Adaptive Backstepping Control Scheme with Integral Action for Quanser 2-DOF Helicopter

Ravi Patel, *Student Member, IEEE*, Dipankar Deb, *Senior Member, IEEE*, Himani Modi and Sunny Shah

***Abstract*—This paper proposes an adaptive integral backstepping control scheme for tracking control of 2-DOF (Degree of Freedom) helicopter. The helicopter is an important model from the control prospective due to its nonlinear behavior, highly cross coupling effects and instability in open loop. Classical control methods (PI, PD and PID Controllers) and baseline controllers with a linear quadratic regulator (LQR) are unable to handle parametric uncertainties and unmodeled dynamics. The key advantage of the proposed scheme is that it gives robustness to parameter uncertainties and unmodeled dynamics. An adaptive update can provide system robustness through estimation of parameters and model uncertainties. Simulation and Experimental results support the expected effectiveness of the proposed adaptive integral backstepping scheme for tracking as compared to the baseline controller (LQR) in presence of uncertainties.**

***Index Terms*—Adaptive control, integral action, backstepping, 2-degree of freedom, helicopter, parameter uncertainties.**

I. Introduction

Modern Electro-mechanical systems are multiple input multiple output (MIMO) systems required to operate at high speed, precision and accuracy. MIMO systems have interactive variables which make it harder to design a controller. Advanced control system plays significant role to meet challenges in MIMO systems [1].

Two degree of freedom (2-DOF) helicopter is a simplified example of MIMO systems. Helicopters are used in the transportation, military reconnaissance, surveillance and as combat aerial vehicles and helicopter models are important from control prospective due to its nonlinear behavior, highly cross coupling effects and instability in open loop. However main problems with helicopter system are parametric uncertainties, external disturbances, and unmodeled dynamics[2].

Different controllers have been developed for stabilization and tracking control of the helicopters. Classical control methods (PI, PD and PID Controllers) are not recommended for highly nonlinear systems because they give satisfactory results around the set points. P. Teppa-Garran and G. Garica developed optimal tuning algorithms using LQR approach for decoupled uncertain MIMO system [3]. M. Ashraf Ahmad et al. presented performance analysis of model-free PID tunning of MIMO system [4]. Balderud et. al presented performance comparison of three optimal control strategies such as model predictive control (MPC), linear quadratic optimal control combined with a state estimator (LQG - Linear Quadratic Gaussian) and optimal linear quadratic output control (PLQ - Parametric Linear Quadratic). These control schemes produced better results than classical control algorithms [5]. The performance of fuzzy and neural network control schemes was degraded due to inability to precisely estimate the uncertain parameters, nonlinear friction forces, external disturbances and cross coupling effects [6],[7].

2-DOF helicopter control by pole placement is discussed in [1]. A baseline controller with a linear quadratic regulator + integral (LQR+I) is also discussed in [8]. Classical controllers such as LQG and LQR are linear and so control of the nonlinear system that is linearized and it is valid only in certain operating region [16]. Above controller is unable to handle parametric uncertainties (mass/inertia) and unmodeled dynamics. Controllers need to be designed such way that they have robustness to the parameter uncertainties and unmodeled dynamics. Zeghlache et. al developed Type-2 fuzzy logic control of 2-DOF helicopter system that provides robust control against parametric uncertainties and noise measurement compared to type-1 fuzzy logic control [14]. 2-sliding mode control based algorithm provides smooth helicopter flight in presence of unbalanced dynamics caused by the disturbance in the center of gravity [15].

An adaptive control scheme has been used to compensate the uncertainties. Adaptive control framework with baseline controller is discussed [9]. Robust model reference adaptive control (MRAC) with baseline controller is presented [10]. An adaptive super-twisting control for a 2-DOF helicopter was designed for estimating non-measurable states and external disturbance [17]. Yao Zou and Wei Huo presented an adaptive backstepping control scheme for the trajectory tracking for the helicopter model with internal unmodeled dynamics and external disturbances [18]. An adaptive control scheme for twin rotor MIMO system that gives better performance compared to PID controller has been presented[19].

Backstepping is a nonlinear control scheme, generally used as an alternative to feedback linearization. Some modifications such as an integral and adaptive action have been suggested in the literature to make the control action through backstepping process, more effective. Some adaptive estimation and comparison methods for parameter uncertainties are applied [11].

