Robust Nonlinear Adaptive Controller Design for Horizontal Position Control of a Rotary Wing Autonomous Vehicle Using Backstepping Method

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Abstract: In this paper, a new approach of designing robust adaptive backstepping controller for horizontal position control of a rotary wing autonomous unmanned vehicle (RAUV) with consideration of parametric uncertainties and external disturbances is proposed. Based on this new approach, the proposed RAUV controller is adaptive to the parametric uncertainties and robust to the external disturbances. To prove the convergence of different tracking error to zero, a control Lyapunov function (CLF) is formulated in every step of the design process of controller and which is guaranteed through the negative definiteness of the derivative of CLF. At last, a numerical evaluation is performed on a highly fidelity nonlinear simulation model to justify the usefulness of the proposed controller. The performance of the designed controller is also compared with a classical PID controller. Simulation results demonstrate that the proposed controller provides an improved performance for the closed-loop system in the presence of parametric and external uncertainties within the UAH model over the existing controller.

Keywords: Adaptive Robust Backstepping Controller, Control Lyapunov Function, External Disturbance, Rotary Wing Autonomous Vehicle, Parametric Uncertainty

1. Introduction

There are variety of rotary wing unmanned autonomous vehicles (RUAV), but among these the unmanned autonomous helicopters (UAHs) constitute one of the most versatile and agile platforms for the development of autonomous flight systems. A small-scale unmanned helicopter can operate in different flight modes, such as vertically take-off/landing, hovering, longitudinal or lateral flight, and bank to turn which gives them the advantage of effective observation from various positions. Hovering and vertically take-off are necessarily needed. Nowadays, there are new trends of UAH controller design due to their high level of agility, maneuverability and capability of operating in adverse weather conditions. To achieve these performances of an UAH, the trajectory tracking and disturbance rejection capability need to be significantly improved. But the problem is that it is a naturally unstable system with nonlinear dynamics. The main difficulties of an UAH are higher nonlinearities which arise from the cross-couplings due to the tail rotor, main rotor, engine and dynamic uncertainties [1]. Besides, it is an underactuated mechanical system with six degrees of freedom (6-DOF) because it has only four control inputs. To cope such problems as mentioned above, different approaches have been proposed by the researchers in literature [2]-[4]. Thus, in order to improve the tracking performance of an UAH in the presence of parametric and external uncertainties within the system a robust adaptive backstepping controller is proposed in this paper.

