ROBUST ADAPTIVE BACKSTEPPING CONTROLLER DESIGN FOR REJECTING EXTERNAL WIND GUSTS EFFECT IN AN UNMANNED AUTONOMOUS VEHICLE

Tushar Kanti Roy
Department of Electronics & Telecommunication Engineering
RUET, Rajshahi

Abstract

In this paper, a nonlinear robust adaptive backstepping controller to reject the external wind gusts effect in an unmanned autonomous helicopter (UAH) is proposed. The proposed controller is designed based on a recuirsive backstepping technique to control the hover and vertically take-off/landing flight of an UAH. The vertical and yaw dynamics of an UAH are considered to derive the proposed controller in order to take into detention the dynamic variations of main rotor and tail rotor thrusts due to any external uncertainties. The proposed controller is designed in such a way that it is adaptive to unknown external disturbances which are estimated through the adaptation laws and the convergences of these adaptation laws are obtained through the negative semi-definiteness of control Lyapunov functions (CLFs). Finally, effectiveness of the designed controller is tested using a high-fidelity MATLAB simulation model by considering the external wind gusts effect into the UAH system for a hover flight and compared the performances of the proposed controller with an existing PD controller. Simulation results demonstrate the robustness of the proposed controller over the existing PD controller in terms of rejecting external wind gusts.

Keywords: Control Lyapunov function, external wind gusts, robust adaptive backstepping controller, small-scale UAH

Introduction

Among different unmanned autonomous vehicles (UAVs), UAHs are more attractive due to their some unique features such as, hovering ability for a long period of time, flying longitudinally and laterally, vertically take-off and landing flight in a constricted space to achieve many missions. For these unique features, UAHs are used for a variety of applications such as, reconnaissance, search and rescue missions, weather data collection, bush fire monitoring, agricultural crop dusting and surveillance, etc (TKRoy et al. 2012). In order to do the aforementioned applications successfully, a fully autonomous UAVs are mostly expected which is not so easy. Because, UAH is a naturally unstable system due to the highly nonlinear dynamics. Beside these, another main difficulty of an UAH are the higher nonlinearities within the vertical and the yaw dynamics which arises due to the cross-couplings among the tail rotor, main rotor, engine and dynamic uncertainties (Fahini et al. 2008). Moreover, during the vertically take-off and landing flight mode the vertical height of an UAH is much lower than a fixed wing aircraft, and due to that the ground effect is an important factor for an autonomous stabilizing flight (Wang et al. 2008). Because this ground effect can provide extra force to the main rotor thrust of an UAH during the time of lifting. Therefore, ground effect should be considered during the design of a controller for a precise altitude control of an UAH. It should be noted that ground effect also depends on the external wind gusts and the hardness on the ground surface. As, the large thrust variations occurs in the rotor of an UAH due to the external wind gusts and ground effect so it is a challenging task to maintain a constant altitude near the ground surface (Roy et al. 2013). Thus, a controller should be designed in such a way which can control the desired height of an UAH in the presence of both parameteric and external uncertainties.

Different conventional linear controllers are available to stabilize the flight of an UAH which are designed based on the linear approximation around an operating point (Shim et al. 1998, Xia et al. 2010) i.e. for hover flight conditions. But these controllers are not appropriate when operating point is changed due to any external or inter uncertainties. Thus, recently, various advance nonlinear control techniques are applied to the control an UAH flight for different operating points under large disturbance (Tushar et al. 2013, Roy et al. 2014, Pota et al. 2012, Troy et al. 2013, TKRoy et al. 2014).

Among different nonlinear control techniques, the backstepping controller is a most promising nonlinear control technique which provides a systematic approach to prove the stability of the closed loop system using Lyapunov function. A nonlinear robust backstepping controller to control the vertical height of an UAH under the external disturbances is proposed in (Roy et al. 2012, Matt et al. 2012). However, ground effect which usually exist in UAH system near ground surface is not taken into account to design their controller. In order to improve the flight performance during altitude control of an UAH by compensating the ground effect an adaptive backstepping controller is proposed in (Roy et al. 2013). But the external disturbances are not considered in this paper. Similar control approach is proposed in (Samal et al. 2012) to control the vertical height of an UAH by considering the external vertical wind gusts along with the consideration of ground effect. Similar uncertainties are considered in (Leishman et al. 2006) to design a robust adaptive backstepping controller for heave dynamics control of an UAH. Although the tail rotor have a significant role on the stability for a hover flight of an UAH but, how to control the yaw dynamics of an UAH during the hover flight are not clear in (Roy et al. 2013, Roy et al. 2012, Matt et al. 2012, Rasel et al. 2013).

