the amphibious robot.

The three limbs are mainly designed with linkage slider mechanism and parallelogram mechanism. The structure is shown in Figure 3(b). By driving the translation of slider \( B_i \), it realizes the rotation of swing rod \( B_i D_i \) and the rotation of parallelogram mechanism \( B_i B_i' D_i D_i' \), so as to control the height of the touch point \( P_i \).

![Figure 2](image2.png)

Figure 2. (a) host computer, (b) drive board and (c) sensors of the landing gear robot.

2.1. Kinematics analysis

This section will mainly introduce the establishment of the kinematics model of the robot. The terrain adaptive landing gear is designed to ensure the horizontal of the aircraft body, so it is assumed that the base remains horizontal. The input parameters of the landing gear are the displacements of the three sliders, and the output parameters are the yaw angle, inclination angle, and centre height of the virtual moving platform formed by the three touch points. From the Figure 3, the geometric constraint relationship between the length of the driving rod and the landing point can be obtained,

\[
A_i P_i = A_i B_i + B_i D_i + D_i P_i \quad (i = 1, 2, 3)
\]

\[
A_i C_i = A_i B_i + B_i C_i \quad (i = 1, 2, 3)
\]
Figure 3. Mechanism diagram of the robot (a) and the limb(b).

Convert the geometric constraint relationship into mathematical relationship as follows,

$$\left| \overrightarrow{AC} \right| = \text{norm}(\overrightarrow{AB_i} + l_{BC} \cdot \overrightarrow{es_{BC_i}}) = l_{AC}$$

$$\overrightarrow{AP_i} = l_i \cdot \overrightarrow{es_{AB_i}} + l_{BD} \cdot \overrightarrow{es_{BC_i}} + \overrightarrow{DP_i}$$

where $\overrightarrow{es_{BC_i}}$ is the unit vector of axis $\overrightarrow{B_iD_i}$, and $\overrightarrow{es_{AB_i}}$ is the unit vector of axis $\overrightarrow{A_iB_i}$.

The forward kinematics solution and the inverse kinematics solution of the limb can be solved by Equation (1) and (2). In this article, the key issue of kinematics modelling is to establish the relationship between the position of three touch points of robot, and the output parameters. This research analysess the relationship by Euler angle and rotation matrix. According to the relationship between the normal of the plane and any straight line on the plane perpendicular to each other, it can be concluded,

$$R_{ZY} \cdot e_z = \text{Normalize}(P_1P_2 \times P_1P_3)$$

$$R_{ZY} \cdot e_z = (h_c e_z + \overrightarrow{OP_i})$$

$$R_{ZY} = \begin{pmatrix}
\cos(\theta_Y) & \cos(\theta_z) & \sin(\theta_z) \\
-\sin(\theta_Y) & \cos(\theta_z) & \sin(\theta_z) \\
0 & -\sin(\theta_z) & \cos(\theta_z)
\end{pmatrix}$$

where $R_{ZY}$ is the rotation matrix of the slope under the base, and $\theta_Y$ and $\theta_Z$ are the angles of rotation around the Y axis and Z axis, respectively. $e_z = \{0, 0, 1\}^T$ is the unit vector of the Z-axis, and $h_c$ is the height of the robot centre from the ground. The forward and inverse kinematics solutions of the landing gear robot can be solved by Equation (2) and (3).

2.2. Workspace

The workspace of a parallel robot refers to the collection of all the position points that the moving platform can reach. In this article, the plane determined by the three touch points is used as the moving platform of robot, and based on the kinematics model of robot, the workspace of robot can be solved. In this article, the main factor affecting the workspace is the limitation of driving variables.

$$l_{\text{min}} \leq l_i \leq l_{\text{max}}$$

This article discretizes the value range of the driving variable, and solves the inclination and height of the slope through the robot forward kinematics. Then the inclination and height are substituted into the inverse kinematics of the robot to obtain the length of the driving rod. Finally, by judging whether the length of the driving rod is within the range of the rod length, it is determined whether the position belongs to the reachable workspace of the robot. The workspace of the robot is finally obtained as shown in the Figure 4.
3. Terrain adaptive control

The terrain adaptive controller needs to collect altitude information and the 3D landing environmental information. In this article, adaptive landing procedure is divided into preparing phase and descent phase. In the preparing stage, the system prejudges the landing attitude of the robot by analysing terrain data. The host computer (shown in Figure 2(a)) collects, analyses and calculates the sensor information, then transmits the joint variables to the drive board (shown in Figure 2(b)). Then, the drive board controls the motor operation to change the attitude of three limbs. In the descent stage, the drone mainly takes the entire system to descend, and the system continues to analyse the terrain data and adjust the landing attitude of the robot.