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This paper primarily contributes in developing an integral backstepping control algorithm with adaptive action for a helicopter with two degrees of freedom. The controller uses integral to eliminate the static error and adaptive action to compensate for the model uncertainties including the uncertain moment of inertia. The proposed solution has been simulated using MATLAB (Simulink) and implemented on the 2-DOF helicopter setup from Quanser. The paper is organized as follows: Section II presents the modeling of 2-DOF helicopter dynamics. Section III and IV present integral backstepping controller and adaptive integral backstepping controller respectively. Section V presents an interface of 2-DOF helicopter hardware system with MATLAB/Simulink and the simulation and experimental results. The conclusion and future works are available in the last Section.

II. Modeling of 2-DOF Helicopter Dynamics

2-DOF Quanser helicopter model (fixed base) with two propellers driven by DC motors, is shown in Fig. 1. The elevation of the nose over the pitch axis is controlled by the front propeller and the rotational motion around the yaw axis is controlled by the back propeller. The voltages across the pitch and yaw motors are $\pm 24V$ and $\pm 15V$ respectively. The pitch angle θ and the yaw angle ψ represent two degrees of freedom. When the nose of helicopter goes up, we get $\theta > 0$, and the yaw axis becomes positive when the rotation of helicopter is in the clockwise direction [12].

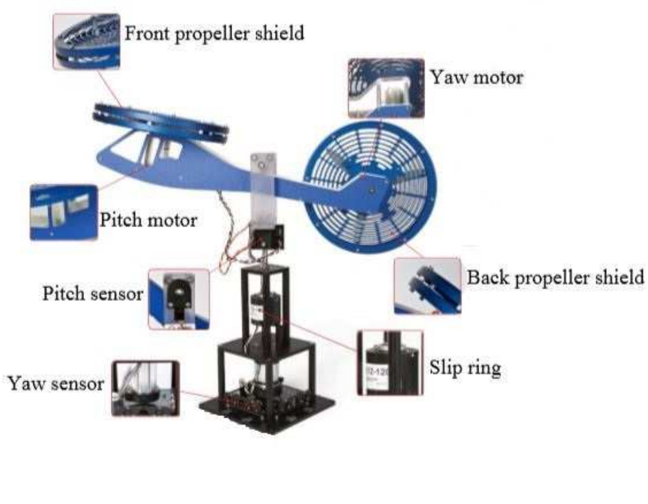

Fig. 1. Quanser 2-DOF Helicopter [10]

The helicopter model dynamics is shown in Fig. 2. The thrust forces F_p and F_y are applied across the pitch and yaw axis respectively. The torques act at a distance r_p and r_y from the respective axis. The gravitational force F_g pulls down the helicopter nose. The center of mass acts at l distance from the pitch axis along the helicopter body length. The position of center of mass is obtained by transformation of coordinates and is given as

$$X_c = l\cos\theta\cos\psi, \quad Y_c = -l\cos\theta sin\psi, \quad Z_c = l\sin\theta,$$

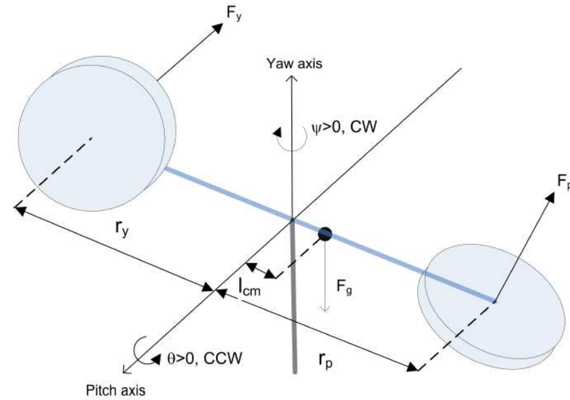

Fig. 2. Dynamics of 2-DOF Helicopter [12].

where l is the distance between the center of mass and the intersection of the pitch and yaw axes.

The potential energy (P) due to gravity and the total kinetic energy (T) due to moment of inertia, are given by

$$\begin{aligned} P &= m\,g\,l\sin\theta, \quad T = T_{r,p} + T_{r,y} + T_t, \qquad (1)\\ T_{r,p} &= \frac{1}{2}J_{eq,p}\dot{\theta}^2, \qquad T_{r,y} = \frac{1}{2}J_{eq,y}\dot{\psi}^2,\\ T_t &= \frac{1}{2}m(\dot{X}_c^2 + \dot{Y}_c^2 + \dot{Z}_c^2) \end{aligned}$$

where $T_{r,p}$ and $T_{r,y}$ are the sum of the rotational kinetic energies acting from the pitch and yaw respectively, and T_t is the translational kinetic energy produced by the center of mass. $J_{eq,p}$ and $J_{eq,y}$ are the moments of inertia of the pitch and yaw motor respectively. For the 2-DOF helicopter system, the Euler-Lagrange equations are given by