Different conventional controllers are available to stabilize to flight of an UAH which are designed on the linear approximation around an operating point [5], [6]. But these controller are not suitable when operating point is changed due to any external or inter uncertainties. Thus, recently, various advance nonlinear control techniques have been applied to the control the UAH for different operating points under large disturbance [7]-[11]. A robust $H_{\infty}$ control method of the longitudinal and lateral dynamics of the BELL 205
helicopters in the presence of model uncertainties is presented in [12]. A robust feedback method is proposed in [13] to reject the external wind gust, where the external wind gust is assumed to be the sum of a fixed number of sinusoids with unknown amplitudes, frequencies and phases. To control of an autonomous scale helicopter under the consideration of parameter uncertainties and uniform time varying three-dimensional wind gusts a backstepping method is proposed in [14]. A nonlinear H∞ horizontal position controller for hovering and landing flight of a RUAV in the presence of horizontal wind gusts is proposed in [15]. Similar pitch motions are controlled by lateral and longitudinal cyclic backstepping controller to control the horizontal position of an proposed controller. Section 5 discusses the simulation characteristics, the dynamic modeling of an UAH is a very complex problem. The motion states and control inputs of an UAH in the 6-DOF form can be represented as follows:
\[
x = \{u, w, q, \theta, v, p, r, \phi, \Psi\}
\]
\[
u_c = \{\delta_{\text{lat}}, \delta_{\text{lon}}, \delta_{\text{hel}}, \delta_{\text{ped}}\}
\]
where \(u, v\) and \(w\) represent linear velocity in body frame; \(p, q\) and \(r\) denote roll, pitch and yaw rates; and \(\phi, \theta\) and \(\Psi\) represent the roll, pitch and yaw angle, respectively of an UAH. A single main rotor helicopter has four independent control inputs such as \(\delta_{\text{lat}}, \delta_{\text{lon}}, \delta_{\text{hel}}\) and \(\delta_{\text{ped}}\) which denote the deflection of the lateral cyclic, longitudinal cyclic, main rotor collective pitch and tail rotor collective pitch, respectively. The collective commands control the magnitude of the main rotor and tail rotor thrust and other two control commands control the inclination of the tip-path-plane (TPP) on the longitudinal and lateral direction. The equations which describing the net forces of the UAH can be expressed as,
\[
m(\ddot{u} - \nu r + \nu wq) = X - mg \sin \theta
\]
\[
m(\ddot{v} - \nu \theta w + \nu ur) = Y + mg \sin \phi \cos \theta
\]
\[
m(\ddot{w} + \nu q w - \nu ur) = Z + mg \cos \phi \cos \theta
\]
The equations which describe the moments of the UAH can be expressed as,
\[
L = I_{xx} \ddot{\phi} - I_{xx} \dot{\phi}^2 + qr(l_{zz} - l_{yy}) - l_{xx} pq
\]
\[
M = I_{yy} \ddot{\theta} + pr(l_{xx} - l_{zz}) + l_{yz} (p^2 - r^2)
\]
\[
N = -I_{zz} \ddot{\phi} + I_{zz} \dot{\phi}^2 + pq(l_{yy} - l_{xx}) + l_{yx} qr
\]
In order to complete the system modeling, the following three equations are essential which relate the Euler angle rates to the angular velocity [19].
\[
\dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta
\]
\[
\dot{\theta} = q \cos \phi - r \sin \phi
\]
\[
\dot{\psi} = \frac{q \sin \phi + r \cos \phi}{\cos \theta}
\]
The longitudinal and lateral cyclic tilt of the main rotor disk is controllable through the cyclic pitch. Therefore, the longitudinal and lateral flapping dynamics can be represented by the following first-order equations [20].
\[
\dot{a}_l = -q \frac{a_l}{\tau} + \frac{1}{\tau} (\frac{\partial a}{\partial u} \nu + A_{\text{det}} \delta_{\text{lon}})
\]
\[
\dot{b}_l = -p - b_l + \frac{1}{\tau} (\frac{\partial b}{\partial v} \nu + A_{\text{det}} \delta_{\text{lat}})
\]
where \(\delta_{\text{lat}}\) and \(\delta_{\text{lon}}\) are the lateral and longitudinal cyclic

2. Dynamical Model of UAH

The UAH has the specific characteristic as compared to fixed wing aircraft such as, it can move vertically, float in the air, turn in place, move forward and laterally and can perform these movements in combinations. Due to these characteristics, the dynamic modeling of an UAH is a very
control inputs, $a_1$ and $b_1$ are the lateral and longitudinal flapping angles and Alon and Blat are the effective steady-state longitudinal and lateral gains from the cyclic inputs to the main rotor flapping angles. The terms $A = \frac{\partial a}{\partial u}$ and $B = \frac{\partial b}{\partial v}$ are constants and represent the longitudinal and lateral Dihedral effect. The Dihedral effect is the change of tip-path-plane (TPP) tilts due to the longitudinal and lateral velocities [21]. The Dihedral effect is modeled by the following equation.

$$\frac{\partial a}{\partial u} = -\frac{\partial b}{\partial v} = \frac{2}{\Omega R_v} \left( \frac{8C_f}{a\sigma} + \sqrt{\frac{C_f}{2}} \right)$$  \hspace{1cm} (12)

where $R_v$ is the main rotor radius, $\sigma$ solidity ratio, ‘$a$’ lift curve slope and $C_f$ thrust coefficient. Since the rotor is symmetric, so the consideration is $A_{aw} = B_v$. In order to design the controller, the linearization is essential to derive a simplified working model, due to the inherent instability under hover and slow flight conditions. So, after linearizing the equations (1)-(8) the following parameterized model of decoupled longitudinal and lateral dynamics can be obtained, where

$$\begin{bmatrix}
\dot{u} \\
\dot{\theta} \\
\dot{\delta}_{aw}
\end{bmatrix} =
\begin{bmatrix}
X_u & X_q & -g & X_s \\
M_u & M_q & 0 & M_s \\
A_v & -1 & 0 & A_{aw}
\end{bmatrix}
\begin{bmatrix}
u \\
\theta \\
\delta_{aw}
\end{bmatrix}
+ \begin{bmatrix}0 \\
0 \\
\delta_{aw}
\end{bmatrix}$$  \hspace{1cm} (13)