The tail rotor of an UAH is also faced side winds during yaw maneuvers when it operates in an effective climb and descent mode. Consequently, it can loss the system stability of an UAH. In addition, it is also affected by the turbulent separated flow which is generated by the main rotor, vertical fin, and fuselage wakes (TKRoy et al. 2013). Under these aerodynamic interactions the accurate modeling of vertical and yaw dynamics is more difficult. To handle this situation, a mode partition method is discussed in (Guan et al. 2012) for identification of yaw dynamics but they did not design any suitable controller to control the yaw dynamics. To compensate the effect of uncertainties with yaw dynamics an adaptive robust H_∞ controller is proposed in (Zhao et al. 2008). But the controller is designed by considering a linear system of an UAH. To overcome the limitation of (Zhao et al. 2008), a nonlinear robust backstepping controller is proposed in (Mahmud et al. 2014) to control the yaw dynamics in the presence of external disturbances. An active modeling based yaw control of an unmanned rotorcraft is proposed in (Peng et al. 2014). In (Han et al. 2006), an adaptive robust tracking controller for the yaw control with time-invariant uncertainties is proposed. Even though the yaw dynamics control problem of an UAH is successfully resolved in (Han et al. 2006, Lik et al. 2013), but the effects of wind disturbances and parametric uncertainties are not taken into account within the UAH system model during the design of their controllers. As we know, due to the light-weight structure, UAH is more likely to be affected by external disturbances than their full-size counterparts. The physical parameters such as mass and moments of inertia can be easily altered by changing in the payload, e.g., fuel consumption and other adverse factors due to their low inertia and limited power, which in turn necessitates the development of more stable and robust flight control systems. It should be emphasized that very few research works have been done on the influence of the ground effect and wind gusts to control the vertical and yaw dynamics of an UAH near the ground surface. Thus, a nonlinear controller needs to be designed by considering the effects of parametric and external uncertainties within the UAH system.

The aim of this paper is to control the vertical and yaw dynamics of an UAH which is very important during take-off and landing flight condions.

The stability of the whole UAH system is ensured through the formulation of control Lyapunov functions (CLFs) at every step of the design procedure and the robustness of the designed controller is analyzed against the rejection of external disturbances. At the end, a nonlinear flight simulation model based on MATLAB is used to evaluate the effectiveness and robustness of proposed controller for a hover flight of an UAH and compared the performances with an existing classical PD controller.

The rest of the paper is organized as follows. Section 2 presents the vertical and a yaw dynamics model of an UAH. The control problem formulation is briefly discussed in Section 3. The design procedure of the proposed controller is shown in Section 4. The wind gust model that will be used in the simulation to test the controller is discussed in Section 5. The simulation results to analyse the effectiveness of the proposed controller are shown in Section 6. Finally, concluding remarks are given in Section 7.

Dynamical Model of Vertical And Yaw Dynamics

In this section, the basic mathematical model of a small-scale helicopter is introduced. The differential equations of an UAH are written as follows:

$$\dot{u} = vr - wq + g\sin\theta + \frac{X}{m} \tag{1}$$

$$\dot{v} = wp - ur + g\sin\phi\cos\theta + \frac{Y}{m} \tag{2}$$

$$\dot{w} = (uq - vp) + g\cos\phi\cos\theta + \frac{Z}{m} \tag{3}$$

$$I_{xx}\dot{p} = (I_{yy} - I_{zz})qr + I_{xz}(\dot{r} + pq) + L \tag{4}$$

$$I_{yy}\dot{q} = (I_{zz} - I_{xx})rp + I_{xz}(r^2 - p^2) + M \tag{5}$$

$$I_{zz}\dot{p} = (I_{xx} - I_{yy})pq + I_{xz}(\dot{p} - qr) + N \tag{6}$$

where the symbols have usual meanings which can be found in (Garrat et al. 2012). If the mass distribution of the body is symmetric with respect to the body frame, the cross product of inertia I_{xz}= 0. Under this assumption, the simplified equations of yaw dynamics can be written as

$$\dot{\Psi} = (q\sin\phi + r\cos\phi)\sec\theta \tag{7}$$

$$\begin{aligned} I_{zz}\dot{p} = {} & (I_{xx} - I_{yy})pq + I_{xz}(\dot{p} - qr) + N_{mr} + N_{tr} \\ & + N_{fus} + N_{tp} + N_{fn} \end{aligned} \tag{8}$$

It is well known that the force and moment produced by the main rotor and tail rotor play a vital role for a hovering flight, so by simplifying the fuselage and vertical fin damping, the yaw dynamics equation can be rewritten as

$$\dot{\psi} = r \tag{9}$$

$$I_{zz}\dot{r} = -Q_{mr} + T_{tr}l_{tr} + b_1 r + b_2\psi \tag{10}$$

where Q_{mr} is the main rotor moment, T_{tr} is the tail rotor thrust, b_1 and b_2 are damping coefficient constant. Again, it can be approximated that torque acting on the main rotor is equal to the engine torque of an UAH i.e., $Q_{mr}=Q_e$. Therefore, the engine torque of an UAH can be written as

$$Q_e=P_e/\Omega_{mr} \qquad (11)$$

Another objective of this paper is to control the height of an UAH for the hovering flight. Thus, it is essential to express equation (3) i.e. vertical dynamics of an UAH in the earth frame. To this end, the rotation matrix between the body and earth frames is used and then vertical dynamics of an UAH can be written as follows:

$$\dot{w} = g + (\cos\phi\cos\theta)\, Z/m \qquad (12)$$

It is well known that for a hovering flight, the vertical dynamics of an UAH can be linearized, i.e., $\phi \approx 0, \theta \approx 0,$ and $\psi \approx 0$. Thus, the linearized vertical dynamics of an UAH can be expressed in a two-order system as follows:

$$\dot{z} = w$$
$$\dot{w} = \frac{mg - T}{m} \qquad (13)$$

Equations (10)-(11) and (13) will be used to design the proposed robust nonlinear adaptive controller. However, before design the proposed controller, it is intended to focus on the problems when there is external disturbances within the system of an UAH, which is discussed in the following section.

Control Problem Formulation

Due to the aerodynamic uncertainties and the nonlinear coupling effect in between main rotor and tail rotor the control of a hover flight an UAH is a challenging tasks. Still it is a challenging task to the control engineers as they are naturally unstable and easily affected by the external disturbances. Moreover, the parameters variation and the external uncertainties are very common during the operation of an UAH system and these variations have significant impact on the stability of the UAH system. If these uncertaint parameters are varying slowly then we can still use the adaptive backstepping controller. But if the parameters vary too fast, achieving asymptotic stability can be very hard, if not impossible. The best we may do this case is make sure that the parameters are bounded i.e. this makes the robust controller. In addition, the designed controller should have adaptive properties to adapt all these factors and must be robust to reject the external disturbances as well as estimate the parameters in an effective way. Under these assumptions, the dynamical model of yaw dynamics and vertical dynamics of an UAH as represented by (9)-(10) and (11) can be rewritten as follows:

Yaw dynamics:

$$\dot{\psi} = r \tag{14}$$

$$I_{zz}\dot{r} = -Q_{mr} + T_{tr}l_{tr} + b_1 r + b_2\psi + d_1 \tag{15}$$

Vertical dynamics:

$$\dot{z} = w \tag{16}$$

$$\dot{w} = \frac{mg - T}{m} + d_2 \tag{17}$$

where d_i with $i = 1,\ 2$ is the external wind gust disturbance. The design procedure of a robust nonlinear adaptive controller is shown in the following section in order to achieve the desired performances.

Proposed Controller Design

In this section, a yaw angle controller is designed for the yaw dynamics based on the model as represented by (14)-(15) and then a vertical height controller controller is designed for the vertical dynamics of an UAH as described by (16)-(17). The design procedure of the proposed controller is elaborately discussed in the following subsections.

A. Yaw Dynamics Controller Design

The objective of this subsection is to design a robust adaptive backstepping controller to stabilize the yaw dynamics of an UAH. The yaw dynamics are dependent on the yaw angle and tail rotor collective pitch. And the yaw angle of an UAH is controlled by T_{tr} through the tail rotor collective pitch. In order to achieve this goal, a nonlinear robust adaptive backstepping approach is used which involves the following steps:

Design step 1: Find r_d

According to the design process the yaw angle tracking error is

$$e_1 = \psi - \psi_d \tag{18}$$

where ψ_d is the desired value of the yaw angle of an UAH. The time derivative of equation (18), after substituting equation (14) can be written as

$$\dot{e}_1 = r - \dot{\psi}_d \tag{19}$$

Here r is is a virtual control variable and r_d is defined as the stabilizing function of equation (19). Let e_2 be an another error variable, which can be defined as follows :

$$e_2 = r - r_d \tag{20}$$

Thus interm of e_2 equation (19), can be written as

$$\dot{e}_1 = e_2 + r_d - \dot{\psi}_d \tag{21}$$

In order to stabilize the yaw angle tracking error as represented by equation (21), the first control Lyapunov function (CLF) can be formulated as follows:

$$V_1 = \frac{1}{2} e_1^{\,2} \tag{22}$$

The time derivative of equation (22) can be wriiten as

$$\dot{V}_1 = e_1 \dot{e}_1 \tag{23}$$

By substituting equation (21) into equation (23), yields

$$\dot{V}_1 = e_1 (e_2 + r_d - \dot{\psi}_d) \tag{24}$$

Now the stabilizing function r_d need to be selected in such a way that which would make $\dot{V}_1 \leq 0.$ Thus, the stabilizing function is chosen as

$$r_d = -\alpha\, e_1 + \dot{\psi}_d \text{ with } \alpha > 0 \tag{25}$$

where α is a positive constant parameter which is used to tune the output response. Then equation (24) reduces to

$$\dot{V}_1 = -\alpha e_1^{\,2} + e_1 e_2 \tag{26}$$

From equation (26), it is clear that if $e_2 = 0$ then

$$\dot{V}_1 = -\alpha\, e_1^{\,2} \leq 0 \tag{27}$$

Now the time derivative of r_d is taken here as it is essential in the next step and it can be expressed as

$$\dot{r}_d = -\alpha\, r + \ddot{\psi}_d \tag{28}$$

As $\dot{\psi} = r$. The derivation of tail rotor pitch control law along with the stability and robustness analysis of yaw dynamics of an UAH is shown in the following step.

