Robust Control of Single Axis Gimbal Platform for Micro Air Vehicles Based on Uncertainty and Disturbance Estimation

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***Abstract*—Stabilization of gimbal platform housing the payload in Micro Air Vehicle (MAV) applications is crucial in operational situations. The gimbal positioning is achieved through a DC servo motor, which needs to be controlled for the desired performance under uncertainty and disturbance. In this work a novel robust control strategy employing the technique of Uncertainty and Disturbance Estimator (UDE) has been developed. The strategy has been validated through numerical solutions and experimentation. A performance comparison of the proposed strategy with well-known Proportional Integral Derivative (PID) controller has also been accomplished.**

Keywords-micro air vehicles (MAV); single axis gimbal; DC servo motor; uncertainty and disturbance estimator (UDE); robust control; uncertainty and disturbance

I. Introduction

Micro Air Vehicles (MAV) are the miniature version of Unmanned Aerial Vehicles (UAV) having dimensions of the order of 15 cm or less in length. The history of MAV starts from early 90s by the performance study of RAND Corporation. Since then the interest in MAVs has been steadily growing. These vehicles are found to be employed in complex applications such as real time surveillance, communication, chemical and biological warfare, safety and rescue missions, region mapping and so on. Based on C. E. Thorne and M. Yim [1] due to MAV's small size, it provides for low acoustic signatures that are ideal for classified operations.

MAV can be classified broadly into three categories namely fixed wing, flapping wing and Quad rotor based. In the recent years there have been many developments in control of MAV such as Quad rotor by Bawek Dean [2], Omnicopter by Yangbo Long [3], 18 cm MAV: QUARK by Murat Bronz [4], Ducted Fan MAV by Shouzhao Sheng and Chenwu Sun [5] to mention a few.

According to Ashraf Qadir [6], an active gimbal mounted payload like camera can be used to estimate the accurate position information of the targets of interest when employed in Unmanned Aircraft Systems (UAS). Randal Beard [7] have indicated that the payloads of MAV can employ vision based road following, target tracking and mapping for their applications. However, for these applications the requirement to design a light weight gimbal mounted payload is inescapable. More so, the intended performance cannot be compromised for weight considerations. Therefore, the design of a gimbal based payload is a complex and challenging task.

With the advent of sophisticated manufacturing technology, sizes of MAV have reduced appreciably which in turn increases the complexity of navigation and control systems. In this work, a fixed wing MAV is considered having a camera as the payload, mounted on a gimbal platform. The camera has the provision to move in two directions namely pan and tilt, accordingly mounted on a two axis gimbal platform. A schematic representation of a single axis gimbal setup is shown in Fig. 1 as referred from Mandadi Srinivas Rao [8]. The movement of the gimbal is controlled by a DC servo motor to the desired orientation.

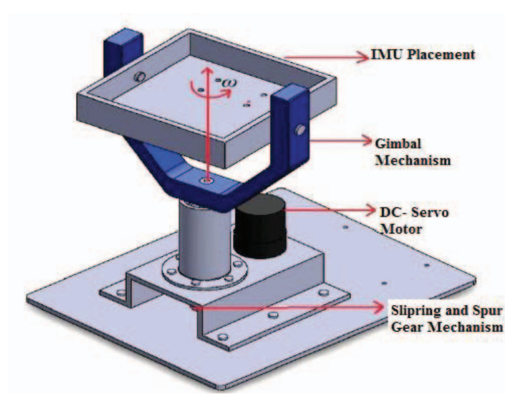


Figure 1. Schematic of gimbal platform.

In practice, many follow the traditional PID controller for the control of DC servo motor as cited in Maraiya Green [9], to quote as an example.

In real time situations, the internal parameters of the DC servo motor undergo many changes and the MAV also is subjected to unmeasurable disturbances like wind etc. particularly in outdoor applications. Therefore, it is essential to design a control strategy for the DC servo motor so that the orientation of the gimbal and the camera is maintained as per the guidance command at all times in presence of uncertainties and disturbances. This calls for the design of a robust control strategy.

