AI-based adaptive control and design of autopilot system for nonlinear UAV

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Abstract. The objective of this paper is to design an autopilot system for unmanned aerial vehicle (UAV) to control the speed and altitude using electronic throttle control system (ETCS) and elevator, respectively. A DC servo motor is used for designing of ETCS to control the throttle position for appropriate amount of air mass flow. Artificial Intelligence (AI)-based controllers such as fuzzy logic PD, fuzzy logic PD + I, self-tuning fuzzy logic PID (STF-PID) controller and fuzzy logic-based sliding mode adaptive controller (FLSMAC) are designed for stable autopilot system and are compared with conventional PI controller. The target of throttle, speed and altitude controls are to achieve a wide range of air speed, improved energy efficiency and fuel economy with reduced pollutant emission. The energy efficiency using specific energy rate per velocity of UAV is also presented in this paper.

Keywords. Autopilot system; AI-based control; DC servo motor; electronic throttle control system; sliding mode control and UAV.

1. Introduction

One of the most difficult aspects of manually controlled aerial vehicle is the coupling between the control over the vehicle speed and altitude. These output variables cannot be controlled independently to each other through the aerial vehicle control devices like elevator and throttle (Amelink *et al* 2003). The proper coordination between output variables and control devices are obtained using autopilot system. An unmanned aerial vehicle (UAV) commonly known as a drone is an aircraft or aerial vehicle without a human pilot on board. UAV flights are either controlled autonomously by computers in the vehicle, or under the remote control, or pilot on the ground or in another vehicle. In recent years, due to successful implementation of UAVs may be observed in military and the wide range of applications such as monitoring of traffic, crops and pollutions, crime and border surveillance; reconnaissance, coast guard, fisheries and environment protection, security of national assets, transport and communications, etc. UAVs significantly

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reduce the cost and risk to human life mainly in nuclear or chemical leakage inspection and are preferred in dull, dirty or dangerous for manned aerial vehicle missions (Manathara & Debasish 2011; Kurnaz *et al* 2009; Chao *et al* 2010; Orsag *et al* 2011; Gu *et al* 2006; Bateman *et al* 2011; Shiau & Ma 2009).

The stability in terms of energy of an UAV with automatic throttle and elevator controls has been investigated in this paper, where it is required to control height or altitude by means of the elevator, and speed using electronic throttle control system (ETCS). The controlling of throttle position using electric motor drives is called ETCS (Yadav & Gaur 2014). The UAV with the ETCS can give the subsonic, transonic, supersonic and hypersonic speeds (Stevens & Lewis 2003) and the dependent variables on throttle position like pollution, fuel consumption, energy efficiency are also improved (Yadav *et al* 2011a). The throttle is used as a valve to regulate air inflow into the engine combustion system and it determines the power developed by the engine by controlling the amount of air mass entering the engine cylinders. An UAV engine that produces thrust operates over a wide range of speed and the fuel/air mixture can be adjusted for maximum efficiency (Vasak *et al* 2007). The aerial vehicle with ETCS and nonlinear dynamics make the complete system as nonlinear and unstable. The linear control techniques cannot be applied to control this problem due to high nonlinearities in the system. In literature, many advanced control techniques such as fuzzy logic control (FLC) (Kurnaz *et al* 2009), adaptive control (Liu *et al* 2008; Han *et al* 2012; Osborne *et al* 2011), Artificial neural networks (Kamalasadan & Ghandakly 2011), robust control Wang & Stengel (2000, 2005), disturbance observer-based control (Liu *et al* 2013), nonlinear energy-based control (Akmeliawati & Mareels 2010), self-organizing control (Shin & Xu 2009), sliding mode control, H_∞ control and some other control techniques have been used for autonomous control of UAVs or similar system like aircraft to guarantee desirable trajectory (Keviczky & Balas 2006; Ducard 2009; Hull 2009; Yadav & Gaur 2013; Goerzen *et al* 2010; Kontogiannis & Ekaterinaris 2013). During military, transport and launching of satellites assignment the UAV is often unloaded at one or more points, each time part of the UAV is unloaded there is seldom a measuring device to obtain new accurate mass measurements. The various disturbances parameters such as wind speed, air density, mass, altitude and centre of gravity position, etc. are present during the flight of UAV. The mass or weight is generally several magnitudes larger than the other parameters. So for this research, the common approach is adopted, that all the parametric uncertainties can be aggregated as an uncertainty in mass and variation of air density. However, UAVs are normally operated in a dynamic environment of different air density, weather and load conditions which create the uncertainties and disturbances. The design of control algorithms must be robust and adaptive with respect to uncertainties so that the controller should be capable of handling the parameter uncertainties.