Design step 2: Find δ_{ped}

In this step, the error dynamic for $e_2 = r - r_d$ is derived whose time derivative is

$$\dot{e}_2 = \dot{r} - \dot{r}_d \tag{29}$$

Inserting equations (15) and (28) into equation (29), it can be written as

$$\dot{e}_2 = \frac{-Q_{mr} + T_{tr} l_{tr} + b_1 r + b_2 \psi}{I_{zz}} + \frac{d_1}{I_{zz}} + \alpha\, r + \ddot{\psi}_d \tag{30}$$

which can be simplified as

$$\dot{e}_2 = A + \frac{T_{tr} l_{tr}}{I_{zz}} + \Im_1 \tag{31}$$

where

$$A = \frac{-Q_{mr} + b_1 r + b_2 \psi}{I_{zz}} + \alpha\, r + \ddot{\psi}_d\,, \quad \Im_1 = \frac{d_1}{I_{zz}}$$

Again, the relationship between tail rotor thrust and tail rotor collective pitch is

$$T_{tr} = (v + r\,l_{tx} + p\,l_{tz} + \frac{2}{3}\Omega_{tr} R_{tr} \delta_{ped} - v_{itr})D \qquad (32)$$

where

$$D = \frac{\rho \Omega_{tr} R_{tr}{}^2 a_{tr} b_{tr} c_{tr}}{4} \quad v_{itr}{}^2 = \sqrt{\left(\frac{\hat{v}_{tr}}{2}\right)^2 + \left(\frac{T_{tr}}{2\rho\pi R_{tr}}\right)^2} - \frac{v_{tr}{}^2}{2}$$

By substituting the value of T_{tr} into equation (31), it can be written as $\dot{e}_2 = A + \Im_1 + \frac{l_{tr}}{I_{zz}} D(v + r\,l_{tx} + p\,l_{tz} + \frac{2}{3}\Omega_{tr} R_{tr} \delta_{ped} - v_{itr})$ and simplified as

$$\dot{e}_2 = E + F\delta_{ped} - \frac{l_{tr}}{I_{zz}} D v_{itr} + \Im_1 \qquad (33)$$

where $E = A + \frac{l_{tr}}{I_{zz}} D\left(v + r\,l_{tx} + p\,l_{tz}\right)$, $F = \frac{2 l_{tr}}{3 I_{zz}} D \Omega_{tr} R_{tr}$

where δ_{ped} is a rudder servo actuator control input which is designed in such a way that can control the desired yaw angle trajectory of an UAH. Since the real value of $v_{i\,tr}$ cannot be measured precisely, it is replaced with the estimated value of $\hat{v}_{i\,tr}$ which depends on the external wind disturbances.

Thus in term of estimation error equation (33), can be written as

$$\dot{e}_2 = E + F\delta_{ped} - \hat{\Delta} - \tilde{\Delta} + \Im_1 \qquad (34)$$

where $\hat{\Delta}$ is equal to the estimation of the unknown parameter $\Delta = \frac{l_{tr}}{I_{zz}} D v_{itr}$ and $\tilde{\Delta} = \Delta - \hat{\Delta}$ is the estimation error. The aim of this designed is to choose the actual control input δ_{ped} in such a way that e_1 and e_2 converge to zero as $t \to \infty$. At this point, the final CLF is chosen as follows:

$$V_2 = V_1 + \frac{1}{2} e_2{}^2 + \frac{1}{2\gamma} \tilde{\Delta}^2 \qquad (35)$$

where γ is an adaptation gain parameter that determines the convergence speed of the unknown parameter estimation. The time derivative of equation (35) can be written as

$$\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 - \frac{1}{\gamma} \tilde{\Delta} \dot{\hat{\Delta}} \qquad (36)$$

By inserting values of $\dot{V}_1$ and $\dot{e}_2$ into equation (36), it can be written as

$$\dot{V}_2 = -\alpha e_1{}^2 + e_2 (e_1 + E + F\delta_{ped} - \hat{\Delta} + \Im_1) - \frac{1}{\gamma} \tilde{\Delta} (\dot{\hat{\Delta}} + \gamma e_2) \qquad (37)$$

The $\tilde{\Delta}$ term can now be eliminated from equation (37) with the following adaptation law:

$$\dot{\hat{\Delta}} = -\gamma e_2 \qquad (38)$$

and accordingly, equation (37) can be simplified as

$$\dot{V}_2 = -\alpha e_1^{\ 2} + e_2(e_1 + E + F\delta_{ped} - \hat{\Delta} + \Im_1) \tag{39}$$