Though many robust control strategies are available in the literature such as H-infinity control by Rezac Martin and Hurak Zdenek [10], sliding mode control by Ozgur Hasturk [11], fuzzy logic based by Saugato Dey [12], LQG based by Gerardo F. Flores [13], for motion control of MAV, it is opined that the technique of Uncertainty and Disturbance Estimator (UDE) proposed by Zhong and Rees [14] in 2004, is also a potential candidate for bringing in robustness. In this technique, the uncertainties and disturbances are estimated using a first order low-pass filter having sufficient bandwidth, and the estimates are used in the control to negate the effects of uncertainties and disturbances. The highlight of this technique is that it does not require the bounds of uncertainties.

The concept of UDE has been employed in the field of aerospace, robotics and other industrial applications as available in the literature. Rohan Vimal Raj [15], have successfully employed this strategy in the robust control of electric motor drive. In this work UDE based control is applied in stabilizing the DC servo motor driven single axis gimbal platform. It would be further shown that the derivation of UDE based control law is quiet simple and attempts have been made in this work to carry out numerical simulations and compare its performance with the well-known PID controller in hardware implementation.

The remaining part of this work is organized as follows. Section II deals with problem formulation followed by a design of a UDE based robust control law in Section III. Simulations and discussions form a part of section IV. Experimental validation of the proposed UDE based strategy is dealt in Section V. Section VI concludes this work with a mention on the future scope.

II. PROBLEM FORMULATION

The main objective of this research work is to design a control formulation which would maintain the orientation of the single axis gimbal framework to the desired orientation in presence of uncertainty and disturbances. The desired orientation of the gimbal framework is achieved by means of an armature controlled DC servo motor coupled mechanically to the gimbal. Therefore the applied voltage to the servo produces a torque which in turn results in the angular motion of the gimbal. Hence it is necessary to find a relation between the applied voltage and the resultant angular position of the gimbal considering the dynamics of DC servo motor.

III. CONTROL LAW DESIGN

The DC servo motors behave as actuators driving the gimbal. Based on Aung Phyo Wai [16], the motor has to be modeled based on its specifications. Fig. 2 shows the schematic of an armature controlled DC motor as referred in [16]. The electrical dynamics on the motor side can be expressed as

$$\mathrm{v} = Ri + L\frac{di}{dt} + e \tag{1}$$

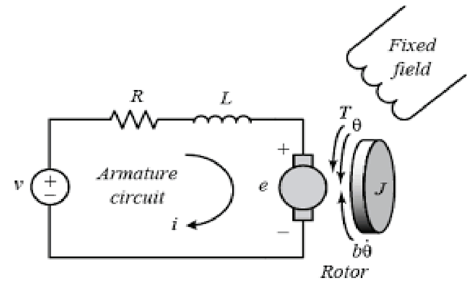


Figure 2. Schematic of DC motor.

The motor torque T thus produced and the armature current (i) are related by,

$$T = K_m i \tag{2}$$

where K_m is the motor torque constant. The back emf (e) and the angular velocity (ω) are related by

$$e = K_e\omega = K_e\frac{d\theta}{dt} \tag{3}$$

where K_e is the back emf constant. Here θ denotes the angular position and $\frac{d\theta}{dt}$ denotes the angular velocity. Assuming $K_m \approx K_{e,}$ we derive the transfer function as under,

$$T = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = Ki \tag{4}$$

$$L\frac{di}{dt} + Ri = \mathrm{v} - K\frac{d\theta}{dt} \tag{5}$$

where J, L, R, K and B are the motor moment of inertia, inductance of the motor armature, resistance of motor armature, motor torque constant and motor friction, respectively.

In this study, the inertia, the friction of the rotational elements in the transmission, gimbals and payload are neglected, for simplicity and the transmission is assumed to be stiff and ideal.