The core of the realization of the terrain adaptive landing is how to convert the sensor data into the driving variables required by the robot. The sensor data mainly includes the three-axes angular velocity of the gyroscope, the depth image of the depth camera, the three-axes acceleration of the accelerometer, and the dual-axis linear velocity of the optical-flow sensor. The driving variables are the displacements of the three driving motors. In this study, the conversion of information is mainly achieved through three steps, centre position calculation, touch point position calculation and driving joint calculation. The whole process is shown in Figure 5.

3.1. Center position calculation

The centre position refers to the point where the centre of the robot landed on the ground, that is the intended landing point. This article calculates the centre position by two steps. First, calculate the vertical position of the robot centre on the ground according to the robot’s attitude angles. Then, correct the robot’s centre position at the next moment by considering the robot’s speed in the horizontal direction.

3.2. Touch point location calculation

The touch point refers to the touch point between the ground and the three motion chains. Based on the centre position of the robot obtained in the above article, the touch point position of the robot is solved according to the geometric relationship of the limbs.

3.3. Driving joint calculation
The eccentric height of the touch point obtained by the calculation of the touch points position is substituted into the inverse kinematics analysed above, and the joint variables of each driving joint can be solved. Finally, input the obtained driving joint variables to the drive board. The displacement of the slider is taken as the target value of the driving board, and a PID controller is carried out to control the motion of the robot.

4. Experiment
Regarding as the landing gear mechanism designed above, this article has produced a landing gear robot prototype and conducted performance verification experiments.

4.1. Experiments Settings
In this article, the landing gear adaptive control algorithm is tested on different slopes. The experimental platform is shown in the Figure 6, it is mainly made up of a frame, cables and terrain platform. One end of the cable is fixed on the robot, and the other end passes through the fixed pulley on the frame as the free end. The take-off and landing process of the robot is simulated by extension and contraction of the cable. The terrain platform is made up of terrain modules, which form different terrains by combining modules of different heights.

In this research, the take-off and landing process of the system is simulated by retracting and releasing the cable. In the preparing altitude, the sensors collect the attitude data and the terrain depth image, and transmits the information to the host computer for processing. According to the algorithm designed above, the host computer outputs the driving joint variables to the drive board. According to the joint variables, the drive board drives the motor to execute the motion.

4.2. Results and analysis
The results of the frame test are shown in Figure 7, various terrains (flat, single step, multi-step, irregular terrain) are shown from top to bottom. From left to right are the experimental screenshots of preparing phase and the descent phase of robot, and the images of the colour camera and depth camera on the robot. It can be seen from the results that the body of the robot is basically in a horizontal attitude after landing. In the multi-step terrain, the inclination angle of the robot is slightly larger than other terrain, because the terrain exceeds the workspace of the robot. In the colour image and depth image of the robot, the red line segments represent the positions of three limbs of the robot. The centre point is the position
of the depth camera. The red, green and blue endpoints represent the three touch points of three limbs. In the depth image and the colour image, the location of the touch point is different because the installation position and angle of view of the colour camera and the depth camera are different. Comparing the monitoring images, the contact position of the depth image is basically the same as the actual position, which shows the effectiveness of the algorithm. After landing, the attitude angles ($\theta_x$ and $\theta_y$) of the base were recorded by the sensor, shown in Table 1. The attitude angles result also verifies the effectiveness of the system.

| Table 1 | Attitude angles of the robot after landed |
|---------|-----------------------------------------|
| Angles(*) | Terrain 1 | Terrain 2 | Terrain 3 | Terrain 4 |
| $\theta_x$ | -1.2 | -1.5 | -4.5 | 1.2 |
| $\theta_y$ | 2.4 | 3.1 | -4.2 | 0.9 |

5. Conclusion

This article designs a new type of landing gear robot based on the application requirements of the adaptive landing of VTOL aircrafts. The robot adopts a parallel mechanism as an adjustment device, and adopts an active adaptive control strategy for adaptive landing. The strategy is based on the terrain information collected by the depth camera. This article analyses the kinematics of the landing gear robot mechanism and its workspace, and proposes an active adaptive landing controller based on data fusion. Finally, based on experiments, the function of terrain adaptive landing of system is verified.

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