The Artificial Intelligence (AI)-based controller such as fuzzy logic control (Goerzen *et al* 2010; Yadav *et al* 2011b), self-tuning fuzzy logic PID controller (Yadav & Gaur 2014; Zulfatman & Rahmat 2009) which are designed to tune the value of K_P , K_i and K_d of the PID controller and fuzzy logic based sliding mode adaptive controller (FLSMAC) are designed and implemented for UAV in this paper. FLSMAC combines the merits of sliding-mode control, the fuzzy inference mechanism and the adaptive algorithm. First a PID, PD or integral type sliding-mode switching surface is designed and then a fuzzy sliding-mode controller is investigated in which a simple fuzzy inference mechanism is used to determine the equivalent control law. The various applications of FLSMAC such as manipulators, aircraft, servo drives, hybrid electric vehicles and robot are presented in (Li & Xu 2010; Sun *et al* 2011; Zhan & Zhou 2013; Wai *et al* 2004; Subudhi & Ge 2012; Asif *et al* 2014). The time domain performance parameters such as overshoot (OS), settling time (ST) and rise time (RT) are used as a measure of autopilot system

of UAV performance. The integral error performance indices (IEPI) such as integral of absolute error (IAE) and integral of square of error (ISE) are also studied to get better all-round performance for autopilot system of UAV. For the better performance analysis of a system, it is required to have proper balance in time domain and IEPI. All the above mentioned performance specifications are considered in this paper. Comparative performance analysis of controllers for UAV is presented in order to identify the superior controller over other controllers designed in this paper. A mathematical software ‘MATLAB’ is used for comparative performance analysis.

2. Problem formulation and mathematical modelling

The motion of a UAV in free flight is extremely complicated. To reduce the complexity of analysis, we usually assume that the UAV is a rigid-body and the motion of UAV consists of small deviation from its equilibrium (trimmed) flight condition. In addition, we assume that the UAV equations of motion can be separated into two groups, namely, longitudinal equations and lateral equations. In this paper, we have considered the longitudinal dynamics only. Using the standard notation of Stevens & Lewis (2003), the equations of motion are written with respect to the body axis of the UAV (Stevens & Lewis 2003; Ducard 2009; Hull 2009). The nomenclature used in this paper is described in table 1.

The nonlinear UAV dynamics, consisting of force, moment, and kinematic equations, can be compactly written as: Force equations:

$$\dot{u} = rv - qw + \frac{1}{m}F_x, \dot{v} = -ru + pw + \frac{1}{m}F_y \text{ and } \dot{w} = -pv + qu + \frac{1}{m}F_z. \quad (1)$$

Table 1. Nomenclature.

Symbol	Description	SI units	Symbol	Description	SI units
u, v, w	Velocity in the x, y, z body axis	m/s	R_a	Armature resistance	Ω
F_x, F_y, F_z	Force in the x, y, z body axis	N	L_a	Armature inductance	H
p, q, r	Roll, Pitch, Yaw rate	rad./s	K_b	Back EMF constant	Vs/rad.
ϕ, θ, ψ	Roll, Pitch, Yaw angle	rad.	K_t	Motor torque constant	Nm/A
α, β	Angle of attack, sideslip angle	rad.	K_{sp}	Throttle spring constant	Nm/rad.
γ	flight path angle	rad	R_{af}	Focal point of airflow on plate	m
δ_e, δ_T	Elevator, Throttle deflections	rad.	δ_{T_0}	Pre-tension angle of spring	rad.
L, M, N	Roll, pitch, yaw moment	kg.m ²	R_p	Throttle plate radius	m
I_{xx}, I_{yy}, I_{zz}	Inertia about x, y, z axis	kg.m ²	B_m	Motor damping constant	Nms/rad.
C_L, C_M	Lift, pitching moment coeff.	–	B_t	Throttle damping constant	Nms/rad.
S, S_{prop}	Wing area, Propeller area	m ²	J_m	Motor inertia	kg.m ²
c	Mean chord	m	J_g	Throttle inertia	kg.m ²
m	Mass of UAV	kg	J	Equivalent inertia	kg.m ²
ρ	Air density	kg/m ³	V	Total velocity or speed of UAV	m/s
*	Desired or reference value	–	h	Altitude	m