Applying Laplace Transforms to (4) and (5), after few algebraic manipulations, the transfer function relating the output angle (θ) and the input voltage (v) is given by,

$$\frac{\theta(s)}{\mathrm{v}(s)} = \frac{K}{JLs^3 + (JR + BL)s^2 + (BR + K^2)s} \tag{6}$$

This can be written in the compact form as,

$$\frac{\theta(s)}{\mathrm{v}(s)} = \frac{K}{a_3s^3 + a_2s^2 + a_1s} \tag{7}$$

with $a_3 = JL$, $a_2 = (JR + BL)$ and $a_1 = (BR + K^2)$.

The time domain representation is then given by,

$$\dddot{\theta} = -\left(\frac{a_2}{a_3}\right)\ddot{\theta} - \left(\frac{a_1}{a_3}\right)\dot{\theta} + \left(\frac{K}{a_3}\right)\mathrm{v} \tag{8}$$

The solution of the above third order differential equation gives the angle (θ) for a given input (v). The performance of the considered system is governed by the coefficients a_1 till a_3. It may be noted that the absence of the constant term in the denominator of (7) results in inherent instability. Hence, there is a need to design an appropriate controller for the desired performance. To design such controller it is but natural to specify the required performance characteristics, a priori. Hence we consider the desired characteristic polynomial for the given third order system to be,

$$(s^2 + 2\zeta\omega_n s + \omega_n^2)(s + \zeta\omega_n) \tag{9}$$

with ζ is the damping factor and ω_n is the natural frequency.

Assuming the desired specifications with a settling time 20 ms and a damping factor of 0.8, the undamped natural frequency works out to be 1.25 rad/s. Substitution of these values in (9) results in the desired characteristic equation to have the form,

$$s^3 + 600s^2 + 142500s + 12500000 = 0 \tag{10}$$

A. Design of Feedback Control Law

For the considered plant given by (8), we choose the feedback controller of the form,

$$\mathrm{v} = \left(\frac{a_3}{K}\right)\left(\mathrm{v}_{equ} + \nu\right) \tag{11}$$

where v_{equ} can be chosen to have the form,

$$\mathrm{v}_{equ} = \left(\frac{a_2}{a_3}\right)\ddot{\theta} + \left(\frac{a_1}{a_3}\right)\dot{\theta} \tag{12}$$

ν is the control that would drive the plant to meet the desired specifications given by (10). Therefore to design ϑ, we define the estimation error in θ as,

$$\theta_e = \theta - \theta_{ref} \tag{13}$$

where θ_{ref} is the desired value of θ. Now ν can be defined as,

$$\nu = (\dddot{\theta}_{ref} - m_2\ddot{\theta}_e - m_1\dot{\theta}_e - m_0\theta_e) \tag{14}$$

which would then give rise to the error dynamics as

$$\dddot{\theta}_e + m_2\ddot{\theta}_e + m_1\dot{\theta}_e + m_0\theta_e = 0 \tag{15}$$

Comparing (10) and (15), the feedback gains m_0, m_1 and m_2 are 12500000, 142500 and 600 respectively. The control law given (11) with v_{equ} and ν given by (12) and (14), respectively, would ensure efficient tracking in absence of uncertainties and disturbances.

B. Design of UDE based Robust Control Law

In practical scenario, uncertainties in J, B, K, R and L cannot be ruled out. Added to this, when the MAV is on flight, effects due to cross-wind disturbances cannot be neglected. Therefore the control law given in (11) needs to be augmented with a term to cancel the effects of uncertainties and disturbances and at the same time retain the tracking ability of the system.

