Flight Control of a Rotary wing UAV including Flapping Dynamics

Bilal Ahmed ∗ and Hemanshu R. Pota ∗∗

∗ Autonomous Systems Laboratory, CSIRO ICT Centre, Brisbane QLD 4069, Australia (e-mail: arain.bilal@gmail.com).
∗∗ School of Engineering and Information Technology
The University of New South Wales at the Australian Defence Force Academy
Canberra ACT 2600 Australia (e-mail: h-pota@adfa.edu.au).

Abstract: This paper presents the development and experimental implementation of a novel two-time scale controller for the hover control of a Rotary wing Unmanned Aerial Vehicle (RUAV). Flapping and servo dynamics, important from a practical point of view, are included in the RUAV model. The two-time scale controller takes advantage of the ‘decoupling’ of the translational and rotation dynamics of the rigid body, resulting in a two-level hierarchical control scheme. The inner loop (attitude control) tracks the altitude commands generated by the outer loop controller and sets the main rotor thrust vector, while the outer loop (position control) tracks the reference position. Hover flight experimental results are presented in this paper using the proposed two-time scale controller.

Keywords: Underactuated robots, Backstepping, Position control, Unmanned aerial vehicles

1. INTRODUCTION

This paper presents a position and attitude controller for a Rotary wing UAV (RUAV) using the two-time scale method which includes the flapping servo actuator dynamics. The novelty of this work is in the inclusion of the flapping dynamics in control design for a fast responding control action. In a hover condition, the desired position for automatic landing and recovery control scheme can be tracked using the proposed two-time scale algorithm.

The nonlinear RUAV model is made up of general rigid body dynamics and forces due to aerodynamic effects, Gavrillets et al. (2001). The basic nonlinear RUAV model is often augmented by considering the first order effects due to flybar and the flapping dynamics, Bogdanov et al. (2004). In Mahony et al. (1999), it is assumed that the main rotor blades are hinged directly from the hub and new model parameters are proposed, which are functions of the flapping angles and the main and tail rotor thrusts.

An approximate input-output linearization approach is used to design a nonlinear controller for RUAVs, Koo et al. (2001). This approach neglects the coupling terms between rolling (pitching) moments and lateral (longitudinal) accelerations. Also, flapping dynamics is not considered explicitly in designing the controller. An extended version of this control approach, called differential flatness, is used in Koo and Sastry (1999) to achieve a bounded tracking performance for RUAVs. The differentially flat outputs for RUAVs can only be obtained using approximate linearization approach as the system (RUAV) has unstable zero dynamics.

A bounded tracking control of RUAV using backstepping is proposed in Mahony and Hamel (2004), which also considers the flapping angles as control inputs, Frazzoli et al. (2000). For a selective literature review, relating to the nonlinear control design techniques, see: sliding mode Pieper (1995), backstepping, Ahmed et al. (2009), neural-network based controller, Ng et al. (2004), fuzzy control, Sanders et al. (1998), composite nonlinear feedback control, Peng et al. (2009), and nonlinear $H_\infty$ control, Yang et al. (2002).

The contribution of this paper is to present the design and implementation of a backstepping-based controller, including flapping correction dynamics, for the hover control of a RUAV. The theoretical innovation in this paper is the extension of existing control algorithms in providing a correction control to compensate for the important flapping and servo dynamics. This correction results in a practical approach to control the flapping dynamics indirectly.

The organization of this paper is as follows. In Section 2, an overview of the nonlinear RUAV model is presented. In Section 3, two-time scale flight control of a RUAV is discussed. This section also discusses a correction control to include flapping dynamics in the attitude control loop. Section 4 presents autonomous flight experimental results of the Eagle RUAV. This is followed by the conclusion of this paper in Section 5.

2. RUAV MODEL

This section introduces the basic system blocks which make up the complete dynamics of the RUAV. This model is based on nonlinear rigid body dynamics and forces and moments due to main rotor, tail rotor, fuselage and empennage, Koo and Sastry (1998). The RUAV model is shown in Fig. 1. A brief description of each sub-system is given in the following paragraphs.