Moment equations:

$$\begin{aligned}\dot{p} &= \frac{1}{I_{xx}}[L - (I_{zz} - I_{yy})qr + I_{xz}(\dot{r} + pq)], \\ \dot{q} &= \frac{1}{I_{yy}}[M - (I_{xx} - I_{zz})pr + I_{xz}(p^2 - r^2)] \text{ and} \\ \dot{r} &= \frac{1}{I_{zz}}[N - (I_{yy} - I_{xx})pq + I_{xz}\dot{p} - I_{xz}qr].\end{aligned}\quad (2)$$

Kinematic equation:

$$\begin{aligned}\dot{\theta} &= q \cos \phi - r \sin \phi, \quad \dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \quad \text{and} \\ \dot{\psi} &= r \cos \phi / \cos \theta + q \sin \phi / \cos \theta.\end{aligned}\quad (3)$$

The definition of the body axis velocities are

$$u = V \cos \alpha \cos \beta, \quad v = V \sin \beta \quad \text{and} \quad w = V \sin \alpha \cos \beta. \quad (4)$$

The total velocity or airspeed V , angle of attack α , and angle of sideslip β can be expressed in term of body axis velocities as

$$V = |V| = (u^2 + v^2 + w^2)^{1/2}, \quad (5)$$

$$\alpha = \tan^{-1} \frac{w}{u} \quad \text{and} \quad \beta = \sin^{-1} \frac{v}{V}. \quad (6)$$

The longitudinal motion of the UAV is considered in this paper. The output states and control inputs are $[h, V, \theta, \alpha, q]$ and $[\delta_e, \delta_T]$, respectively. The trimming conditions for longitudinal motion are assumed as $\beta = 0$, $\theta = \alpha$, $\phi = 0$, $p = q = r = 0$. For longitudinal motion, the force balance along the x-direction of the body axis is as shown in figure 1, and represented in the form of equation as:

$$F_x = F_{Weight} + F_{Lift} + F_{Thrust} + F_{Drag}. \quad (7)$$

Figure 1. Forces on UAV in longitudinal motion.

Writing the force equation in expended form (Manathara & Debasish 2011):

$$F_x = -mg \sin \theta + \frac{1}{2} \rho V^2 S \left(C_{L_0} + C_{L_\alpha} \alpha + C_{L_q} \frac{cq}{2V} + C_{L_{\delta_e}} \delta_e \right) + \frac{1}{2} \rho S_{prop} k_{Engine}^2 C_{X_{\delta_T}}^2 \delta_T^2 - \frac{1}{2} \rho S_{prop} V^2, \quad (8)$$

where k_{Engine} and $C_{X_{\delta_T}}$ are dimensionless engine parameters, C_{L_0} , C_{L_α} , C_{L_q} and $C_{L_{\delta_e}}$ are lift control derivative of the UAV model. Here m is total mass of aerial vehicle and defined as $m_{UAV} + m_{fuel}$, where m_{fuel} decreases linearly at the rate of 1.1 kg/km. After applying trim conditions the simplified form of (1) is as

$$V = \left[\frac{2mg \sin \alpha - \rho S_{prop} k_{Engine}^2 C_{X_{\delta_T}}^2 \delta_T^2}{\rho S (C_{L_0} + C_{L_\alpha} \alpha + C_{L_{\delta_e}} \delta_e) - \rho S_{prop}} \right]^{0.5}. \quad (9)$$

The differential equation for the pitch angle θ and altitude h are as follows:

$$\dot{\theta} = q \quad (10)$$

$$\dot{h} = V \sin \gamma. \quad (11)$$

The flight path angle is denoted by $\gamma = \tan^{-1}(w/u) = \tan^{-1}(V \sin \alpha / V \cos \alpha)$, where $V = \sqrt{u^2 + w^2}$ and $\alpha = (\theta - \gamma)$ (Akmeliawati & Mareels 2010; Hull 2009).