To ensure the asymptotic stability of the yaw dynamics, the derivative of V_2 should be negative definite, i.e., $\dot{V}_2 \le 0$ which can be achieved by choosing the following control law:

$$\delta_{ped} = \frac{1}{F}\left(-e_1 - E + \hat{\Delta} - \beta e_2 + \Gamma \operatorname{sgn}(e_2)\right) \tag{40}$$

where sgn is the signum function which can be written as follows:

$$\operatorname{sgn}(e_2) = \begin{cases} +1 & if \quad e_2 > 0 \\ 0 & if \quad e_2 = 0 \\ -1 & if \quad e_2 < 0 \end{cases} \tag{41}$$

The external disturbance $\Im_1$ is assumed to be bounded by known constant Γ that is, $\| \Im_1 \| \le \Gamma$ Under this situation, equation (39) can be rewritten as

$$\dot{V}_2 \le -\alpha e_1^{\ 2} - \beta e_2^{\ 2} - \| e_2 \| \left[\Gamma - \| d_1 \|\right] \tag{42}$$

Since $\| \Im_1 \| \le \Gamma$, so $\dot{V}_2 \le 0$.

From (42), it is obvious that the error dynamics of the yaw dynamics is asymptotically stable. The robust adaptive backstepping controller for vertical dynamics is discussed in the following subsection.

B. Vertical Dynamics Controller Design

This subsection deals with the design of a robust adaptive backstepping controller for the vertical dynamics of an UAH. The vertical dynamics is depended on the vertical height *z* and the control input collective pitch θ_c. Again, the vertical height *z* of a helicopter is controlled by *T* through the collective pitch control input, θ_c.

Using the same procedure as mentioned in the previous subsection, the control input of the vertical dynamics of an UAH can be wriiten as

$$\theta_c = \frac{3\, m\left[e_3 + g + \hat{\eta} + \alpha_1\, w + \beta_1\, e_4 + F_v \operatorname{sgn}(e_4)\right]}{B(1 + \frac{3}{2}\mu^2)} \tag{43}$$

where $\hat{\eta}$ is an estimation of the unknown parameter $\eta = \frac{B}{2m}\lambda'$ and F_v is the bounded parameters on the external disturbances. In order to render the non-positivity of the Lyapunov function, the adaptation law is chosen for the estimated parameter $\hat{\eta}$ as follows

$$\dot{\hat{\eta}} = -\gamma_1\, e_4 \tag{44}$$

Similarly, the stability of the vertical dynamics can be proved. Simulation studies are conducted in the following section to show the effectiveness of this proposed controller. But before showing the simulation results of the proposed controller the external gusts model is discussed in the following section which is used in the simulation model to test the controller performance.

Wind Gust Model

The objective to incorporate the wind gusts into the simulation model is to guarantee that the proposed controller can cope with a real-world environment. For usefulness performance analysis of an UAH, the wind gusts can be treated as either spectral turbulence or discrete. For arbitrary gusts, the typical spectral models contain the Von Karman and Dryden turbulence models. However, due to the computational difficulty of the Von Karman model, the Dryden model is usually used to analyse the charaterics of aerospace vehicles. There are many sources for wind models based upon experiential data that consist of passing band limited white noise through appropriate forming filters. The wind model is scaled with respect to height, speed, wing span of an UAH. From the practical point of view, vertical wind gusts can be neglected compared with its horizontal counterparts as the main factor influencing on thrust comes from the horizontal gusts for hovering flight near ground. Thus, the horizontal wind gusts model by including $H_u(s)$ for longitudinal direction and $H_v(s)$ for lateral direction take the following transfer function forms [11]:

$$H_u(s) = \sigma_u \sqrt{\frac{2L_u}{\pi U}} \frac{1}{1 + \frac{L_u}{U} s} \tag{45}$$

$$H_v(s) = \sigma_v \sqrt{\frac{L_v}{\pi U}} \frac{1 + \frac{\sqrt{3} L_v}{U} s}{\left(1 + \frac{L_v}{U} s\right)^2} \tag{46}$$

where U is the true speed of an UAH, σ_u and σ_v are the root mean square intensities of the turbulence and L_u and L_v are the turbulence scale lengths that describe the behaviour of the wind gusts. In this paper, the scale of turbulence L_u and L_v are assigned constant values of $L_u = L_v = 722.5m$. And for low altitude region (altitude < 1000ft) the σ_u, σ_v and σ_w turbulence intensities are defined as follows

$$\sigma_w = 0.1 W_{20} \tag{47}$$

$$\frac{\sigma_u}{\sigma_w} = \frac{\sigma_v}{\sigma_w} = \frac{1}{(0.177 + 0.000823h)^{0.4}} \tag{48}$$

where W_{20} is the wind speed at 20 ft (6m) above the ground and can be approximated by U and altitude is described by h. In this paper, typical level of wind speed and altitude are considered as 10 m/s and -2 m, respectively. Simulation studies are conducted in the following section to demonstrate the effectiveness of the proposed controller.