$$\begin{aligned} \dot{X}_c &= \frac{\partial X_c}{\partial \Psi}\frac{\partial \psi}{\partial t} + \frac{\partial X_c}{\partial \theta}\frac{\partial \theta}{\partial t},\\ &= -l\cos\theta\sin\psi\dot{\psi} - l\sin\theta\cos\psi\dot{\theta},\\ \dot{X}_c^2 &= l^2(\cos^2\theta\sin^2\psi\dot{\psi}^2 + 2\sin\theta\cos\theta\sin\psi\cos\psi\dot{\psi}\dot{\theta}\\ &\quad + \sin^2\theta\cos^2\psi\dot{\theta}^2),\\ \dot{Y}_c &= -l\cos\theta\cos\psi\dot{\psi} + l\sin\theta\sin\psi\dot{\theta},\\ \dot{Y}_c^2 &= l^2(\cos^2\theta\cos^2\psi\dot{\psi}^2 - 2\sin\theta\cos\theta\sin\psi\cos\psi\dot{\psi}\dot{\theta}\\ &\quad + \sin^2\theta\sin^2\psi\dot{\theta}^2),\\ \dot{Z}_c &= l\cos\theta\dot{\theta}, \qquad \dot{Z}_c^2 = l^2\cos^2\theta\dot{\theta}^2,\\ \dot{X}_c^2 &= -\dot{Y}_c^2 - \dot{Z}_c^2 + l^2(\cos^2\theta\dot{\psi}^2 + \dot{\theta}^2). \end{aligned}$$

Substituting the values in (1), the total kinetic energy is defined as follow

$$T = \frac{1}{2}J_{eq,p}\dot{\theta}^2 + \frac{1}{2}J_{eq,p}\dot{\psi}^2 + \frac{1}{2}ml^2(\cos^2\theta\dot{\psi}^2 + \dot{\theta}^2). \qquad (2)$$

Euler-Lagrange equations of motion are defined as

$$\frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta} = Q_1, \qquad \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\psi}} - \frac{\partial L}{\partial \psi} = Q_2. \qquad (3)$$

where L, the Lagrange variable defined as $T - P$, is calculated from (1) and (2), as

$$\begin{aligned} L &= \frac{1}{2}J_{eq,p}\dot{\theta}^2 + \frac{1}{2}J_{eq,p}\dot{\psi}^2 + \frac{1}{2}ml^2(\cos^2\theta\dot{\psi}^2 + \dot{\theta}^2)\\ &\quad - mgl\sin\theta. \qquad (4) \end{aligned}$$

The generalized coordinates are

$$x = [\theta \ \ \psi \ \ \dot{\theta} \ \ \dot{\psi}]^T, \tag{5}$$

and the generalized forces are

$$\begin{aligned} Q_1 &= K_{pp}V_{mp} + K_{py}V_{my} - B_p\dot{\theta}, \\ Q_2 &= K_{yp}V_{mp} + K_{yy}V_{my} - B_y\dot{\psi}, \end{aligned}$$

where B_p and B_y are the viscous damping about the pitch and yaw axis respectively, and V_{mp} and V_{my} are the input motor voltages for the pitch and yaw respectively. K_{pp}, K_{yy}, K_{py} and K_{yp} are the thrust torque constants for the pitch and yaw respectively as given by Quanser [12]. We determine

$$\begin{aligned} \frac{\partial L}{\partial \theta} &= -mgl\cos\theta - ml^2\sin\theta\cos\theta\dot{\psi}^2, \\ \frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\theta}} &= J_{eq,p}\ddot{\theta} + ml^2\ddot{\theta}. \end{aligned}$$

From the above equations, we get

$$\begin{aligned} J_{eq,p}\ddot{\theta} + ml^2\ddot{\theta} + mgl\cos\theta + ml^2\sin\theta\cos\theta\dot{\psi}^2 = \\ K_{pp}V_{mp} + K_{py}V_{my} - B_p\dot{\theta}, \end{aligned}$$

$$\begin{aligned} \ddot{\theta} &= \frac{1}{J_{eq,p} + ml^2}\Big[[K_{pp}V_{mp} + K_{py}V_{my}] - [B_p\dot{\theta} + \\ & mgl\cos\theta + ml^2\sin\theta\cos\theta\dot{\psi}^2]\Big]. \end{aligned}$$