The pitching moment M is written as (Wang & Stengel 2000; Hull 2009)

$$M = \frac{1}{2} \rho V^2 S c \left(C_{M_0} + C_{M_\alpha} \alpha + C_{M_q} \frac{cq}{2V} + C_{M_{\delta_e}} \delta_e \right), \quad (12)$$

where C_{M_0} , C_{M_α} , C_{M_q} and $C_{M_{\delta_e}}$ are pitching moment control derivative of the UAV model. After applying trim condition on (12), yield (13)

$$\alpha = -(C_{M_0} + C_{M_{\delta_e}} \delta_e) / C_{M_\alpha}. \quad (13)$$

Equations (9) to (13) give the complete model of nonlinear UAV. The Mechatronic system of UAV engine that provides thrust force, with electronic throttle control system (ETCS) is shown in figure 2.

In figure 2 the throttle position is shown with δ_T and if δ_T is controlled the kinetic energy given by $E_k = (1/2) m V^2$ may be controlled using (9). In figure 2 the ETCS consists of DC servo motor to rotate the throttle plate. Here the DC servo motor is controlled by the applied motor voltage E_a (Yadav & Gaur 2014; Vasak *et al* 2007).

$$\frac{di_a}{dt} = \left(\frac{1}{L_a} \right) \left(-R_a i_a - K_b \frac{d\theta_m}{dt} + E_a \right), \quad (14)$$

where i_a is armature current (A), θ_m is armature angular position (rad). The back EMF E_b due to the motor rotation is $K_b(d\theta_m/dt)$. The meaning of symbols used in equations is given in table 1. The motor and rotational dynamics of throttle is as follows:

$$\frac{d^2\theta_m}{dt^2} = \left(\frac{1}{J_m} \right) \left(-B_m \left(\frac{d\theta_m}{dt} \right) - T_L + T_m \right), \quad (15)$$

$$\frac{d^2\delta_T}{dt^2} = \left(\frac{1}{J_g} \right) \left(-T_{sp} - B_t \left(\frac{d\delta_T}{dt} \right) - T_a + T_g \right), \quad (16)$$

Figure 3. Autopilot system for longitudinal motion of UAV.

Equations (17) to (23) present complete model of nonlinear ETCS. The complete block diagram of autopilot system for longitudinal motion of UAV is represented by figure 3. It contains a DC motor that is a part of ETCS. The nonlinear UAV model was augmented with an inner-loop controller based on pitch rate, pitch angle and throttle position feedback. The inner-loop controller has to stabilize the pitch and throttle valve. The simulation values in SI unit of UAV and ETCS are listed in table 2.

The value of air density ρ as given in table 2 is a mean value and it is considered as unpredictable parameter and varying randomly. The Mach number ' M_a ' is defined as the quotient of aerial vehicle speed V and local speed of sound ' a ' and given as $M_a = V/a$ (Wang & Stengel 2005). The M_a related with air speeds such as $M_a < 1$, $0.8 < M_a \leq 1.2$, $1 < M_a < 5$ and $5 \leq M_a$ for subsonic, transonic, supersonic and hypersonic speeds, respectively.