The origin of the RUAV, in the inertial frame, is given by $\zeta = [x, y, z]^T$; linear velocity of the center of mass of the RUAV, also in inertial frame, is $V = [u, v, w]^T$; the angular velocity is $\omega = [p, q, r]^T$. Euler angles $\eta = [\phi, \theta, \psi]^T$ establish a kinematic relationship with the angular velocities $\dot{\eta} = \Pi \omega$, where $\Pi$ is given in, Ahmed and Pota (2008).
Fig. 1. Block diagram of a Rotary wing UAV dynamics

2.1 Rigid body dynamics

The nonlinear rigid body dynamics in terms of translational and rotational dynamics of the airframe is given by, Ahmed et al. (2009);

\[ \dot{\zeta} = V \]

\[ m\dot{V} = mg_{e3} + \mathcal{R}(\eta) f_{\text{b}} \]

\[ \dot{\eta} = \Pi \omega \]

\[ \dot{\omega} = -\omega \times \omega + M \]

where \( I \in \mathbb{R}^3 \) is the diagonal inertia matrix, \( \delta \in \mathbb{R}^3 \) is the disturbance vector, \( m \in \mathbb{R}^3 \) is the mass of the body and \( \mathcal{R} \in SO(3) \) is the rotation matrix between the body and inertial frames. The gravitational force \( mg_{e3} \) is explicitly included where \( e_3 = [0, 0, 1]^T \). The external forces \( f_{\text{b}} = [X, Y, Z]^T \) and moments \( M = [L, R, N]^T \) (due to main and tail rotor, fuselage and empennage) act on the center of mass of the body.

2.2 Main and tail rotor

In helicopters and RUAVs, the dominant response is due to the main and the tail rotor thrusts \( T_{\text{mr}}, T_{\text{r}} \). The compilation of the forces and moments due to the main and the tail rotor of a RUAV are given as follows:

\[
\begin{bmatrix}
X_m \\
Y_m \\
Z_m
\end{bmatrix} = \begin{bmatrix}
-T_{\text{mr}}a_1 \\
0 \\
T_{\text{mr}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
L_m \\
R_m \\
N_m
\end{bmatrix} = \begin{bmatrix}
L_{\text{mr}}b_1 + T_{\text{mr}}b_1M_Z + T_TZ \\
-Ma_{13} + Xa_1M_Z + T_TX \\
M_Q + T_{\text{mr}}b_1M_X + T_TX
\end{bmatrix}
\]

where \( L_{\text{mr}}, M_{\text{f}}, M_{\text{r}} \) are the effective flap-stiffness constants; \( a_1, b_1 \) are the main rotor flapping angles. The constants \( M_X, M_Z \) are the main rotor offsets and \( T_X, T_Z \) are the tail rotor offsets between the origin of the body frame and the origin of the rotor frame. The main rotor torque \( M_Q \) is computed using the approximation given in Koo and Sastry (1998).

The cyclic longitudinal and lateral tilt of the main rotor disk is controllable via pilot controls \( (u_{\text{lat}}, u_{\text{lon}}) \). Main rotor flapping dynamics of the RUAV is given by:

\[ \tau_f \dot{a}_1 = -a_1 + \tau_f q + A_c + A_{\text{lon}} \delta_{\text{lon}} \]

\[ \tau_f \dot{b}_1 = -b_1 - \tau_f p + B_d + B_{\text{lat}} \delta_{\text{lat}} \]

\[ \tau_c \dot{c} = -c + \tau_c q + C_{\text{lon}} \delta_{\text{lon}} \]

\[ \tau_d \dot{d} = -d - \tau_d p + D_{\text{lat}} \delta_{\text{lat}} \]

where \( \delta_{\text{lat}}, \delta_{\text{lon}} \) are the servo actuator outputs; \( c, d \) are flybar flapping angles. The identified values of the parameters are shown in Table 1.

