Research on UAV Adaptive Landing Gear Control System

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Abstract. Aiming at the severe requirement of landing terrain environment for UAVs, especially large UAVs, an adaptive landing gear is designed in this paper. The control system and PID controller based on attitude feedback, height feedback and force feedback are designed synthetically using high precision force sensor, attitude sensor and laser ranging sensor. The SIMULINK model is built in MATLAB and debugged in the actual system. The simulation and physical experiments show that the control system in this paper has the characteristics of good control robustness and fast response speed, which provides a beneficial attempt for engineering application of adaptive landing gear.

Keywords: self-adaptive landing gear, PID controller, attitude feedback, altitude feedback, force distribution

1. Introduction

UAV processed great potentials in both civil and military applications because of its excellent characteristics such as small volume, simple structure, flexible operation, vertical take-off and landing, etc.[1] During take-off and landing process, the height and velocity of an aircraft was very low, and the control ability was reduced.[2] However, the slope of the landing surface can severely limit viable landing areas.[3] As a result, take-off and landing process can be dangerous. When an aircraft experiences a hard landing, it must be inspected for damage before its next flight,[4] which cost a lot of time. An adaptive landing gear can solve the problem.

Some research institutions have made some progress in the development of adaptive landing gear. As figure1 shows, a recent example of robotic landing gear was developed by the Georgia Institute of Technology under the DARPA’s Mission Adaptive Rotor (MAR) program consisting of four articulated robotic legs that adapt their position to ensure that the helicopter stays level during landing. [5] During the landing process, each leg can be adjusted in real time to ensure the helicopter remains stable and minimizes the risk of the propeller touching the ground.

![Figure 1. DARPA Robotic Landing Gear.](image-url)
This paper mainly completed the following work: mechanical design, electronic circuit design, control algorithm design and software implementation of adaptive landing gear. In the end, the SIMULINK system simulation was built to test whether the system achieves the desired goal.

2. Platform building
Mechanical platform is designed to carry 470 helicopters to accomplish take-off and landing missions stably in different terrains, which is built mainly by plastic with 3d printing technology as figure 2 shows. In theory, the adaptive landing gear only needs two degrees of freedom: attitude control in the pitch and roll directions. However, for future function expansion, the landing gear platform is finally designed into four legs. The four legs are designed can only move vertically, which brings two advantages: the plantar pressure on the four legs are relatively even, resulting in upgrade of structural life, and the plantar pressure on the centre of gravity arm are constant, which brings convenience to torque solution. The transmission structure is designed into four-bar linkage. This paper got suitable length of each link with mathematical tools to ensure that legs can barely move horizontally.

![Figure 2. Mechanical Design of Adaptive Landing Gear Platform.](image)

For aspects of actuator, sensors, and controllers, this paper chooses servo motor with reducer as actuators, output current and torque of the motor can be controlled by sending PWM pulse to the motor driver. The vertical pressure is measured at the plantar with mount force sensors. This paper installed mpu6050 module on the platform to receive three-axis acceleration, angular velocity, and Euler angel information. Ultrasonic range finder HY-SRF05 or laser range finder LIDAR Lite V2 was set up at the bottom of the platform to measure the height of the body to the ground. This paper also chooses stm32f429 minimum system board as controller for its powerful computing resources and abundant peripherals.

3. Attitude Dynamics Analysis and Controller Design
The primary goal of adaptive landing gear is to ensure that the UAV lands smoothly when it takes off, that is required to control the body's pitch and roll angle, and set the control target to $0^\circ$. In this paper, the posture of the body is measured by the attitude sensor module, and finally the attitude of the body is controlled by adjusting the supporting force provided by the four legs respectively.

Figure 3 defines the number of legs and coordinate direction of the system. From a top-down perspective, the serial numbers of the four legs are 1, 2, 3 and 4 in the clockwise direction respectively. The coordinate system is the ENU system: the front of the body is the Y axis while the right is the X axis. The positive direction is determined according to the right hand rule: the pitch angle $\theta$ is around the X axis, and the roll angle $\phi$ is around the Y axis.
Figure 3. Coordinate system and definition of leg number.

The attitude dynamics equation is established as follows:

\[
\begin{cases}
\dot{\Theta} = T_L + M_G + T_g \\
\dot{\omega} = \Theta
\end{cases}
\]  \hspace{1cm} (1)

In formula 1, \(J\) is the moment of inertia of the body in the x-axis and the y-axis, \(\Theta\) is the Euler angle of the two axes, \(\omega\) is the angular velocity of the two axes, \(T_L\) is the torque of the four leg plantar pressure relative to the geometric center of the body, \(M_G\) is the gyro torque generated by Z-axis rotor’s rotation on the x-axis and y-axis, \(T_g\) is the torque generated by deviation between center of gravity and geometric centre. In this system, we tried to ensure the centre of gravity and geometric centre on the same vertical line, so the impact of \(T_g\) can be ignored. \(M_G\) expression is as follows:

\[
M_G = J_R \omega \times \omega
\]  \hspace{1cm} (2)