3. Controller design and implementation

In this section, conventional PI, Fuzzy logic PD (FL-PD), Fuzzy logic PD+I, self-tuning fuzzy PID (STF-PID) controllers and fuzzy logic based sliding mode adaptive controller (FLSMAC) design algorithm are presented which are used in autopilot design for UAV. PI controllers are widely used in industrial control applications which have a simple structure and can offer a satisfactory performance over a wide range of operation. The conventional tuning of PI controller like Ziegler Nichols does not apply for all nonlinear, time varying systems, hence the PID controller is tuned by hand tuning rule with the help of fuzzy logic. This may be called self-tuning fuzzy logic PID controller. The transfer function of generalized PID controller is given in (Yadav & Gaur 2014; Yadav *et al* 2011a) and is written below:

$$C(s) = K_P + \frac{K_i}{s} + K_d s = K_P \left(1 + \frac{1}{T_i s} + T_d s \right), \quad (24)$$

where K_p , K_i , and K_d are proportional, integral and derivative gains, respectively. T_i is reset time which is equal to K_p/K_i , and T_d is rate time which is equal to K_d/K_p .

Table 2. Numerical values of UAV used in simulation.

C_{L_0}	C_{L_α}	C_{L_q}	$C_{L_{\delta_e}}$	$C_{X_{\delta_T}}$	C_{M_0}	C_{M_α}	$C_{M_{\delta_e}}$	ρ	k_{Engine}	S_{prop}	S	m	c
0.28	-2.7	0.0	0.83	1	0.15	-0.17	-0.88	1.27	20	4.5	36	5000	1.98
R_a	L_a	K_b	N	K_t	K_{sp}	R_{af}	R_p	B_m	B_t	J_m	J_g	J	B
2	0.003	0.11	4	0.1	0.4	0.002	0.0015	0.03	0.002	0.001	0.005	0.021	0.482

Figure 4. (a) Structure of FL-PD controller. (b) Structure of self-tuning fuzzy PID controller.

The FLC can be designed with knowledge base of the input and output variables of the controller. For designing the FLC four components are used namely rule base, inference engine, fuzzification and defuzzification (Yadav & Gaur 2013; Yadav *et al* 2011b). The proposed structure of FL-PD controller is given in figure 4(a). The inputs to the FLC are the error $e(t) = V^*(t) - V(t)$ and change in error that is $\dot{e}(t)$ and output variable is the desired throttle position δ_T^* . The universe of discourse of the variables cover a range of $[-2, 2]$ for error, $[-4, 4]$ for change in error and $[-10, 10]$ for output. A standard choice for the triangular membership functions is used with three membership functions for the three fuzzy variables (meaning $9 = 3^2$ rules in the rule base) as three membership functions are found sufficient to design the controller in this case. The resulting rule base is shown in the table 3. To obtain the crisp output, the center of gravity defuzzification method is used.

3.1 Self-tuning fuzzy PID controller

In STF-PID controller, the three parameters of PID controller K_p , K_i and K_d are tuned by using fuzzy logic (Yadav & Gaur 2014; Zulfatman & Rahmat 2009), because often the gains of the PID controller are not properly tuned for the desired UAV altitude with unpredictable parameter variations like density of air and mass. The conventional PID training rules are not effective when there is high altitude uncertainty. Hence, it is necessary to tune the PID controller parameters using STF-PID. The structure of the proposed self-tuning fuzzy PID controller is shown

Table 3. Fuzzy rule bases for FL-PD.

$e \backslash \dot{e}$	P	ZE	N
P	PB	P	ZE
ZE	P	ZE	N
N	ZE	N	NB

in figure 4b. For designing and implementation of self-tuning fuzzy logic PID controller, there are two inputs to fuzzy inference that are error in altitude $e_h(t) = h^*(t) - h(t)$ and derivative of error in altitude $\dot{e}_h(t)$, and three outputs for each PID controller parameter K'_p , K'_i and K'_d respectively. In this controller, the designing process of the rules is based on properties of the PID controller and the characteristic of the plant (Yadav & Gaur 2014).