The forces and moments due to fuselage and empennage are given as follows (Padfield, 1996, p. 115):

\[
\begin{bmatrix}
X_{fs} \\
Y_{fs} \\
Z_{fs}
\end{bmatrix} = \begin{bmatrix}
F_{nx} |u|u \\
F_{ny} |v|v \\
F_{nz} |w|w - 2v_{\text{imr}}(w - 2v_{\text{imr}})
\end{bmatrix}
\]

\[
\begin{bmatrix}
L_{fs}, R_{fs}, N_{fs}\end{bmatrix} = [0, 0, 0]^T
\]

\[
\begin{bmatrix}
X_v, Y_v, Z_v\end{bmatrix} = [0, F_{vt}, 0]^T
\]

\[
\begin{bmatrix}
L_v, R_v, N_v\end{bmatrix} = [F_{vt} u_{\text{lat}}, 0, F_{vt} u_{\text{lon}}]^T
\]

where, \( F_{nx}, F_{ny}, F_{nz} \) are the equivalent flat plate area drag coefficients relative to the center of gravity of the body and \( F_{vt} \) is an aerodynamic force due to vertical tail. The parameters \( u_{\text{lat}}, u_{\text{lon}} \) are the vertical tail lengths with respect to the center of mass of the body and \( v_{\text{imr}} \) is the main rotor induced velocity.

The forces in (2) and moments in (4) of the RUAV dynamic equations can be written in terms of the components given in (5)–(6) and (11)–(14) as follows:

\[
f_b = \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
X_m + X_{fs} + X_v \\
Y_m + Y_{fs} + Y_v \\
Z_m + Z_{fs} + Z_v
\end{bmatrix}
\]

\[
M = \begin{bmatrix}
L \\
R \\
N
\end{bmatrix} = \begin{bmatrix}
L_m + L_{fs} + L_v \\
R_m + R_{fs} + R_v \\
N_m + N_{fs} + N_v
\end{bmatrix}
\]

2.3 Fuselage and Empennage

In this paper, we consider the RUAV as a rigid body with the aerodynamic forces and moments acting on its center of mass. The aerodynamic forces and moments are due to the main rotor, the tail rotor, the fuselage and the empennage. However the aerodynamic forces and moments due to the empennage and the fuselage are negligible in a hover flight condition and are thus neglected for control design.

The values of the identified parameters for the Eagle experimental platform are given in Table 1. The details of the servo actuator dynamics are presented in the next section.

2.4 Servo dynamics

The first order servo actuator (JR DS8231) model is given by:

\[
\dot{\delta}_i = -\tau_i \delta_i + u_i
\]

where \( i = \text{lat}, \text{lon} \). The identified value of the time constant \( \tau_i \) is 0.049 s and the rate limits, for the input \( u_i \), is 300°/s.

The experimental platform is equipped with fast digital servo actuator (NES-8700G) for the tail rotor pitch control with active yaw damping system. It is assumed that the time-constant of the rigid body dynamics is much larger than the time-constant of the collective and yaw servo dynamics. This enables us to assume that \( \zeta_{\text{col}} \approx K_{\text{col}} u_{\text{col}} \) and \( \zeta_{\text{ped}} \approx K_{\text{ped}} u_{\text{ped}} \) where the identified values of \( K_{\text{col}}, K_{\text{ped}} = 150 \) PWM (μs) and \( (u_{\text{col}}, u_{\text{ped}}, u_{\text{lat}}, u_{\text{lon}}) \) are the servo actuator inputs. The servo actuator dynamics for the cyclic pitch control \( (\delta_{\text{lat}}, \delta_{\text{lon}}) \) is
comparable with that of the flapping dynamics \((a_1, b_1, c, d)\) and thus we need to consider it for the controller design.