Similarly, we get for the yaw axis angle ψ,

$$\begin{aligned} \ddot{\psi} &= \frac{1}{J_{eq,y} + ml^2\cos^2\theta}\Big[[K_{yp}V_{mp} + K_{yy}V_{my}] - [B_y\dot{\psi} + \\ & 2ml^2\sin\theta\cos\theta\dot{\psi}\dot{\theta}]\Big]. \end{aligned}$$

For a state vector $x = [x_1 \ x_2 \ x_3 \ x_4]^T = [\theta \ \dot{\theta} \ \psi \ \dot{\psi}]^T$, the state space model of helicopter system is given by

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= \frac{1}{J_{eq,p} + ml^2}\Big[[K_{pp}u_1 + K_{py}u_2] - [B_px_2 + \\ & ml^2x_4^2\sin x_1\cos x_1 + mgl\cos x_1]\Big], \\ \dot{x}_3 &= x_4, \\ \dot{x}_4 &= \frac{[K_{yp}u_1 + K_{yy}u_2] - [B_yx_4 + 2ml^2x_2x_4\sin x_1\cos x_1]}{J_{eq,p} + ml^2\cos^2 x_1}, \end{aligned}$$

where $u_1 = V_{mp}$ and $u_2 = V_{my}$ are the inputs.

III. Integral Backstepping Control Scheme

Integral Backstepping would be helpful when uncertainties are not modeled as normally happens. The control objective is to develop an efficacious scheme to track the pitch and yaw angles. Generalized mathematical equations for applying a integral backstepping algorithm are as follows

$$\dot{x}_1 = x_2, \qquad \dot{x}_2 = au + b, \tag{6}$$

where a and b are the parameters or constant terms of the system mathematical model. Tracking errors e_1 and e_2 are defined as

$$e_1 = x_{1d} - x_1, \qquad e_2 = x_{2d} - x_2, \tag{7}$$

where x_{1d} is desired tracking path and x_{2d} is the virtual control which is defined as

$$x_{2d} = c_1e_1 + \dot{x}_{1d} + \lambda\chi, \tag{8}$$

such that $\chi = \int e_1(\tau)d\tau$ shows the integral action. Using (8), we get

$$\begin{aligned} \dot{e}_1 &= \dot{x}_{1d} - \dot{x}_1 = \dot{x}_{1d} - x_2 = -c_1e_1 - \lambda\chi + e_2. && (9) \\ \dot{e}_2 &= \dot{x}_{2d} - \dot{x}_2 = c_1\dot{e}_1 + \ddot{x}_{1d} + \lambda e_1 - au - b. && (10) \end{aligned}$$

Substituting the values of (9) in (10) and re-writing the derivative of the error $\dot{e}_2$, we get

$$\dot{e}_2 = -c_1^2e_1 - c_1\lambda\chi + c_1e_2 + \ddot{x}_{1d} + \lambda e_1 - au - b. \tag{11}$$

To ensure that $\dot{e}_2 = -c_2e_2 - e_1$, $(c_2 > 0)$, we choose a control law u given by

$$u = \frac{1}{a}[(1 - c_1^2 + \lambda)e_1 + (c_1 + c_2)e_2 - c_1\lambda\chi + \ddot{x}_{1d}] - \frac{b}{a}. \tag{12}$$

To check the system stability, we can construct a positive definite Lyapunov function as follows

$$V = \frac{1}{2}\lambda\chi^2 + \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2. \tag{13}$$

By taking differentiation of V, we obtain

$$\dot{V} = -c_1e_1^2 - c_2e_2^2 \ < 0, \tag{14}$$

where c_1, c_2 and λ are positive constants. From (14) we can say that the helicopter system will be stable based on the Lyapunov theory. We can construct the control law for pitch and yaw angle by using (12). For the helicopter system, convert the state equations as per (6).

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= \frac{1}{J_{eq,p} + ml^2}u_p - \frac{B_px_2 + ml^2x_4^2\sin x_1 cos x_1 + mgl\cos x_1}{J_{eq,p} + ml^2}, \\ \dot{x}_3 &= x_4, \\ \dot{x}_4 &= \frac{1}{J_{eq,y} + ml^2\cos x_1}u_y - \frac{B_yx_4 + 2ml^2x_2x_4\sin x_1\cos x_1}{J_{eq,y} + ml^2\cos x_1}. \end{aligned}$$