Numerous robust control strategies have been reported in the literature. One such strategy is the Uncertainty and Disturbance Estimator (UDE) proposed in Zhong, Q.C. and Rees, D [14]. It is an elegant and systematic strategy where prior knowledge of the magnitude of the uncertainties is not required except for their bandwidth. The same strategy has been employed in this work to formulate a robust control law for the single axis gimbal setup. Considering (8), which is given below once again,

$$\dddot{\theta} = -\left(\frac{a_2}{a_3}\right)\ddot{\theta} - \left(\frac{a_1}{a_3}\right)\dot{\theta} + \left(\frac{K}{a_3}\right)\mathrm{v}$$

Defining $x_1 = \theta$; $x_2 = \dot{\theta}$ and $x_3 = \ddot{\theta} = \dot{x}_2$; we get

$$\dot{x}_3 = -\left(\frac{a_2}{a_3}\right)x_3 - \left(\frac{a_1}{a_3}\right)x_2 + \left(\frac{K}{a_3}\right)\mathrm{v} \tag{16}$$

Letting $A_1 = \left(\frac{a_2}{a_3}\right)$ and $A_2 = \left(\frac{a_1}{a_3}\right)$; introducing the associated uncertainties ($\Delta A_1, \Delta A_2$) in them in addition to a disturbance (d) in (16), we get

$$\dot{x}_3 = -\left(A_1 + \Delta A_1\right)x_3 - \left(A_2 + \Delta A_2\right)x_2 + \left(\frac{K}{a_3}\right)\mathrm{v} + d \tag{17}$$

Assuming the lumped uncertainty $(D \approx -\left(\Delta A_1\right)x_3 - \left(\Delta A_2\right)x_2 + d)$, the dynamics of the plant in presence of uncertainties can be expressed as,

$$\dot{x}_3 = -\left(A_1\right)x_3 - \left(A_2\right)x_2 + \left(\frac{K}{a_3}\right)\mathrm{v} + D \tag{18}$$

Introducing a new control variable v_d to compensate the effects of D, the control v can be expressed as,

$$\mathrm{v} = \left(\frac{a_3}{K}\right)\left(\mathrm{v}_{equ} + \nu + \mathrm{v}_d\right) \tag{19}$$

with v_{equ} and ν as has been defined in (12) and (14).

On substituting for v from (19) in (18), we get a relation,

$$\dot{x}_3 = \mathrm{v} + \mathrm{v}_d + D \tag{20}$$

Then we can express

$$D = \dot{x}_3 - \mathrm{v} - \mathrm{v}_d \quad (21)$$

When v_d is defined as $-\hat{D}$, where $\hat{D}$ is the estimate of D. Following [14], the relation between $\hat{D}$ and D is given by,

$$\hat{D} = G_f(s)D \quad (22)$$

where $G_f(s)$ is a first order filter of the form,

$$G_f(s) = \frac{1}{1+s\tau} \quad (23)$$

with τ as the filter time constant which encompasses the bandwidth of uncertainty and disturbances. Using (21), (22) and (23), we can derive the expression for the v_d as,

$$\mathrm{v}_d = -\frac{1}{\tau}\left[x_3 - \int \nu dt\right] \quad (24)$$

The final form of the UDE based robust control law is then given by,

$$\mathrm{v} = \left(\frac{a_3}{K}\right)\left(\mathrm{v}_{equ} + \nu - \frac{1}{\tau}\left[x_3 - \int \nu dt\right]\right) \quad (25)$$

with v_{equ} and ν as has been defined in (12) and (14). The stability analysis for similar systems employing UDE has been dealt in literature and hence omitted.

IV. NUMERICAL SIMULATION

The proposed UDE based control strategy was tested for its efficacy through numerical simulations in which a Hi-Tec HS-5485HB DC servo motor was considered. The servo motor specifications are given in Table I.