In formula 2, \(J_R\) represents the moment of inertia of the rotor to the z-axis, and \(\omega_R\) represents the angular velocity at which the rotor rotates. For a UAV, the gyroscopic torque can be neglected due to the small value of \(\omega\). Therefore, the system attitude dynamics model is simplified as:

\[
\ddot{\Theta} = T_L
\]  \hspace{1cm} (3)

The matrix form is:

\[
\begin{bmatrix}
J_x \dot{\Theta} \\
J_y \dot{\Phi}
\end{bmatrix} =
\begin{bmatrix}
T_1 d_y - T_2 d_y - T_3 d_y + T_4 d_y \\
-T_1 d_x - T_2 d_x + T_3 d_x + T_4 d_x
\end{bmatrix}
\]  \hspace{1cm} (4)

\(J_x\) and \(J_y\) represent the moment of inertia of the frame to the x-axis and the y-axis, \(T_1\) through \(T_4\) respectively represent the plantar pressures on the four legs, \(d_x\) represents the distance from the plantar to the center of gravity in x axis, and \(d_y\) represents the distance from the plantar to the centre of gravity in y axis.

In order to improve the robustness of the system, attitude control system adopts the form of attitude controller as outer loop and angular velocity controller as inner loop. The goal of attitude controller is: after knowing target attitude angle \(\Theta_0 = [\Theta_0 \Phi_0]\), controller \(\omega_a\) is designed to make \(\lim_{t \to \infty} ||\Theta(t)|| = 0\), where \(\Theta_0 = \Theta - \Theta_0\). For \(\Theta = \omega\), a PID controller is designed to determine the angular velocity expectation \(\omega_a\):

\[
\omega_a = -K_{\phi \phi} e_\Theta - K_{\phi \theta} \int e_\Theta - K_{\phi \phi} e_\Theta
\]  \hspace{1cm} (5)

The goal of angular velocity controller is: after knowing target angular velocity \(\omega_0\), controller \(\tau_a\) is designed to make \(\lim_{t \to \infty} ||\omega(t)|| = 0\), where \(\omega_0 = \omega - \omega_0\). For \(\dot{\Theta} = T_L\), a PID controller is designed to determine the torque expectation \(\tau_a\):

\[
\tau_a = -K_{\omega \omega} e_\omega - K_{\omega \phi} \int e_\omega - K_{\omega \omega} e_\omega
\]  \hspace{1cm} (6)
4. Dynamics Analysis and Altitude Controller Design

The adaptive landing gear needs to ensure that the distance between the UAV’s body and the ground is stable and the distance can be controlled according to the terrain condition or other instructions. In this paper, the body altitude data can obtain from laser range finder or ultrasonic range finder, and z-axis velocity data can obtain from the derivation of altitude data, or the integration of z-axis acceleration data. Finally, the total supporting force provided by the four legs is adjusted to control the altitude of the UAV.

So, the dynamics model is as follows:

\[ \begin{bmatrix} m\ddot{v}_x & T_1 & + & T_2 & + & T_3 & + & T_4 & - & mg & + & f_z \end{bmatrix} \\
\dot{z} = v_z \]

(7)

In formula 7, \( m \) is the total mass of the system, \( z \) is the distance between the body and the ground, \( v_z \) is the z-axis velocity of the body, \( f_z \) is the disturbance of z-axis, including the gravity of equipment mounted on UAV, elevating force provided by rotors and so on.

For the reason that \( f_z \) is uncontrollable, altitude control system adopts the form of altitude controller as outer loop and velocity controller as inner loop to ensure that the system perform well in different missions. The goal of altitude controller is: after knowing target altitude \( z_0 \), controller \( a_z \) is designed to make \( \lim_{t \to \infty} \|\Delta z(t)\| = 0 \), where \( \Delta z = z - z_0 \). For \( \dot{z} = v_z \), a PID controller is then designed to determine the z-axis velocity expectation \( v_z \):

\[ v_z = -K_{sp}\Delta z - K_{vi}\int \Delta z - K_{zd}\Delta z \]

(8)

The goal of velocity controller is: after knowing target velocity \( v_0 \), controller \( T_z \) is designed to make \( \lim_{t \to \infty} \|\Delta v(t)\| = 0 \), where \( \Delta v = v - v_0 \). For \( mv_z = T_1 + T_2 + T_3 + T_4 - mg \), a PID controller is designed to determine the total supporting force expectation \( T_z \):

\[ T_z = -K_{vp}\Delta v - K_{vi}\int \Delta v - K_{vd}\Delta v \]

(9)

5. Optimization of Landing Gear Force Distribution

In this paper, the system has four drivers to control four degrees of freedom, two degrees for attitude control, one degree for altitude control of the z-axis, and the last one can be used to distribute the forces on each leg and optimize working status of legs. \( D(T) \) was set as the variance of four leg forces \( T \):

\[ \begin{bmatrix} T_1 & T_2 & T_3 & T_4 \end{bmatrix} \]

\[ D(T) = E(T^2) - [E(T)]^2 \]

(10)

In order to make the pressure of each leg relatively even, \( T \) should be fitted to make \( D(T) \) the minimum value.