where u_p and u_y are the inputs which are defined as

$$u_p = K_{pp}u_1 + K_{py}u_2, \qquad u_y = K_{yp}u_1 + K_{yy}u_2,$$

Control law for pitch, u_p and yaw, u_y are defined as

$$\begin{aligned} u_p &= (J_{eq,p} + ml^2)[(1 - c_{1\theta}^2 + \lambda_\theta)e_{1\theta} + \\ & (c_{1\theta} + c_{2\theta})e_{2\theta} - c_{1\theta}\lambda_\theta\chi_\theta + \ddot{x}_{1d\theta}] + \\ & (B_px_2 + ml^2x_4^2\sin x_1\cos x_1 + mgl\cos x_1), && (15) \\ u_y &= (J_{eq,y} + ml^2 cos x_1)[(1 - c_{1\psi}^2 + \lambda_\psi)e_{1\psi} + \\ & (c_{1\psi} + c_{2\psi})e_{2\psi} - c_{1\psi}\lambda_\psi\chi_\psi + \ddot{x}_{2d\psi}] + \\ & (B_yx_4 + 2ml^2x_2x_4\sin x_1\cos x_1), && (16) \end{aligned}$$

where $c_{1\theta}$,$c_{2\theta}$,λ_θ,λ_ψ,$c_{1\psi}$ and $c_{2\psi}$ are positive.

IV. Adaptive Integral Backstepping Control Scheme for Pitch Angle

Under conditions of uncertainty in mass of the helicopter, integral backstepping control does not gives satisfactory performance. The actual value of mass m is not measured accurately, and so we replace it with an estimate, given by $\hat{m}$. Estimation error of mass $\tilde{m}$ is defined as

$$\tilde{m} = m - \hat{m}. \tag{17}$$

The control law of the pitch angle is rewritten as

$$\begin{aligned} u_p &= (J_{eq,p} + \hat{m}l^2)[(1 - c_{1\theta}^2 + \lambda_\theta)e_{1\theta} + (c_{1\theta} + c_{2\theta})e_{2\theta} - \\ &\quad c_{1\theta}\lambda_\theta\chi_\theta + \ddot{x}_{1d\theta}] + (B_p x_2 + \hat{m}l^2 x_4^2 \sin x_1 \cos x_1 + \\ &\quad \hat{m}gl\cos x_1). \end{aligned} \tag{18}$$

Substituting the value of u_p into (11), we get

$$\begin{aligned} \dot{e}_2 &= -c_1^2 e_1 - c_1\lambda\chi + c_1 e_2 + \ddot{x}_{1d} + \lambda e_1 - \frac{1}{J_{eq,p} + ml^2} u_p \\ &\quad + \frac{(B_p x_2 + ml^2 x_4^2 \sin x_1 \cos x_1 + mgl\cos x_1)}{J_{eq,p} + ml^2} \\ &= -c_1^2 e_1 - c_1\lambda\chi + c_1 e_2 + \ddot{x}_{1d} + \lambda e_1 - \frac{1}{J_{eq,p} + ml^2} \\ &\quad \Big[(J_{eq,p} + \hat{m}l^2)[(1 - c_1^2 + \lambda)e_1 + (c_1 + c_2)e_2 - c_1\lambda\chi \\ &\quad + \ddot{x}_{1d}] + (B_p x_2 + \hat{m}l^2 x_4^2 \sin x_1 \cos x_1 + \hat{m}gl\cos x_1)\Big] \\ &\quad - \Big[\frac{(B_p x_2 + ml^2 x_4^2 \sin x_1 \cos x_1 + mgl\cos x_1)}{J_{eq,p} + ml^2}\Big]. \end{aligned}$$

Let us consider$(1 - c_1^2 + \lambda)e_1 + (c_1 + c_{\theta 2})e_{\theta 2} - c_{\theta 1}\lambda\chi + \ddot{x}_{1d} = P$ for simplicity and re-write the equation as

$$\begin{aligned} \dot{e}_2 &= -c_2 e_2 - e_1 - \frac{\tilde{m}}{J_{eq,p} + ml^2}[l^2 p + l^2 x_4^2 \sin x_1 \cos x_1 + \\ &\quad gl\cos x_1]. \end{aligned} \tag{19}$$

To check the stability and defining adaptive law, construct a Lyapunov function is

$$V = \frac{1}{2}\lambda\chi^2 + \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{\tilde{m}^2}{2\gamma(J_{eq,p} + ml^2)}. \tag{20}$$

γ is the positive adaptive gain constant. The differentiation of Lyapunov function is

$$\begin{aligned} \dot{V} &= -c_1 e_1^2 - c_2 e_2^2 - \frac{\tilde{m}}{J_{eq,p} + ml^2} \\ &\quad \big[e_2(l^2 p + l^2 x_4^2 \sin x_1 \cos x_1 + gl\cos x_1) + \frac{\dot{\hat{m}}}{\gamma}\big]. \end{aligned}$$