$$\begin{bmatrix}
\dot{v} \\
\dot{p} \\
\dot{\delta}_{aw}
\end{bmatrix} =
\begin{bmatrix}
Y_v & Y_p & g & Y_s \\
L_v & L_p & 0 & L_s \\
B_v & -1 & 0 & B_{aw}
\end{bmatrix}
\begin{bmatrix}
v \\
p \\
\delta_{aw}
\end{bmatrix}
+ \begin{bmatrix}0 \\
0 \\
\delta_{aw}
\end{bmatrix}$$  \hspace{1cm} (14)

where $X_u = \frac{1}{m} \frac{\partial X}{\partial u}$, $M_u = \frac{1}{I_{yy}} \frac{\partial M}{\partial u}$ are the force and moment derivatives normalized by the mass of the helicopter or respective moment of inertia. The pitching flap-stiffness constant is represented by $M_v$ that can be computed as follows $M_v = \frac{mM_s}{I_{yy}} + \frac{K_{\delta}}{I_{yy}}$, where $M_s$ is the height of the rotor hub above the fuselage center of gravity, $I_{yy}$ is the pitching moment of inertia and $K_{\delta}$ is the rotor blade spring stiffness. Similarly the lateral flap-stiffness constant $L_v$ can be computed as follows $L_v = \frac{mM_s}{I_{yy}} + \frac{K_{\delta}}{I_{yy}}$. The proposed linear model as described by equations (13)-(14), has been successfully espoused for control applications in a large number of small-scale unmanned helicopters [22]-[27]. The nonlinear robust adaptive nonlinear controller will be designed using backstepping technique based on equations (13)-(14). However, before design the controller the control problem formulation is discussed in the following section.

### 3. Control Problem Formulation

From the longitudinal dynamics model as described by equation (13), it can be seen that the longitudinal flapping $a_1$ is a function of $u$ and $g$. Similarly, from the lateral dynamics model, it can be seen that the lateral flapping $b_1$ is a function of $v$ and $p$. Under this condition, to continue the design procedure of the proposed controller is not possible. From [28], it is clear that the effect of lateral and longitudinal forces produced by the flapping angles can be neglected as they have a minimal effect on the translational dynamics as compared to the propulsion forces produced by the stability derivatives $X_v$, $X_s$, $Y_v$, $Y_s$, $L_v$, $L_s$. Moreover, according to the control purposes, the dynamics of an UAH should be separated into two interconnected subsystems. The first subsystem accounts for the longitudinal dynamics and second subsystem for lateral dynamics. Now, after neglecting the effect of parameters $X_v$, $Y_v$, $X_s$ and $Y_s$, the longitudinal-lateral dynamics will have a strict feedback form which is suitable for the proposed controller. Again, as the mass of an UAH is continuously varying so the parameters of an UAH is not fixed. Moreover, the dynamics of the UAH will be affected by the external wind gusts. Thus, under the above assumptions, the simplified model equations of the longitudinal dynamics can be written as follows:

$$\dot{x} = u$$

$$\dot{u} = X_u u - g \theta$$  \hspace{1cm} (15)

$$\dot{\theta} = q$$

$$\dot{q} = \delta M_u u + M_q q + M_a a_1 + d_1$$

Similarly, the simplified model equations of the lateral dynamics can be written as follows:

$$\dot{y} = v$$

$$\dot{v} = Y_v v + g \phi$$  \hspace{1cm} (16)

$$\dot{\phi} = p$$

$$\dot{p} = \eta L_v v + L_p p + L_b b_1 + d_2$$

where $d_1$ and $d_2$ are the external disturbances. Based on equations (15)-(16), the proposed robust adaptive backstepping controller design procedure is shown in the following section.

### 4. Controller Design

In this section, the design procedure of the proposed controller for the longitudinal and lateral dynamics of an UAH is presented based on the appropriate decoupled model as described by equations (15)-(16). The objective of this control is to regulate the several physical quantities (e.g. position, attitude etc.) for improving the flight condition of an UAH.
4.1. Longitudinal Dynamics

In this subsection, the design procedure of the adaptive robust backstepping controller is shown based on the Lyapunov function for the longitudinal dynamics as described by equation (15) under consideration of internal and external uncertainties. The design procedure is divided into four steps which is elaborately discussed as follows.