Assume that the range of PID controller parameters K_p, K_i, K_d are $[K_{pmin}, K_{pmax}]$, $[K_{imin}, K_{imax}]$, $[K_{dmin}, K_{dmax}]$, respectively. The range of each parameter is considered from the knowledge base and hence the range of PID controller parameters K_p, K_i and K_d is taken between 0.01 and 0.1. These parameters are calibrated as follows: (Yadav & Gaur 2014; Zulfatman & Rahmat 2009)

$$\begin{aligned} K'_p &= \frac{K_p - K_{pmin}}{K_{pmax} - K_{pmin}} = \frac{K_p - 0.01}{0.1 - 0.01}, \quad K'_i = \frac{K_i - K_{imin}}{K_{imax} - K_{imin}} = \frac{K_i - 0.01}{0.1 - 0.01}, \quad \text{and} \\ K'_d &= \frac{K_d - K_{dmin}}{K_{dmax} - K_{dmin}} = \frac{K_d - 0.01}{0.1 - 0.01}. \end{aligned} \quad (25)$$

After simplification of (25), we get new PID controller parameters which are:

$$K_p = 0.99K'_p + 0.01, \quad K_i = 0.99K'_i + 0.01, \quad \text{and} \quad K_d = 0.99K'_d + 0.01. \quad (26)$$

The universe of discourse for input is between -0.1 and 0.1 , for output variables it is 0 to 1 and the triangular membership functions for inputs and outputs are selected. The fuzzy rules for STF-PID are shown in table 4.

3.2 Fuzzy logic based sliding mode adaptive controller (Yadav & Gaur 2014; Li & Xu 2010; Sun *et al* 2011; Zhan & Zhou 2013; Wai *et al* 2004; Subudhi & Ge 2012; Asif *et al* 2014)

Sliding mode control (SMC) is a variable structure control with high frequency discontinuous control action that switches between several functions depending on the system states (Yadav & Gaur 2014). It is one of the most effective and robust nonlinear control techniques for autopilot system of UAV. The principle of SMC is to define a control law to drive the nonlinear state trajectory onto a switching surface and to maintain this trajectory sliding on this surface for all subsequent time (Yadav & Gaur 2014). The control law is based on fuzzy logic and Lyapunov theory to guarantee the motion of the state trajectory towards the sliding surface. This is done by choosing a hitting control gain to maintain the derivative of Lyapunov function which is always a negative definite.

In order to design FLSMAC, first an integral type sliding surface is designed and defined as follows:

$$s(t) = e(t) + \lambda \int e(t)dt, \quad (27)$$

Table 4. Rule base matrix for STF-PID.

$e_h \backslash \dot{e}_h$	NB	NS	ZE	PS	PB
NB	S	S	MS	MS	M
NS	S	MS	MS	M	MB
ZE	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

where error $e(t)$ is described as $e(t) = V^*(t) - V(t)$ and λ is non-zero positive design parameters. As far as the guideline for the selection of control gains λ is concerned, the gains should be chosen such that the error dynamics at the sliding surface $s = 0$ will be forced to decay exponentially to zero.

Consider the control of autopilot system of UAV with dynamics (9) to (13) and figure 3; the speed controller is designed as

$$\delta_T^* = u = u_{eq} + u_s + u_a, \quad (28)$$

where u_{eq} is equivalent control law, u_s is switching control law and u_a is adaptive control law. The equivalent control law u_{eq} is designed using fuzzy logic based sliding mode control technique. The SMC law can be found using Lyapunov theory and defining the Lyapunov function as $v = s^2/2$. According to Lyapunov theory, if the derivative of v is negative definite, this will ensure that the state trajectory will be driven and attracted toward the sliding surface s , and once reached; it will remain sliding on it until the origin is reached asymptotically (Yadav & Gaur 2014). The time derivative of the Lyapunov function v can be calculated as $\dot{v} = s\dot{s}$. In order to make $\dot{v}$ as negative definite, a fuzzy logic control law is proposed in this paper that removes a lot of mathematical complications. It can be designed with the knowledge of the inputs s and $\dot{s}$ and the output variable u_{eq} of the controller. The proposed structure of FLSMAC is given in figure 5a. The universe of discourse with suitable membership functions of the input and output variable for FLSMAC is described in figure 5b and c. The resulting rule base is shown in the table 5.

The switching control law u_s is designed as

$$u_s = -\eta \cdot \text{sgn}(s), \quad (29)$$

Figure 5. (a) Structure of proposed FLSMAC. (b) Membership function for input variables s and $\dot{s}$. (c) Membership function for output variable u_{eq} .