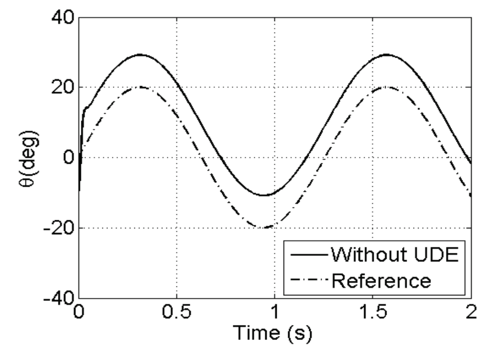
TABLE I. HI-TEC HS-5485HB SPECIFICATIONS

Modulation	Digital
Torque	4.8V: 5.18 kg-cm 6.0V: 6.41 kg-cm
Speed	4.8V: 0.20s/60^0 6.0V: 0.17s/60^0
Weight	45.1 g
Dimension	Length : 39.9 mm Width : 19.8 mm Height : 37.8 mm
Rotational Range	60^0
Pulse Cycle	20 ms
Pulse Width	900-1200 µs

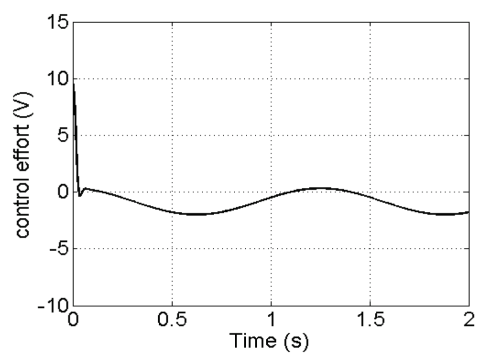
The nominal servo parameters considered in (6) are found through experimental results, which are J = 0.0002 kgm^2/s^2, K = 0.5729 Nm/A, B = 0.00508 Nms/rad, L= 0.012 H and R = 5 ohms.

A. Plant with Uncertainties and Disturbances

In this condition, uncertainties were introduced in J and B as +/- 2J and +/- 2B. In addition, a disturbance off 1000 N was also introduced. The uncertainties in the plant were considered to be extreme and external disturbances can be induced due to cross winds, gusts when the MAV is in its flight. With the filter time constant as 0.01 and the feedback gains in Section III, simulations were carried out for a reference signal of the form 20sin5t. Initially the tracking performance was tested using the control $\mathrm{v}_{equ} + \nu$ and the results are given in Fig. 3. Next, the simulation was carried out using the control law defined in (25) and the results are presented in Fig. 4. Comparing the output response from Figs. 3a and 4a, it is evident the proposed UDE based control strategy is able to ensure satisfactory tracking performance even in the presence of uncertainties and disturbance. This was possible by the augmentation of $\mathrm{v}_{equ} + \nu$ with an additional control component v_d , given by (24). The uncertainty estimation capability of the proposed strategy is also satisfactory as can be seen in Fig. 4c.

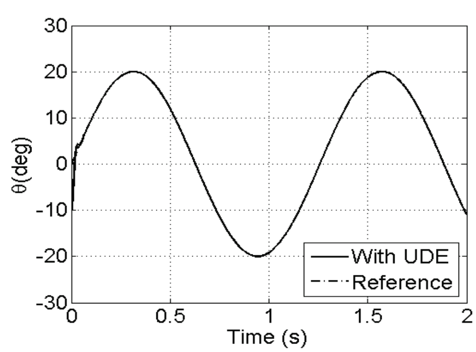


(a)



(b)

Figure 3. Tracking performance without UDE: (a) Output Response, (b) Control effort.



(a)

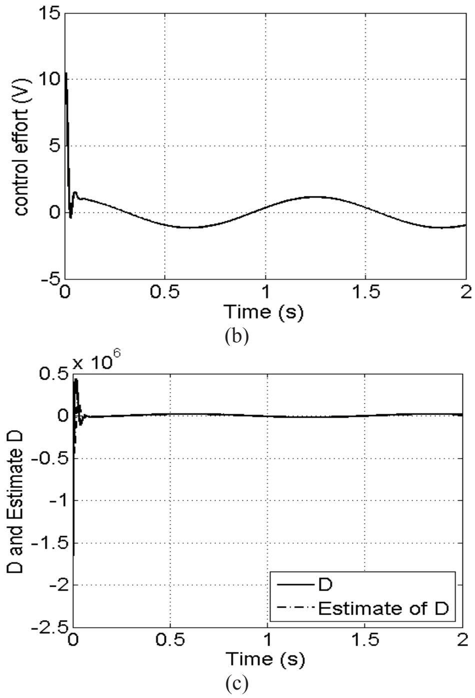


Figure 4. Tracking performance with UDE: (a) Output Response, (b) Control effort, (c) Estimate of uncertainty and disturbance.