3. TWO-TIME SCALE CONTROL

This section presents a two-time scale controller, which essentially makes use of the separation in the nonlinear translational and rotational dynamics of the RUAV. The block diagram of the closed-loop system is shown in Fig. 2. The two-level hierarchical control scheme contains an inner loop fast controller (attitude control) and an outer loop slow controller (position control). The main idea is to compute the control inputs to achieve the desired thrust and flapping angles for the commanded position. The proposed control law is elaborated in the following paragraphs.

Fig. 2. Two-time scale based hover control of a RUAV

3.1 Design of attitude controller

Equations of the flapping body rotational dynamics (3)–(4), the flapping dynamics (7)–(10), and the servo actuator dynamics (17) are used to design a control law \(u = [u_{lat}, u_{lon}, \delta_{ped}]\) for the system to track the desired attitude \(\eta_d = [\phi_d, \theta_d, \psi_d]\). The desired attitude \(\dot{\eta}_d\) is generated by the position controller.

As the first step in using backstepping, let the starting Lyapunov Function Candidate (LFC) be:

\[
W_1(\eta) = \frac{1}{2} \eta^T K_\eta \eta + \frac{1}{2} \tilde{\eta}^T K_{\tilde{\eta}} \tilde{\eta}
\]

where \(K_{\eta}\) is a positive definite matrix. The time derivative

\[
\dot{W}_1 = \eta^T \dot{\eta} + \frac{1}{2} \eta^T I_0 \dot{\eta} + \frac{1}{2} \tilde{\eta}^T \dot{K}_{\eta} \tilde{\eta}
\]

(18)

\[
(\dot{I} - 2C) is a skew-symmetric and \(\Psi(\eta) = I(\eta)^{-1}\). If

\[
\Psi^T M = -K_{\eta} \tilde{\eta} - K_{\omega} \dot{\eta}
\]

then \(\dot{W}_1 = -\eta^T K_{\eta} \dot{\eta} - 0.

Remark 1. The inputs to the attitude controller are the desired attitude \(\eta_d\) and a nominal value of the main rotor thrust \(T_{mr}\). To achieve the desired attitude the moments \(M\) should be as given by (19) and this is achieved by applying \(u_1, b_1, T_1\) obtained from the three equations in (16).

The flapping angles \(a_1, b_1\) can only be controlled indirectly. A feedback system is used to minimize the error between the actual flapping angles and the desired flapping angles. For feedback, the actual values of the flapping angles are obtained by constructing an estimator using the rotor moment relationships given in Gavrilets et al. (2001). The flapping error dynamics (including servo dynamics) using (7)–(10) and (17) can be written as,

\[
\dot{X}_c = A_c X_c + B_c \tilde{u}
\]

where,

\[
X_c = [a_1 - a_1^T b_1 - b_1^T c - c^T d - d^T \delta_{lat} - \delta_{lon} - \delta_{ped}^T P, q]^T
\]

\[
\tilde{u} = u_{lat} - u_{lon} - u_{ped}^T T_{lat}.
\]

(21)

The steady-state control inputs \(u_{lat}, u_{lon}\) can be obtained by setting \(a_1, b_1, c, d, \delta_{lat}, \delta_{lon} = 0\) in (7)–(10) and (17).

Let us choose a system LFC given by:

\[
W_2(\eta, z_2, X_c) = W_1 + X_c^T P X_c,
\]

(22)

where \(P\) is a positive definite matrix such that \(A_c^T P + A_c P < 0\). Let \(M = U_{m}^d + \tilde{U}_m\), where \(U_{m}^d\) is given in (19) with \(a_1^T b_1^T T_1^d\); the term \(\tilde{U}_m\) is yet to be computed “correction” which is chosen to make \(\dot{W}_2\) non-positive in the presence of flapping dynamics. When flapping dynamics is ignored \(\tilde{U}_m = 0\).