**Design step 1:** First, for the longitudinal position tracking objective, let define the longitudinal position tracking error as

\[ z_1 = x - x_d, \quad \dot{z}_1 = \dot{x} - \dot{x}_d, \quad \ddot{z}_1 = u \]  

(17)

Here \( u \) is assumed as a virtual control variable and its desired value \( u_d \) is a stabilizing function for equation (17). Let \( z_2 \) be another error variable representing the difference between the actual \( u \) and its desired value \( u_d \), i.e.,

\[ z_2 = u - u_d, \quad u = z_2 + u_d \]

Therefore, in terms of \( z_2 \) the equation (17) can be written as

\[ \ddot{z}_1 = z_2 + u_d \]  

(18)

At this stage a virtual control law should be designed for \( u_d \) in such a way that which would make \( z_1 \to 0 \) as \( t \to \infty \).

Now, consider the first CLF as follows:

\[ W_1 = \frac{1}{2} z_1^2 \]

whose time derivative after substituting the value of \( z_1 \) is

\[ \dot{W}_1 = z_1 (z_2 + u_d) \]  

(19)

Now an appropriate virtual control law \( u_d \) need to be selected in such a way that which would make \( \dot{W}_1 \leq 0 \). Under this condition, the stabilizing function is chosen as

\[ u_d = -k_1 z_1 \]  

(20)

where \( k_1 \) is a scalar parameter which can be used to tune the output response. Then equation (19) can be written as

\[ \dot{W}_1 = -k_1 z_1^2 + z_1 z_2 \]  

(21)

From equation (21), it can be seen that if \( z_2 = 0 \) then

\[ \dot{W}_1 = -k_1 z_1^2 \leq 0. \]

The second coupling term of equation (21) will be cancelled in the next step. Now the time derivative of \( u_d \) which is essential in the next step can be written as

\[ \dot{u}_d = -k_1 u \]  

(22)

As \( \dot{z}_1 = u \).

**Design step 2:** In this step, the error dynamics for \( z_2 = u - u_d \) is derived whose time derivative can be written as follows:

\[ \dot{z}_2 = x_u - g \theta + k_1 u \]

(23)

In which \( \theta \) is viewed as an another virtual control variable.

Now define a virtual control law \( \theta_d \) and let \( z_3 \) be another error variable which is representing the difference between actual control and virtual control i.e., \( z_3 = \theta - \theta_d \) and after taking time derivative it can be written as

\[ \dot{z}_3 = (x_u + k_1) u - g (z_3 + \theta_d) \]

(24)

Now choose a second CLF as follows:

\[ W_2 = W_1^2 + \frac{1}{2} z_1^2 \]

(25)

whose time derivative by inserting equations (21) and (24) can be written as

\[ \dot{W}_2 = -k_1 z_1^2 - z_2 \{ z_1 + (x_u + k_1) u - g (z_3 + \theta_d) \} - g z_2 z_3 \]  

(26)

Now an appropriate stabilizing function \( \theta_d \) can be selected in such a way to cancel out the terms related to \( z_1, z_2 \) and \( u \), while the term involving \( z_3 \) cannot be removed and this is

\[ \theta_d = g^{-1} \{ z_1 + (x_u + k_1) u + k_2 z_2 \} \]

(27)

Then equation (26) can be written as

\[ \dot{W}_2 = -k_1 z_1^2 - k_2 z_2^2 - g z_2 z_3 \]

(28)

From equation (28), it is clear that if \( z_3 = 0 \) then \( \dot{W}_2 = -k_1 z_1^2 - k_2 z_2^2 \leq 0 \) which is negative definite. In order to complete the next step, the time derivative of \( \theta_d \) is essential which can be written as

\[ \dot{\theta}_d = g^{-1} \{ u + (x_u + k_1) (x_u - g \theta) + k_2 z_2 \} \]

(29)

**Design step 3:** Here the error dynamics for \( z_3 = \theta - \theta_d \) is derived whose time derivative is

\[ \dot{z}_3 = \dot{\theta} - \dot{\theta}_d \]

(30)

By substituting the values of \( \dot{\theta} \) and \( \dot{\theta}_d \) into equation (30), it can be written as
The objective is to design the actual control. Thus, the final and
\[ \hat{z} = z + q - q_d - g^{-1} \{ u + (x_u + k_1)(x_u - g\theta) \} 
- g^{-1} k_2 \{ (x_u + k_1)u - g(z + \theta) \} \]  
(31)

In which q is viewed as the virtual control input. Now define a stabilizing control law qd and let z4 be an error variable representing the difference between actual and virtual control input, i.e.,
\[ z_4 = q - q_d \]  
and interm of this error variable the equation (31) can be written as
\[ \dot{z}_4 = z + q_d - g^{-1} \{ u + (x_u + k_1)(x_u - g\theta) \} 
- g^{-1} k_2 \{ (x_u + k_1)u - g(z + \theta) \} \]  
(32)