To make a system stable, we choose a adaptive law for mass of the helicopter as follows

$$\dot{\hat{m}} = -\gamma e_2(l^2 p + l^2 x_4^2 \sin x_1 \cos x_1 + gl\cos x_1). \tag{21}$$

So that we can obtain a derivative of Lyapunov function as

$$\dot{V} = -c_1 e_1^2 - c_2 e_2^2 < 0. \tag{22}$$

V is the +ve definite function and $V(t) \in L_\infty$ as well as $e_1, \dot{e}_1, e_2, \dot{e}_2, \tilde{m}, \dot{\hat{m}} \in L_\infty$. Thus, we can say that all the signals in the proposed adaptive scheme are bounded in closed-loop operation and from the barbalat's lemma, we have $\lim_{t\to\infty}$ e(t)=0. The controller performance is verified by simulation and experimentally in Section V. It will be seen that the pitch state with parameter uncertainties is successfully controlled by the proposed adaptive controller and the yaw state without parameter uncertainties is controlled by the non-adaptive controller.

V. Simulation And Experimental Results

Data acquisition device (Q2-USB), linear voltage amplifier (VoltPAQ-X2) and real-time control software (QUARC) are required to set up 2-DOF helicopter system with MATLAB/Simulink. Data acquisition system provides reliable real-time performance through USB interface. Q-USB provides closed loop control rate up to 2 kHz. A combination of Q2-USB with terminal board provides easy and quick access to signals.Q2-USB has a 2 ADCs, 2 DACs, 2 encoders, 2 PWM outputs and 8 configurable DIO with 16-bit resolution and frequency range 2.385 Hz to 40 MHz. An efficient rapid prototyping and hardware in loop (HIL) development environment is provided by Q2-USB with a power amplifier[13].

Fig. 3. Q2-USB Data Acquisition Device [13]

VoltPAQ linear voltage amplifier is achieved high performance with HIL implementation. With the Q2-USB data acquisition board and QUARC software, VoltPAQ amplifier can drive experiments, motors or actuators. VoltPAQ-X2 is used for 2-DOF devices. QUARC HIL API provides a way of accessing hardware, creating a flexible framework supporting DAQ and external devices. QUARC is easily interfacing controllers with MATLAB GUIs, LabVIEW panels, Java GUI etc. [13]. The experimental setup of 2-DOF helicopter system with Q2-USB DAQ, VoltPAQ-X2 linear voltage amplifier, and helicopter model is shown in Fig. 4

Through simulations and experiment on the Quanser setup, the performance ability of adaptive controller is compared with LQR controller and also with the integral backstepping control scheme. The main objectives of our work are:

1) Check the system stability with theoretically proof and validate with experiments.

Fig. 4. Experimental Setup of 2-DOF Helicopter System

2) Tracking ability with different reference signal.
3) Adaptive effect of estimating parameter uncertainties.

Initial conditions of the helicopter are give as, pitch angle (θ) = $-40°$, yaw angle (ψ) = $0°$, mass of the helicopter (m) = 1.3872 kg and sample time = 50 ms. Values of Constants (C_1, C_2 & χ) and adaptive gain (γ) are obtained by using trail and error method, where C_1=7.8, C_2=1.9, χ=3.5 and γ=10.

A. Simulation Results

The Simulink model of 2-DOF helicopter system with adaptive integral backstepping controller and LQR controller shown in the Fig. 5.

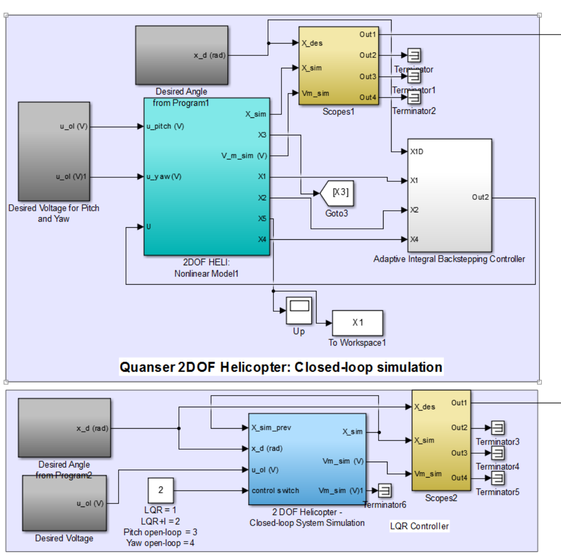

Fig. 5. Simulink Model of 2-DOF Helicopter System

The performance of the pitch angle control with existi LQR controller is compared with its performance using adaptive controller with different reference signals such as square wave, sine wave, and sawtooth wave. The adaptive control law for the state of pitch has been developed in the section IV. The control law for the state of yaw is taken from existing LQR controller developed by Quanser. The adaptive controller will remain in throughout the duration of the helicopter flight. It serves only to compensate for parameter uncertainties during flight mode.