V. Experimental Validation

From the numerical simulations it was found that the proposed strategy is indeed robust and able to meet the desired performance criterion. Hence, it is but natural to validate the same under experimental setup, compare it with an established control strategy like PID.

The experimental setup consists of a Remote Controller (RC) Transmitter which sends out PWM signals indicating the reference (desired) orientation of the gimbal. The on-board Receiver in the MAV collects this reference and passes it on to a APV4 Module consisting of a PSoC controller, which also gets the input of the actual orientation of the gimbal through IMU sensors. The error between the desired and actual orientation is then utilized by the proposed control strategy (which is embedded into the PSoC controller) to generate the required control signal. This control signal is then fed to the DC servo motor to operate in the desired direction to maintain the orientation of the gimbal to the required value. The experimental setup is as shown in Fig. 5. The performance specifications are as given in Section III.

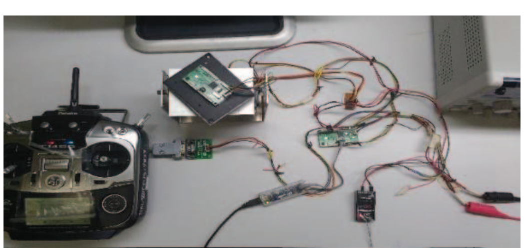


Figure 5. Experimental setup.

A. Performance of PID Controller

For the desired performance criteria of 20 ms settling time and 0.8 damping factor, the PID gains following Ziegler-Nichols method were computed as $K_p = 5.3760$, $K_i = 0.4908$ and $K_d = 0.1227$. With these values the PID control strategy is embedded in the PSoC controller to obtain the desired orientation of 15^0 (reference). The output response is shown in Fig. 6. As can be observed the response is not satisfactory. To overcome this situation the PID gains were retuned manually by trial and error and the best possible combinations were found to be $K_p = 0.5$, $K_i = 0.05$ and $K_d = 0.05$. The results thus obtained with the new values of PID gains are shown in Fig. 7. It is evident from the output response, the settling time while using a PID controller is close to 500 ms against the requirement of 20 ms. It may also be noted that no uncertainty and disturbances have been introduced in this set up except for those inherently present. A closer look at the output response also reveals that the tracking is not that perfect.