The time derivative of (22) along the system trajectories is given by:

\[
\dot{W}_2 = \dot{W}_1 + \omega^T \tilde{U}_m + X_c^T (A_c^T P + A_c P) X_c
\]

\[
+ \tilde{u}^T (B_c^T P + B_c P) X_c
\]

(23)

The term \(\dot{W}_2\) can be made to be non-positive, by the proper selection of \(\tilde{u}\) and \(T_r\). The control selection is based on the following three separate situations.

1. \(X_c\) equals to zero: In this case, \(\tilde{U}_m\) is zero because the actual flapping angles are at their desired values. The control \(U_{m}^d\) will make \(\dot{W}_2 \leq 0\).
2. \(X_c\) is non-zero and \(B_c^T P + B_c P\) is not orthogonal to \(X_c\): In this case Proposition 1 below can be used to choose control \(\tilde{u}\) in (20) to make \(\dot{W}_2\) non-positive.
3. \(B_c^T P + B_c P\) \(X_c \neq 0\): In this case Proposition 2 below can be used to introduce the tail rotor thrust to set \(\dot{W}_2 \leq 0\).

Proposition 1. When \((B_c^T P + B_c P) X_c \neq 0\), \(\dot{W}_2 \leq 0\) if the correction control \(\tilde{u} = K X_c\), where \(K\) is such that \((A_c + B_c K)^T P + P (A_c + B_c K) + W \leq 0\), where

\[
W = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & -M_{\beta} T_{mr} M_Z & 0 \\
0 & 0 & 0 & 0 & L_{\beta} + T_{mr} M_Z & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

Proof: The proof is obtained by substituting the correction control \(\tilde{u} = K X_c\) in (23).

Proposition 2. When \((B_c^T P + B_c P) X_c = 0\) the tail rotor thrust \(T_{r} = T_{r} + \tilde{T}_r\) can be chosen such that \(\dot{W}_2 \leq 0\), provided \(\omega(1) = 0\) or \(\omega(3) = 0\).

Proof: See Ahmed et al. (2008) for a proof.

3.2 Design of position controller

The translational dynamics of the system from (1)–(2) is given by:

\[
10375
\]
The control objective is to design a control law $u = [\phi_d, \theta_d, \delta_{col}]$ for the system (24)–(25) such that the tracking error $X_p = [\zeta - \zeta_d, V - V_d]^T \in \mathbb{R}^6$ converge asymptotically to zero. Note that the outer loop position controller runs at a slower sampling time period than the inner loop attitude controller. The attitude converges to the reference commands within the sampling time-step of the position controller.

**Remark 2.** The reference trajectories $(\zeta_d, V_d, \psi_d, \dot{\psi}_d)$ are provided by the user or computed by the guidance-system. The desired roll and pitch angles $(\phi_d, \theta_d)$ and their derivatives are computed by the outer-loop position controller.

The system error dynamics using (24)–(25) can be written as,

$$
\dot{X}_p = AX_p + B \left( \mu - \bar{V}_d \right)
$$

where $\mu = \frac{1}{2}R(\eta) f_b (\bar{a}_1, \bar{b}_1, \bar{T}_f, T_{mr}^d) + gc_3 \in \mathbb{R}^3$ is a intermediary control vector, and

$$
A = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}, 
B = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}.
$$

Choose

$$
\mu = -K_{\mu} X_p + \bar{V}_d, 
$$

such that the matrix $\hat{A} = (A - B K_{\mu})$ is Hurwitz. Note that $K_{\mu} \in \mathbb{R}^{3 \times 6}$ is a constant gain matrix.

**Remark 3.** The forces $f_b$ in (15) are in terms of $\bar{a}_1, \bar{b}_1, \bar{T}_f, T_{mr}$. Note that at this stage $\bar{a}_1, \bar{b}_1, \bar{T}_f$ are set by the fast or attitude controller and the current values of $\bar{a}_1, \bar{b}_1, \bar{T}_f$ are used in (27). The three nonlinear algebraic equations (27) are solved for $\phi, \theta, T_{mr}$. These values become the reference command, $\phi_d, \theta_d, T_{mr}^d$, for the attitude control.