The initial values of the parameter (mass) should be constant under normal condition. In the case of parameter uncertainties, the update laws will steer the values of mass so as to allow for close tracking of the reference system states. The tracking performance of non-adaptive backstepping with integral control is shown in Fig. 6 to 8.

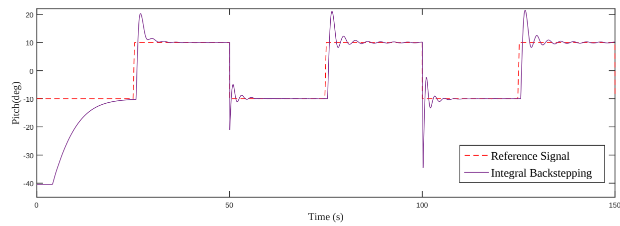

Fig. 6. Integral Backstepping Controller with Square Wave Reference.

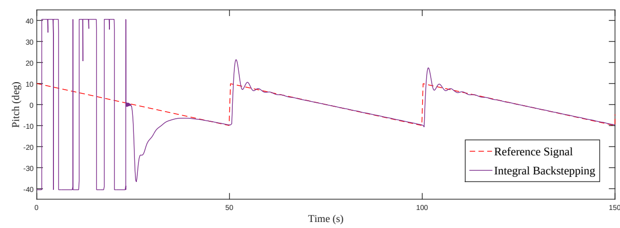

Fig. 7. Integral Backstepping Controller with Sawtooth Wave Reference.

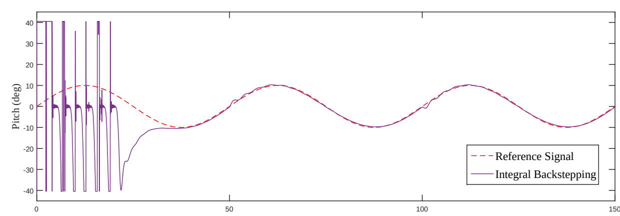

Fig. 8. Integral Backstepping Controller with Sine Wave Reference.

Tracking performance comparison of the proposed adaptive controller and LQR controller with different reference signals shown in the Fig. 9 to 11. We considered the mass of the helicopter as parametric uncertainties. In the simulation, mass value changes from 1.3872 (kg) to 2.5 (kg).

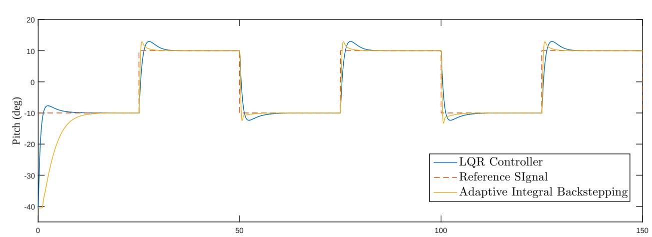

Fig. 9. Adaptive Integral Backstepping Controller And LQR with Square Wave Reference.

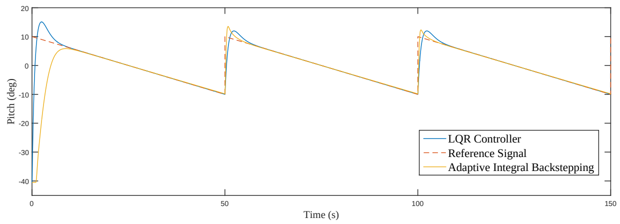

Fig. 10. Adaptive Integral Backstepping Controller And LQR with Saw-tooth Wave Reference.

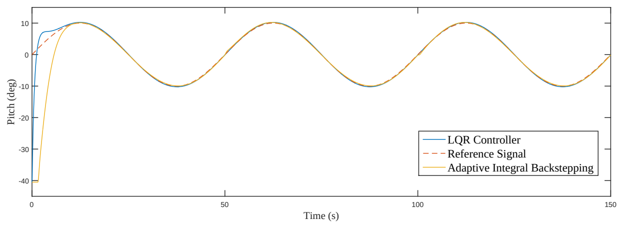

Fig. 11. Adaptive Integral Backstepping Controller And LQR with Sine Wave Reference.