From the above we can see the constraints are as follows:

\[ \begin{bmatrix} j_x\dot{\varphi} \\ j_y\dot{\varphi} \\ m\dot{z} + mg \end{bmatrix} = \begin{bmatrix} T_1d_y - T_2d_y - T_3d_y + T_4d_y \\ -T_1d_x - T_2d_x + T_3d_x + T_4d_x \\ T_1 + T_2 + T_3 + T_4 \end{bmatrix} \]

(11)

Formula11 can be simplified to the following form:

\[ \begin{bmatrix} T_1 - T_2 - T_3 + T_4 = X \\ -T_1 - T_2 + T_3 + T_4 = Y \\ T_1 + T_2 + T_3 + T_4 = Z \end{bmatrix} \]

(12)

From Formula12 we get:

\[ T_1 = \frac{x+y}{2} - T_4, \quad T_2 = -\frac{x+y}{2} + T_4, \quad T_3 = \frac{y+z}{2} - T_4 \]

(13)

Bring Formula13 in \( D(T) \):

\[ D(T) = E(T^2) - [E(T)]^2 \]

\[ D(T) = \frac{T_1^2 + T_2^2 + T_3^2 + T_4^2}{4} - \left( \frac{T_1 + T_2 + T_3 + T_4}{4} \right)^2 \]
\[ D(T) = \frac{T_1^2 + T_2^2 + T_3^2 + T_4^2}{4} - \frac{Z^2}{16} \]  

From Formula 14 we get if \( T_1^2 + T_2^2 + T_3^2 + T_4^2 \) take the minimum, \( D(T) \) take the minimum, and:

\[ T_1^2 + T_2^2 + T_3^2 + T_4^2 = 4T_4^2 - (2X + 2Y + 2Z)T_4 + \frac{(X+Y+Z)^2 + (X+Y)^2 + (Y+Z)^2}{4} \]  

If \( T_4 = \frac{X+Y+Z}{4}, T_1^2 + T_2^2 + T_3^2 + T_4^2 \) take the minimum, and \( D(T) \) take the minimum, Bring \( T_4 \) in Formula 13:

\[ T_1 = \frac{X-Y+Z}{4}, T_2 = \frac{-X-Y+Z}{4}, T_3 = \frac{-X+Y+Z}{4}, T_4 = \frac{X+Y+Z}{4} \]  

However, the leg force in this system is limited between 0N and 30N, which means that the input \( X, Y, Z \) need to be limited, otherwise leg force may be out of range. Solution to the following formula is:

\[ 0 \leq T_1, T_2, T_3, T_4 \leq 30 \]  

We get:

\[ |X| + |Y| \leq \min(120 - Z, Z) \]  

The conclusion is that we only need to limit \( |X| + |Y| \) value to ensure all leg force within a limited range. Therefore if \( |X| + |Y| > \min(120 - Z, Z) \), the values of \( |X| \) and \( |Y| \) are prorated:

\[ X = \frac{X+\min(120-Z,Z)}{|X|+|Y|}, Y = \frac{Y+\min(120-Z,Z)}{|X|+|Y|} \]  

6. Adaptive landing gear control system simulation

The decision-making process of adaptive landing gear system is as follows: when the drone is ready to take off, we can place the drone on the ground, start the attitude and altitude control channels, so that the UAV can adapt to any terrain until the drone successfully take off. When the drone works normally, reduce air resistance and prevent obstruction of the camera sight, stop the attitude and altitude control channels, and the landing gears all move to the highest position. When the drone switches to landing mode, the landing gear all moves down to the lowest position, and start leg force control channel, the force control target is set to 0. When the drone altitude drops to the set value \( z_0 \) (\( z_{\min} < z_0 < z_{\max} \)), start the attitude and altitude control channels, the drone land on the ground stably, until the mission complete or restart. The decision flow chart is as Figure 4:

![System decision flow chart](image-url)
Simulink simulation model of the system is shown in Figure 5:

![Simulink simulation model](image)

**Figure 5.** Simulation model of the system.

As shown in Figure 6, we set the initial pitch angle to 10°, roll angle to -5°, the current altitude to 0.2 meters. Target attitude angle are set to 0, target altitude to 0.2 meters, and the rotor elevating force are set to drop from the initial 30N to 0 slowly to simulate the actual landing conditions.

It can be seen from Figure 6 and 8 that there is a twist in attitude and altitude response, which is the result of extra lift force applied by the rotor. All leg forces are limited between 0 and 30N as is shown in Figure 9.

![Condition setup](image)

**Figure 6.** Condition set up.

![Attitude response](image)

**Figure 7.** Attitude response.
7. Conclusions
In this paper, we completed the design of UAV landing gear, the construction of the platform, the algorithm design, the model and simulation of the system. Now the UAV can take off and land on most terrains. The simulation and experimental results show that the designed system has the advantages of simple structure, strong adaptive ability and good engineering application value.

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