### 4. EXPERIMENTAL RESULTS

The experimental platform was constructed from a 60 size Eagle RUAV kit. There are two main settings for the flight computer onboard the Eagle RUAV: (a) open-loop flight setting; (b) closed-loop flight setting. In the open-loop setting, the Eagle RUAV flies with the pilot providing feedback for proper navigation and stable flight. The pilot provides collective, lateral and longitudinal cyclic, and yaw control commands $(u_{col}, u_{lat}, u_{col}, u_{ped})$, via the radio transmitter, in response to the visual sensing of the position and orientation of the Eagle RUAV. In the closed-loop setting, the radio-transmitted signals are interpreted by the onboard computer as attitude reference signals and the feedback is provided by the controller onboard. The closed-loop setting has another feature called hands-free. In this flight mode, only the reference position is provided to the onboard computer and the feedback is provided by the computer itself using GPS and attitude sensors.

Two types of flight tests were conducted on the Eagle RUAV to demonstrate the practical application of the proposed controller. The first was to verify that the fast attitude control loop (Section 3.1) was working correctly. This was done using the closed-loop mode and providing reference attitudes using the radio transmitter such that the Eagle RUAV remained in its flight zone. The second test was done in the hands-free mode, where the Eagle RUAV was commanded to hover at a particular position.

### 4.1 Attitude control

In this experiment, the pilot used transmitter stick positions as reference attitude commands to test the fast attitude control loop. The Eagle RUAV can be switched between the manual (pilot) and the autonomous (flight computer) for experimental and safety purposes. The Eagle RUAV was flown at about 2.0 m above the ground before being switched to the flight computer. Also, during the flight test, heading angle of the Eagle RUAV was kept constant ($\psi = 0^\circ$) to point in the North direction.

Flight test results of the Eagle RUAV attitude control are shown in Fig. 3. The plots show data from a 50 s closed-loop flight test with the pilot-in-the-loop providing reference attitude commands. The reference attitude commands were provided within $\pm 20^\circ / s$ to keep the Eagle RUAV in the visual range for a safe flight operation.

![Flight test results using the proposed attitude controller including flapping correction dynamics](image-url)
Experimental data, with the proposed controller including flapping correction dynamics, shows that the Eagle RUAV tracked the reference attitude commands (pilot stick positions). The roll and pitch angles of the Eagle RUAV vary from their mean value ($0^\circ$) with standard deviation of $1.04^\circ$ and $0.77^\circ$ respectively; there was a mean error of less than $0.5^\circ$ in roll, pitch, and yaw angles. This error occurs because the pilot provides the reference commands while controlling the aileron, elevator, and rudder control inputs separately to keep the Eagle RUAV around the hover flight condition. The response time of the Eagle RUAV to follow the reference attitude commands is approximately $0.15$ s which is fast enough to permit a safe closed loop flight operation.

The attitude controller sent PWM commands to the lateral and longitudinal servo actuators, which varied between $3200 \mu s$ and $3800 \mu s$. The allowable range of the lateral and longitudinal servo actuators is $2316–4938 \mu s$. The control signals sent to the tail rotor servo actuator varied between $3755 \mu s$ and $3780 \mu s$. The allowable range of tail rotor servo actuator is $2442–4562 \mu s$.

The gain matrices $K_\eta$, $K_{\omega}$, $K$ in (19) and Proposition 1 used for implementing the attitude control law are given as follows:

$$
K_\eta = \begin{bmatrix}
340 & 0 & 0 \\
0 & 280 & 0 \\
0 & 0 & 100
\end{bmatrix},
K_{\omega} = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix},
K = \begin{bmatrix}
0.5 & 0 & 0 \\
0 & 0.2 & 0
\end{bmatrix}
$$

In this flight test we have chosen $K_{\omega}$ to be zero. This choice of $K_{\omega}$ means that the time derivative of the Lyapunov function is negative semi-definite but this choice of $K_{\omega}$ greatly simplifies numerical computations. The flight computer (MPC555) on board the Eagle RUAV has limited computation capability thus it was decided to keep the computation load to a minimum. Moreover, there is an in-built mechanical damping in the system due to the flybar which ensures that the system approaches its equilibrium point. Thus in practice it is possible to choose $K_{\omega}$ to be zero.