The tracking performance of the pitch angle with a square wave with parametric uncertainties shown in Fig. 12. We can see that LQR controller cannot give good tracking performance with the mass changing condition, whereas, proposed adaptive controller gives good tracking performance.

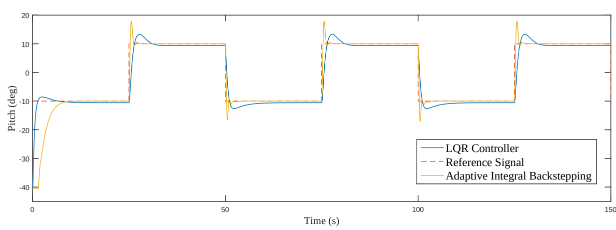

Fig. 12. Adaptive Integral Backstepping And LQR Controller With Parameter Uncertainties (Mass).

B. Experimental Results

To assess the robustness of the control algorithm against unmodelled dynamics, we introduced external disturbance and parameter uncertainties at the pitch angle. External disturbance gave by applying small force on the front propeller using hands. The performance of an adaptive integral backstepping and LQR controller under external disturbance shown in Fig. 13 and 14 respectively.

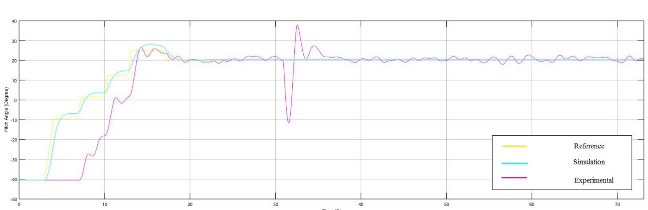

Fig. 13. Performance of Proposed Controller with External Disturbance

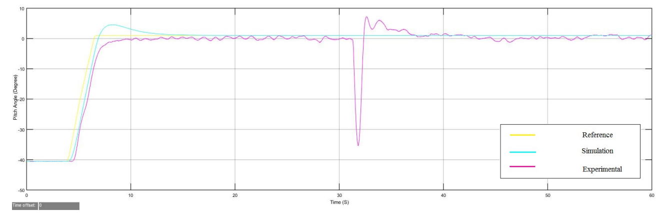

Fig. 14. Performance of LQR Controller with External Disturbance

Mass uncertainty is given by putting a marker pen on the front propeller shield and get the results. We put a mass on the front propeller at 30 seconds. The performance of a proposed and LQR controller with mass uncertainty shown in Fig. 15 and 16 respectively. Thus it is seen that the adaptive integral backstepping controller is effective under mass uncertainties compared to existing LQR controller.

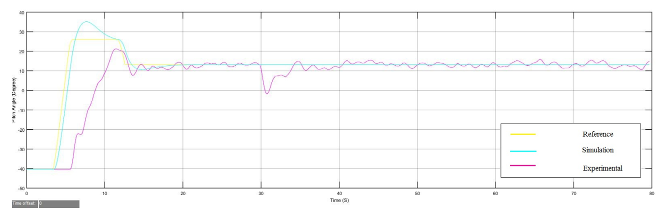

Fig. 15. Performance of Proposed Controller with mass uncertainties

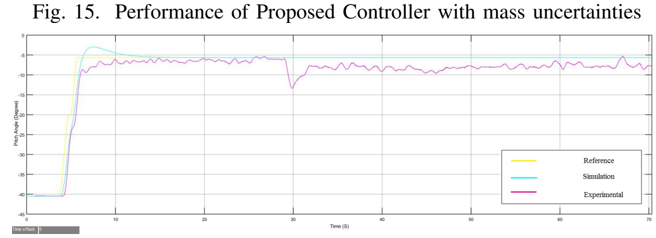

Fig. 16. Performance of LQR Controller with mass uncertainties

VI. Conclusion

An adaptive backstepping controller with integral action is designed and implemented on Quanser's nonlinear 2-DOF helicopter system. Proposed adaptive controller has been proposed by making used a Lyapunov function for improved robustness of the helicopter system against uncertainties and external disturbances. The effectiveness of the helicopter system tracking under mass uncertainty has been assessed in the simulation. The results show that the adaptive integral backstepping controller significantly improves the performance of the 2-DOF helicopter closed loop system. The adequacy of the proposed methodology has been validated through Quanser 2-DOF helicopter system. With mass uncertainty, the proposed controller gives much better performance compared with existing LQR controllers.

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