Now choose another CLF as
\[ W_3 = W_2 + \frac{1}{2} z_4 \]  
(33)
whose time derivative is
\[ \dot{W}_3 = -k_1 z_4 - k_2 z_4^2 - g\gamma z_4 z + z_4 \{ z_4 + q_d \} 
- g^{-1} \{ u + (x_u + k_1)(x_u - g\theta) \} 
- g^{-1} k_2 \{ (x_u + k_1)u - g(z + \theta) \} \]  
At this stage, the stabilizing qd need to be selected in such a way that cancel out the terms related to z1, z2, z3, and u, while the term involving z4 cannot be removed. Thus, the stabilizing function qd is
\[ q_d = g\gamma z_4 + g^{-1} \{ u + (x_u + k_1)(x_u - g\theta) \} 
+ g^{-1} k_2 \{ (x_u + k_1)u - g(z + \theta) \} \]  
(34)

After that selection,
\[ \dot{W}_3 = -k_1 z_4 - k_2 z_4^2 - k_3 z_4^2 + z_4 \]  
(35)

From equation (35), it is clear that if \( z_4 = 0 \) then equation (35) simplified to
\[ \dot{W}_3 = -k_1 z_4^2 - k_2 z_4^2 - k_3 z_4^2 \leq 0 \]  
(36)
In order to complete the final step, the time derivative of qd can be written as
\[ \dot{q}_d = f \]  
(37)
where
\[ f = g\gamma z_4 + g^{-1} \{ u + (x_u + k_1)(x_u - \theta) \} + g^{-1} k_2 \{ (x_u + k_1)u - g(\dot{z} + \theta) \} \] - k_3 \dot{z}_4

The derivation of longitudinal dynamics control law along with the stability and robustness analysis of the system is shown in the following step.

**Design step 4:** The dynamics of final error can be obtained as following by taking time derivative of \( z_4 \)
\[ \dot{z}_4 = \delta M_a u + M_q q + d_1 + M_a a_1 - f \]  
(38)

In equation (38), the actual control input appears. By incorporating the estimation error of unknown parameter \( \delta \), equation (38) can be rewritten as
\[ \dot{z}_4 = (\delta + \hat{\delta}) M_a u + M_q q + d_1 + M_a a_1 - f \]  
(39)
where \( \hat{\delta} = \delta - \delta \) is the estimation error of unknown parameter \( \delta \). The objective is to design the actual control input \( a_1 \) such that \( z_1, z_2, z_3, \) and \( z_4 \) converge to zero as \( t \to \infty \).

The presence of the parameter estimation error suggests the following form of the CLF
\[ W_4 = W_3 + \frac{1}{2} z_4^2 + \frac{1}{2} \delta^2 \]  
(40)

The time derivative of \( W_4 \) becomes
\[ \dot{W}_4 = \dot{W}_3 + z_4 \dot{z}_4 - \frac{1}{2} \delta \dot{\delta} \]  
(41)
where \( \gamma_4 \) is a positive design constant which determines the convergence speed of the estimation. By substituting the values of \( \dot{W}_3 \) and \( \dot{z}_4 \) into equation (41), it can be written as
\[ \dot{W}_4 = -k_1 z_4 - k_2 z_4^2 - k_3 z_4^2 \leq 0 \]  
(42)

Now the final control law and adaptation law are chosen in such a way that which would make \( \dot{W}_4 \leq 0 \). Thus, the final control law and adaptation law are chosen as follows:
\[ a_1 = -\{ z_4 + \hat{\delta} M_a u + M_q q - f + k u z_4 + \Gamma \text{sgn}(z_4) + \hat{d}_1 \} \]  
\[ \hat{\delta} = \gamma_4 M_a u \]  
(43)

where \( \hat{d}_1 \) is an estimate parameter which represents a best guess for the unknown external disturbance \( d_1 \) and sgn is the signum function which can be written as
\[ \text{sgn}(z_4) = \begin{cases} +1 & \text{if } z_4 > 0 \\ 0 & \text{if } z_4 = 0 \\ -1 & \text{if } z_4 < 0 \end{cases} \]  
(44)

The estimation error on \( d_1 \) is assumed to be bounded by knowing the constant, \( \Gamma \), i.e., \( || d_1 - \hat{d}_1 || \leq \Gamma \). Then by using the Schwartz inequality the derivative of \( W_4 \) becomes
\[ \dot{W}_4 \leq -k_1 z_4^2 - k_2 z_4^2 - k_3 z_4^2 - k_4 z_4^2 || y \leq \Gamma || d_1 - \hat{d}_1 || \]  
Since \( || d_1 - \hat{d}_1 || \leq \Gamma \), so \( \dot{W}_4 \leq 0 \).
4.2. Lateral Dynamics