Controller Performance Evaluation And Discussion

The simulation results are presented in this section to analyse the performance of the designed robust adaptive backstepping controller for vertical and yaw dynamics of an UAH. In order to show the superiority of the designed controller over an existing controller, the performance is also compared with a PD controller. The bound of the robust controllers are selected as Γ=0.3 m/s and F_v=0.4 m/s based on the tail rotor and main rotor induced velocities vibration due to the external wind gusts.

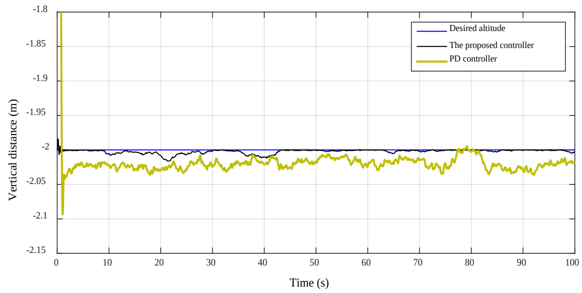

Fig. 1. Altitude response of an UAH

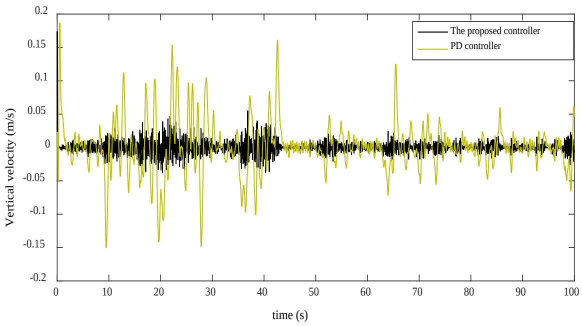

Fig. 2. Vertical velocity response of an UAH

The corresponding vertical height response of an UAH with both the designed controller and the PD under consideration of ground effect compensation is shown in Fig.1. From Fig. 1, it is clear that altitude tracking performance is significantly improved by compensating the ground effect with proposed controller (solid black line), while large deviation appears at the altitude tracking error when existing PD is used. The vertical velocity response of an UAH is shown in Fig. 2, from where it can be seen that velocity response is more stable with the proposed controller than the existing controller.

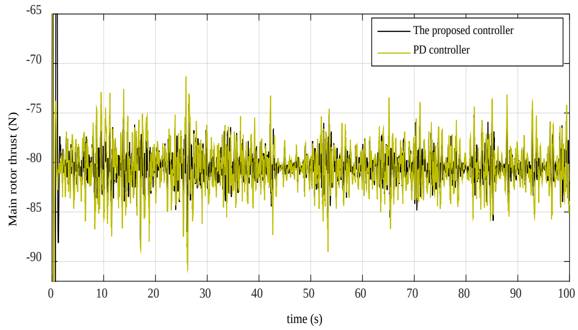

Fig. 3. Main rotor thrust variations response of an UAH

The corresponding main rotor thrust response of an UAH in the presence of ground effect and external wind gusts effect near the ground surface with both controllers is shown in Fig. 3. From Fig. 3, it can be seen that main rotor thrust is little bit oscillating with the proposed controller but the response is more oscillating when existing PD controller is used. The corresponding control input of both controllers is shown in Fig. 4. From Fig. 4, it can be seen that vertical height control input signal is more stable than the PD controller and they did not exceed the constraints for altitude control of an UAH.

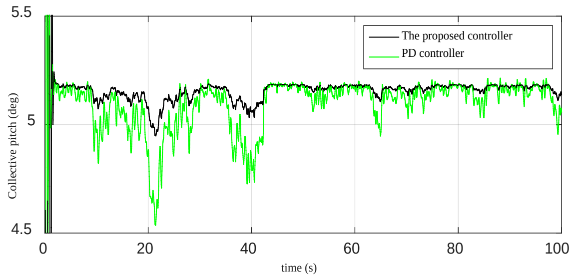

Fig. 4. Control input of vertical dynamics

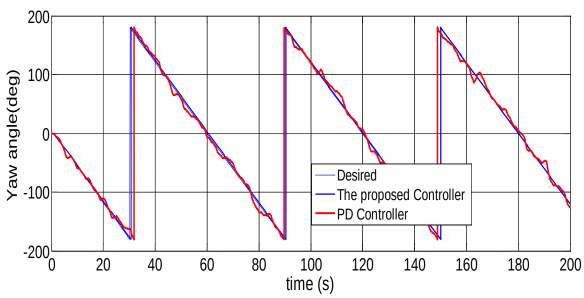

Fig. 5. Yaw angle tracking curves with sawtooth-wave command signal

From the above simulation results, it can be concluded that the proposed controller can stabilize the vertical dynamics of an UAH in a better way as compared to an existing PD controller.