Table 5. Rule base matrix of FLSMAC.

$s \backslash \dot{s}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

where η is hitting control gain and function sgn is defined as

$$sgn(s) = \begin{cases} -1 & \text{if } s < 0 \\ +1 & \text{if } s > 0 \end{cases}.$$

The use of sgn function in the switching control law u_s in (30), causes high-frequency chattering due to the discontinuous control action that represents a severe problem when the system state is close to the sliding surface (Yadav & Gaur 2014). To alleviate the chattering phenomenon, the discontinuous control law term $sgn(s)$ in (30) is replaced by a $sat(s)$ function around the switching surface (Sun *et al* 2011; Zhan & Zhou 2013; Wai *et al* 2004; Subudhi & Ge 2012; Asif *et al* 2014) the final switching control law is written as

$$u_s = -\eta \cdot sat(s/\varepsilon), \quad (30)$$

where $\varepsilon > 0$ is the width of the boundary, and the function of $sat(s/\varepsilon)$ is defined as

$$sat\left(\frac{s}{\varepsilon}\right) = \begin{cases} 1, & \text{for } \left|\left(\frac{s}{\varepsilon}\right)\right| \leq 1 \\ sgn\left(\frac{s}{\varepsilon}\right), & \text{for } \left|\left(\frac{s}{\varepsilon}\right)\right| \geq 1. \end{cases} \quad (31)$$

The adaptive control law u_a is designed as

$$u_a = -\frac{s}{\|s\| + \mu} \varphi, \quad (32)$$

with the adaptation law

$$\dot{\varphi} = \frac{\|s\|^2}{\|s\| + \mu}, \quad (33)$$

where $\|\cdot\|$ denotes the standard Euclidean norm and $\mu > 0$ is chosen such that $\int_0^\infty \mu dt < \infty$ (Sun *et al* 2011), then $\dot{s}(t) = 0$ due to this the speed tracking error $e(t)$ and $\dot{e}(t)$ will asymptotically converge to zero (Wai *et al* 2004; Asif *et al* 2014).

The linguistic variable levels for membership functions used in FL-PD, STF-PID and FLSMAC are assigned as: positive (P), negative (N), positive medium (PM), negative medium (NM), negative big (NB), negative small (NS), zero (ZE), positive small (PS), positive big (PB), small (S), medium small (MS), medium (M), medium big (MB) and big (B). The total control law of the FLSMAC is represented by (28) and could be written in general form as $u_{total} = u_{eq} + u_s + u_a$. The equivalent control u_{eq} defines the control action that keeps the

and specific energy or energy per unit weight is

$$\frac{E}{W} = h + \frac{V^2}{2g}. \quad (35)$$

The specific energy rate ($\dot{E}_s$) and the specific energy rate per velocity are described in (Akmeliawati & Mareels 2010) and are given below.

$$\dot{E}_s = \frac{\dot{E}}{W} = \dot{h} + V \frac{\dot{V}}{g}, \quad (36)$$

$$\frac{\dot{E}_s}{V} = \frac{\dot{h}}{V} + \frac{\dot{V}}{g} = \sin \gamma + \frac{\dot{V}}{g}. \quad (37)$$

5. Simulation results and discussion

In this section, the results obtained from MATLAB and SIMULINK are presented. In this work, the PI controller is designed as per conventional control technique and fuzzy logic PD, fuzzy PD+I, FLSMAC and STF-PID controller are based on AI-based control. All the controllers as seen in figure 3 are PI controllers. For AI-based control inner loop controllers such as pitch rate, pitch angle and throttle position control are PI controllers but outer loop controllers such as speed and altitude controllers are replaced by fuzzy logic PD, fuzzy PD+I, FLSMAC and STF-PID respectively. All the PI controllers of figure 3 are tuned by Hand-tuning rule through quarter decay ratio of Ziegler–Nichols tuning method. The value of all the designed controllers parameters are given in table 6. The response with PI controllers for pitch rate, pitch angle and throttle position in the inner loop of the line diagram of UAV in figure 3 are shown in figures 7 (a), (b) and (c), respectively.