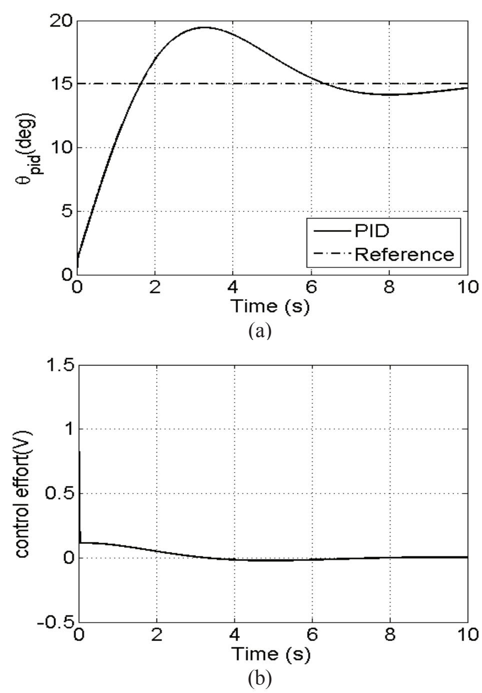
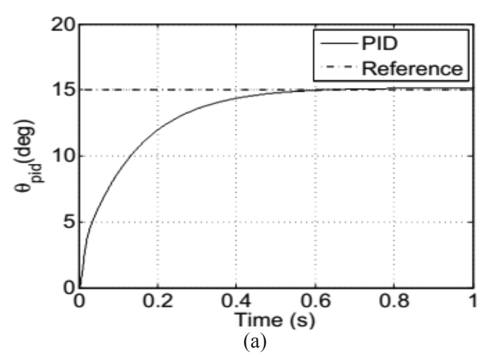
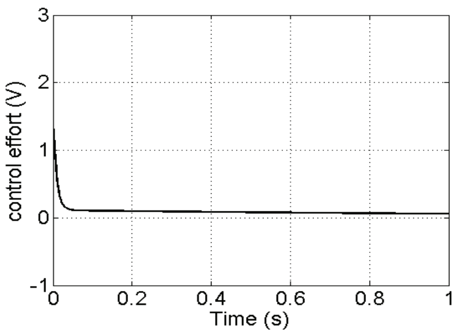


Figure 6. Performance of PID with Z-N tuned method: (a) Output Response, (b) Control effort.



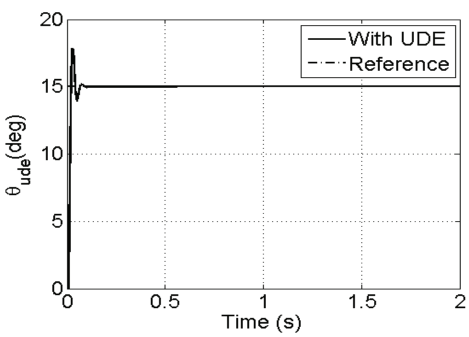


(b)

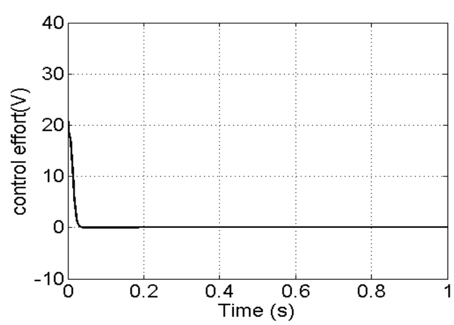
Figure 7. Performance of PID with tuned values: (a) Output Response, (b) Control effort.

B. Performance of UDE Based Controller

The performance of the proposed UDE based control strategy on this experimental setup was then tested for the desired criteria. The results thus obtained can be seen in Fig. 8. While comparing the output responses of both the control laws from Figs. 7a and 8a, it can be inferred that the proposed strategy is able to perform satisfactorily for the tracking requirement and at the same time meeting the performance standards.



(a)



(b)

Figure 8. Performance with UDE: (a) Output Response, (b) Control effort.

VI. CONCLUSION

In this research work the robust control technique for single axis gimbal platform for Micro Air Vehicles (MAV) using Uncertainty and Disturbance Estimator (UDE) has been successfully developed. Numerical simulations have confirmed the efficacy of the proposed formulation. Experimental validation has also been carried out while comparing the performance with a Proportional Integral Derivative (PID) controller. The proposed strategy has proved itself worthy of meeting the desired performance criteria and at the same time fulfilling the tracking requirements in presence of uncertainty and disturbance. Our future work would include development of Uncertainty and Disturbance Estimator (UDE) based control strategy for two axis gimbal platform for Micro Air Vehicles (MAV) applications with time varying uncertainties and disturbances. The overshoot observed in the output response while validating the strategy on an experimental setup would also be taken into account while formulating the control law for the two axis gimbal.

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REFERENCES

[1] C. E. Thorne and M. Yim, "Towards the development of gyroscopically controlled micro air vehicles," Robotics and Automation (ICRA), 2011 IEEE International Conference on, Shanghai, 2011, pp. 26-31.