The second simulation is done to verify the tracking performance and robustness of the proposed yaw controller. For this proposed yaw dynamics controller, the corresponding yaw dynamics responses of an UAH are shown from Fig. 5 to Fig. 8. The yaw angle response with proppoosed controller and PD controller is shown in Fig. 5, from where it is clear that the actual trajectory of yaw angle is almost identical to the desired angle with the proposed controller (solid blue line) but it slightly deviates from the desired trajectory when PD controller (solid green line) is used. The yaw rate response of an UAH with the proposed controller and PD controller is shown in Fig. 6. From Fig. 6, it can be seen that the yaw rate is more stable despite the presence of external disturbances on the UAH system with the designed controller but it is oscillating when existing PD controller is used.

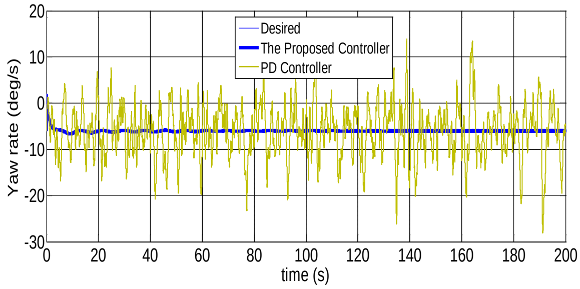

Fig. 6. Yaw rate of an UAH

Fig. 7. represents the variation of the tail rotor thrust in the presence of external wind gusts near the ground surface. From Fig. 7, it can be observed that when designed controller is used the tail rotor thrust to be less away from its balance position compared to the PD controller. The corresponding control input with both controllers is shown in Fig. 8, from where it can be seen that the control input with proposed controller is more stable than the existing controller. The external wind disturbance is shown in Fig. 9, which is used in the simulation model to test the controllers.

From the simulation results, it is clear that the proposed control method can effectively compensate the effect of horizontal wind gusts and the UAH can hover at the desired height. Though the PD controller successfully controls the altitude and yaw angle of the UAH, but it can be seen that the UAH is not hovering at the desired height. Therefore, it can be concluded that the proposed robust adaptive backstepping controller not only improves the control efficiency but also enhanced the robustness property against external wind disturbances.

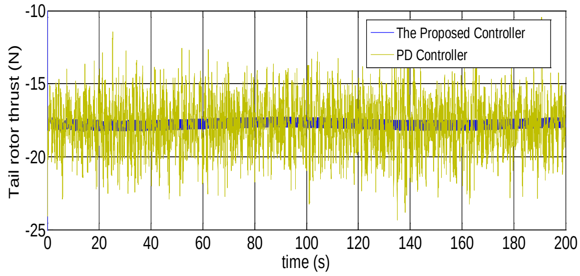

Fig. 7. Tail rotor thrust variations response of an UAH

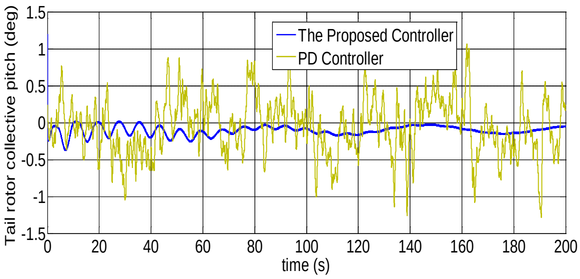

Fig. 8. Control input of yaw dynamics of an UAH

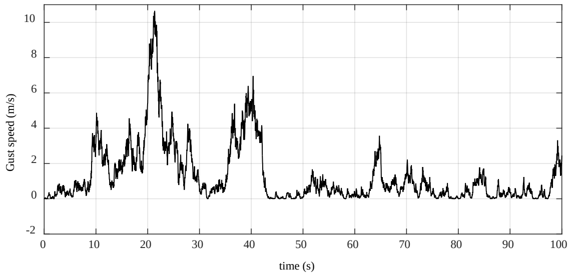

Fig. 9. Wind disturbance to test the controller

Conclusion

A nonlinear robust adaptive controller is proposed in this paper to control the height and yaw angle of an UAH, which takes full advantage of the known part of system model to design control law, and compensates the influence of disturbance of external uncertainties and ground effect. Based on the new approach, an adaptive control law for uncertain parameters is introduced and the external disturbances are also bounded to avoid the deterioration of the proposed controller performance. The theoretical stability of vertical and yaw dynamics of an UAH is proved through the negative definiteness of the derivative of control Lyapunov functions. From the simulation results, it can be seen that the proposed controller can track the predefined vertical height and yaw angle reference trajectory in a better way than the existing PD controller despite the presence of external uncertainties and ground effect in the system. Future works will be devoted on a real flight test to prove the feasibility of the designed controller in the gusty environment near the ground surface.

References:

T. K. Roy, (2012). Robust backstepping control for small helicopter. Masters thesis, UNSW, Australia.

M. Saffarian, & F. A. Fahini (2008). Comprehensive kinematic analysis of a model helicopter's actuating mechanism. *in Proc. of the 46th AIAA Aerospace Sciences Meeting and Exhibit*.

X. Wang, & X. Zhao (2008). A practical survey on the flight control system of small-scale unmanned helicopter. *in Proc. of the 7th WCICA*, pp.364–369.