### 4.2 Hover control

In this experiment, stabilization of the Eagle RUAV was considered by hovering it at a fixed height above the ground and heading approximately in the North-West direction ($\psi = -35^\circ$). Experimental results from $80 \text{s}$ autonomous flight test around the hover flight condition are shown in Fig. 4 and Fig. 5. The closed loop flight of Eagle RUAV drifted approximately $1.3 \text{ m}$ in North and East and stayed within $2.0 \text{ m}$ of the datum height as measured by the GPS. The drift in the $x$–$y$ direction of the flight trajectory, shown in Fig. 4, is not significant for the autonomous hover flight. The delay in communication between onboard computers (PC104 and MPC555) and gusty conditions is a significant source of drift error of the Eagle RUAV in $x$–$y$ positions. The pitch and roll angles of the Eagle RUAV, shown in Fig. 5, are well limited to $\pm 5^\circ$ and are within the performance line of the attitude controller for autonomous hover flight.

The control inputs, shown in Fig. 6, were generated during the closed-loop flight test. The backstepping-based position controller sent PWM commands to the lateral and longitudinal servo actuators, which varied between $3200 \mu s$ and $3800 \mu s$. The allowable range of the lateral and longitudinal servo actuators is $2316–4938 \mu s$. To keep the heading of Eagle RUAV constant, the PWM commands sent to the tail rotor servo actuator varied between $3745 \mu s$ and $3770 \mu s$. The allowable range of tail rotor servo actuator is $2442–4562 \mu s$. During the manoeuvring, fixed height of about $2.5 \text{ m}$ above the ground was achieved. The PWM control signals sent to the collective pitch servo varied between extremes of $3750 \mu s$ and $4000 \mu s$. The allowable range of the collective servo actuator is $2442–4762 \mu s$. The authors have previously shown that the control inputs generated by this controller are comparable with an already implemented PID controller. It is evident from Fig. 4 that a successful autonomous hover flight is achieved in windy conditions and the servo actuators are within their allowable range during the hover flight experiment as seen in Fig. 6. From these results we can conclude that this controller is suitable for practical implementation, Ahmed et al. (2008).

The experimental results show that the autonomous hover flight test was successful in the presence of external disturbances like wind gusts, etc. This controller can be used for the control of autonomous forward flight. The gain matrix $K_\mu$ in (27) used for implementing the position control law is given as follows:

$$
K_\mu = \begin{bmatrix}
0.01 & 0 & 0 & 0.08 & 0 & 0 \\
0 & 0.05 & 0 & 0 & 0.1 & 0 \\
0 & 0 & 300 & 0 & 0 & 250
\end{bmatrix}
$$

Note that the first two gain values in the gain matrix $K_\mu$ are small compared to the last gain value. These small gain values correspond to feedback correction in the $x$, $y$ directions. To achieve a successful hover flight condition, the feedback correction in the $z$-direction should result in maintaining a constant height above the ground. The feedback corrections in the $x$, $y$ directions are not particularly significant in hover flight as the inner-loop provides the attitude stabilization of the RUAV.

### 5. CONCLUSION

Position control of the RUAV, including the flapping and the servo actuator dynamics, is presented in this paper. The proposed controller is based on a two-level hierarchical control scheme, i.e., inner loop attitude control and outer loop position control. Simulation and experimental results demonstrate the practical applicability of the attitude and position control. This paper contributes novel results in presenting a detailed analysis of the flapping correction dynamics which is an essential part
of the control implementation on RUAVs. The RUAV model presented in this paper is based on the minimum complexity helicopter model, but captures the key dynamics of the platform as demonstrated by the successful experimental implementation.

REFERENCES