[2] Bawek Dean, "Design and implementation of a control system for a quadrotor for MAV," Master's Thesis, University of Maryland, USA (2012).

[3] Yangbo Long, Sean Lyttle, Nicholas Pagano, David J. Cappelleri, "Design and quaternion based attitude control of omnicopter MAV using feedback linearization, "Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2012 August 12-15, 2012, Chicago, IL, USA

[4] Murat Bronz, Jean-Philippe Condomines, Gautier Hattenberger, "Development of an 18cm Micro Air Vehicle: QUARK," IMAV 2013, International Micro Air Vehicle Conference and Flight Competition, Sep 2013, Toulouse, France. pp. 1-10, 2013

[5] Shouzhao Sheng and Chenwu Sun, "A near hover adaptive attitude control strategy of a ducted fan micro air vehicle with actuator dynamics," *Applied Sciences*, 5, 666–681.

[6] Ashraf Qadir, Jeremiah Neubert and William Semke, "Implementation of onboard visual tracking system with small unmanned aircraft vehicle," International Journal of Innovative Technology and Creative Engineering, Vol. No.1, pp.1– 11, October 2011.

[7] Randal Beard, Clark Taylor, Jeffery Saunders, Ryan Holt, and Timothy McLain. "Payload Directed Flight of Miniature Air Vehicles", AIAA Infotech@Aerospace Conference, Infotech@Aerospace Conferences, Seattle, USA, 6-9 April 2009.

[8] Mandadi Srinivas Rao, C.M. Ananda and L.R.Manohar, "Design of single axis rate table for calibration of gyro sensor used in micro air vehicles," International Journal of Emerging Technology in Computer Science & Electronics (IJETCSE) ISSN: 0976-1353 Volume 14 Issue 2 –APRIL 2015.

[9] Maraiya Green, "Some studies on control of a dc servo motor," Master's Thesis, NIT, Rourkela, India, 2011.

[10] Rezac Martin and Hurak Zdenek, "Structured MIMO H-Infinity Design for Dual-Stage Inertial Stabilization: Case Study for HIFOO," Proceedings of the 18th IFAC World Congress, 2011, Vol.No. 8, pp. 7456-7461.

[11] Ozgur Hasturk, Aydan M. Erkmen and İsmet Erkmen, “Proxy based sliding mode stabilization of a two-axis gimbaled platform,” Proc. World Congress on Engineering and Computer Science, San Francisco, USA, Vol.No.1, pp. 1–7.

[12] Saugato Dey, Souvik Halder and M.P.Nandakumar, “Gyroscopic stabilization of two dimensional gimbal platform using fuzzy logic control,” International Journal of Electrical, Electronics and Data Communication, ISSN: 2320-2084 Volume-2, Issue-8, Aug.-2014, pp. 36-42

[13] Gerardo F. Flores, Rogelio Lozano Leal and Guillaume Sanahuja, “Lyapunov based switching control for a road estimation and tracking applied on a convertible MAV,” AIAA Guidance, Navigation and Control (GNC) Conference, Boston, USA, pp. 1-13.

[14] Zhong, Q.C. and Rees, D, “Control of LTI systems based on an uncertainty and disturbance estimator,” ASME Trans: J. of Dynamic systems, measurement and control, Vol. No.126(4), pp. 905–910

[15] Rohan Vimal Raj, Venkata Sreecharan Poluru and T.S. Chandar, “Robust control of Electric motor drive based on UDE,” Proceedings of the 9th IFAC Symposium on Control of Power and Energy Systems, Indian Institute of Technology – Delhi, India, December 9-11,2015, pp. 37-42.

[16] Aung Phyo Wai, “Analysis on modeling and simulation of dc motor and its driving system used for wheeled mobile robot,” World Academy of Science, Engineering and Technology International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering Vol:1, No:8, 2007,pp. 1141-1148