T. K. Roy & A. A. Suman (2013). Adaptive backstepping controller for altitude control of a small-scale helicopter by considering the ground effect compensation. *in Proc. of the IEEE2nd International Conference on Informatics, Electronics and Vision (ICIEV)*, pp. 1-5, Bangladesh.

H. Shim, T. J. Koo, & F. Hoffmann (1998). A comprehensive study of control design for an autonomous helicopter. *in Proc. of the 37th International Conf. on Decision and Control*, pp. 3653-3658.

T. K. Roy & H. M. Rasel (2013). Altitude control of an unmanned autonomous helicopter via adaptive backstepping controller under horizontal wind gusts. *IJCEE*, vol. 5, no. 1, pp. 1-7.

X. H. Xia, & Y. J. Ge (2010). Finite-horizon optimal linear control for autonomous soft landing of small-scale helicopter. *In Proc. of the International Conf. on Information and Automation*, pp. 1160-1164.

T. K. Roy (2013). Horizontal position control of a small scale helicopter using adaptive backstepping controller. *Internal Journal of CCNet*, vol. 2, no. 2, p. 1 – 14.

T. K. Roy, M. A. Mahmud, M. Z. I. Sarkar, & M. F. Pervej (2014). Longitudinal-lateral and heave dynamics control of rotary wing autonomous vehicles using adaptive backstepping controllers. *in IEEE Proc. of the International Forum on Strategic Technology (IFOST)*, 2014.

T. K. Roy & M. Garrattt (2012). Altitude control of an unmanned autonomous helicopter via robust backstepping controller under horizontal wind gusts. *in Proc. of the 7th IEEE International Conference on Electrical and Computer Engineering*, pp. 771-774, Bangladesh.

T. K. Roy**,** Matt Garratt, H. R. Pota & H. Teimoori (2012). Robust altitude control of an unmanned autonomous helicopter using backstepping. *in Proc. of The 10th World Congress on Intelligent Control and Automation (WCICA)*, pp. 1650-1654, Beijing, China.

T. K. Roy, M. Garratt, H. R. Pota & M. K. Samal (2012). Robust altitude control for a small helicopter by considering the ground effect compensation. *in Proc. of the 10th World Congress on Intelligent Control and Automation (WCICA),* pp. 1796–1800, Beijing, China.

J. G. Leishman (2006). *Principles of Helicopter Aerodynamics II*. Cambridge: Cambridge University Press, 257–684.

T. K. Roy (2013). Robust adaptive backstepping controller of altitude control of a small sacle helicopter by considering the groud effect compensation. *Universal Journal of Control and Automation*, vo. 1, no. 2, pp. 52-57.

W. GuanLin, X. Hui, Y. XiaMing, F. Yong, & Z. JiHong (2012). Modeling the yaw dynamics of an unmanned helicopter through modes partition method. *Science China, Technological Sciences*, vol. 55, no. 1, pp. 182–192.

T. K. Roy (2013). Longitudinal and lateral dynamics control of a small scale helicopter using adaptive backstepping controller under horizontal wind gusts. *Asian Transaction Engineering*, vol. 3, no. 1.

X. Zhao, & J. Han (2008). Yaw control of RUAVs: an adaptive robust H_∞ control method. *in Proc. of the 17th World Congress, IFAC.*

T. K. Roy, M. A. Mahmud, M. Z. I. Sarkar, & M. F. Pervej (2014). Robust backstepping controller for yaw dynamics control of an unmanned autonomous helicopter. *in Proc. of the International Forum on Strategic Technology (IFOST).*

Y. Peng, W. Guo, M. Liu, & S. Xie (2014). Active modeling based yaw control of unmanned rotorcraft. *IJSSIS*, vol. 7, no.1.

T. K. Roy (2012). Position control of a small helicopter using robust backstepping. *in Proc. of the 7th Int. Conference on Electrical and Computer Engineering*, pp. 787-790.

X. G. Zhao, Z. Jiang, J. D. Han, & G. J. Liu (2006). Adaptive robust control techniques applied to the yaw control of a small-scale helicopter. *in Proce. of the IEEE International Conference on Intelligent Robots and Systems*, pp.143-148.

Y. Iik, & H. Korul (2013). Performance comparison of yaw rate damping controllers. *World Applied Sciences Journal*, vol. 22, no. 11, pp. 1581-1585.

T. K. Roy, H. R. Pota, Matt Garrat, & H. Teimoori (2012). Robust control for longitudinal and lateral dynamics of small scale helicopter. *in Proc. of the 31st Chines Control Conference,* pp. 2607-2612.

T. K. Roy, M. Garrat, H. R. Pota, & H. Teimoori (2012). Robust backstepping control for longitudinal and lateral dynamics of small scale helicopter. *Journal of University of Science and Technology of China*, vol. 42, no. 7.

T. K. Roy (2014). Robust controller for vertical-longitudinal-lateral dynamics control of small helicopter. *Universal Journal of Control and Automation*, vol.2, no.1,pp.14-24.