In this subsection, the robust adaptive backstepping controller is designed based on the Lyapunov function for the lateral dynamics in the presence of parametric and external uncertainties. Again, consider a CLF which is used to augment the estimated parameter error,

\[ W_i = W_i' + \frac{1}{2} z_i^2 + \frac{1}{2} \eta_i^2 \]  

(44)

Using the similar procedure as mentioned in the previous subsection, the following control input can be obtained for the lateral dynamics

\[ b_i = -L_i^{-1}(z_i + \eta_i L_v + L_{\phi} p - f(z_a, z_\phi, v, \phi, \phi_\theta)) + k_i z_\phi + \Gamma_i \text{sgn}(z_\phi) + \dot{\hat{\phi}} \]  

(45)

Finally, we get the following equation.

\[ W_{i0} = -k_a z_a^2 - k_v z_v^2 - k_k z_k^2 \leq 0 \]  

(47)

Thus, it can be proved that the system is Lyapunov stable and the errors are asymptotically converging to an arbitrarily small neighborhood of zero. Note that the detailed design procedure of the proposed controller for lateral dynamics is not illustrated in this paper. Simulation studies are conducted in the following section to show the effectiveness of this proposed controller.

Remark 1: Control inputs in the controller design process are set to be longitudinal and lateral flapping angles. They will be converted later into longitudinal cyclic and lateral cyclic for implementation.

5. Simulation Results

The performance of the designed controller has been conducted on a nonlinear simulation model using the MATLAB simulink. To show the superiority of the proposed robust adaptive backstepping controller over an existing controller, the performance is also compared with a classical PID controller. The simulation is conducted in the case where the desired positions are set to \( x = 0 \) m and \( y = 0 \) m. The roll angle trim \( \phi_{\text{ref}} \) is initialized at 4.50 to compensate the effect of tail rotor thrust.

The corresponding system responses with both controllers are shown in Fig. 1 to Fig. 3. The horizontal position responses of an UAH with both controllers is shown in Fig. 1. It is clear that the position tracking error is almost zero with the proposed controller (solid blue line) but it is relatively large with the PID controller (solid green line) and it is oscillating.

From the simulation result, it is clear that the proposed controller is more robust than the PID control under the condition of parametric and external disturbances within the system of an UAH. The corresponding velocity response of an UAH is shown in Fig. 2, from where it is clear that horizontal velocities settle to approximately 0 m/s at about 3 s after the start of the simulation in both \( y \) direction and \( x \) direction from the beginning of the simulation. But for the PID controller, it can be seen that they are oscillating and are not completely damped.

Thus, from the simulation results, it is obvious that the proposed controller is able to achieve the desired horizontal
positions in the presence of parametric and external disturbances by providing more stabilize hovering flight.

The corresponding roll and pitch angle responses of an UAH during hover flight are shown in Fig. 3. From where, it can be seen that due to the proposed controller, the roll angle settles to the desired value at 4.5° within few second, but for the PID controller, it settles in between about 2.5° to 3.90°. It can be seen that the angle responses are more stable with the proposed controller than the existing controller in terms of settling time and damping of oscillations.

![Roll angle of UAH.](image)

**Fig. 3.** Roll and Pitch angles response using the adaptive robust backstepping and PID controllers.

![Pitch angle of UAH.](image)

The control signals for the both controllers is shown in Fig. 4, from where it can be seen that control signals do not exceed the physical constraints of the helicopter. From the simulation results, it is clear that the designed controller is more effective than an existing controller in terms of settling time and damping of oscillation.

6. Conclusion

In this paper, a backstepping method to design a robust adaptive controller for an UAH is proposed to enhance the stabilization of horizontal position control of a hovering flight. Based on the proposed formulation, the designed controller is adaptive to the unknown parameters and robust to the external disturbances. From the theoretical and numerical evaluations, it can be concluded that the proposed controller has the capability to stabilize the longitudinal and lateral dynamics as it can track the pre-defined reference trajectory despite the presence of parametric and external uncertainties within the UAH system model. Future work will be devoted on the implementation of the controller to a real system, e.g., flight test under the consideration of parametric and external uncertainties to prove the feasibility in the real life.

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