The air speed and altitude of autopilot system with conventional PI and AI-based controllers like fuzzy logic PD, fuzzy PD+I, FLSMAC as speed controller and STF-PID as altitude controller are represented by figures 8 (a) and (b), respectively. The all phases of UAV such as initial climbs, low altitude flight, climb, cruise, loiter over target zone, descent, initial and final approach and finally landing are also shown in figure 8 (b). The variations in air density during simulation are considered as disturbance here and it is given in figure 8 (c). The IEPI and time domain performance indices of UAV with all designed controllers are given in table 7. The values of time domain performance index as given in table 7 is determined from enlarged views as seen in figures 8 (a) and (b).

Table 6. Values for controller parameter.

	Conventional PI		Fuzzy PD	STF-PID	FLSMAC
Controller	K_P	K_I	$g_p = 0.001$	$g_e = 1.2$	$\lambda = 0.1$
Pitch rate	1.2	10	$g_d = 0.001$	$g_{\dot{e}} = 0.009$	$\eta = 0.1$
Pitch angle	3	0.01	$g_u = 1200$	$g_p = 0.01$	$\mu = 100$
Throttle position	10	12		$g_i = 0.01$	$g_s = 1/400$
Altitude	0.04	0.025		$g_d = 0.01$	$g_{\dot{s}} = 1/1500$
Speed	0.04	4.3		-	$g_{u_{eq}} = 700$

Figure 7. Response of UAV with PI controller (a) Pitch rate, (b) Pitch angle, (c) Throttle position.

The dynamics of air speed and altitude are dependent on each other as seen in modelling of section 2. But once if autopilot system is stabilized, then they do not affect the performance of each other. This is verifying with the comparisons of results in figures 8(a) and (b) and the values of performance index as given in table 7. In figure 8(a), speed is changed at 150 sec and the enlarged view is also shown in the same figure, but it does not affect the response of altitude at the same time. In figure 8 (b), altitudes is changed in steps according to phases of UAV flight, but it does not affect the response of air speed, it is also verified with IAE and ISE values given in table 7, that shows that it is nearly same using STF-PID while speed controllers are different. The enlarged view in figure 8 (b) gives some undesirable and poor transient response; it is due to transition of manual to automatic control. Figure 9 (b) represents the different air speeds such as subsonic, transonic, supersonic and hypersonic speed which are changed in the sequence in every 10 s and the comparison of PI and AI-based controllers for different airspeed is also presented in same figure.

The PI and AI-based controllers are designed for the UAV in the present work for wide speed range as shown in figure 9. The air speed changes in four steps of 10 s each that is from 0–100, 100–400, 400–1000 and 1000–2000 m/s and finally 2000 m/s to 1500 m/s in last 10 s as shown in figure 9. From figure 8 (a), figure 9 and table 7, it is concluded that the response of air speed with FLSMAC is far better than the response of conventional PI and other designed AI-based controllers. It gives least OS, RT, ST, steady state error (E_{ss}), IAE and ISE as compared to other designed controllers. The response of altitude with STF-PID is far better than the response of PI

Figure 8. (a) UAV speed control with conventional PI and AI based control. (b) UAV Altitude control with conventional PI and AI-based control. (c) Variation in air density as disturbance.

controller as clearly shown with values of ISE and IAE as given in table 7. According to proper balance in time domain and IEPI, autopilot system for UAV with FLSMAC as speed controller and STF-PID as altitude gives best control performance.

In order to see the effect of air density disturbance rejection and mass uncertainty of autopilot system using the proposed FLSMAC technique, the constant sliding surface parameter λ is modified to a time varying parameter $\lambda(t)$ and estimated online according to adaptation rule

Table 7. Performance index of autopilot system with different combination of controllers.

Perf. index →	Speed						Altitude				
	IEPI		Time domain				IEPI	Time domain			
Controller	IAE	ISE	RT (s)	ST(s)	OS (%)	E_{ss} (%)	Controller	IAE	ISE	ST (s)	OS (%)
PI	386.9	6.3×10^4	0.71	1.5	9.5	0.01	PI	2035	3.8×10^5	18.2	12.8
Fuzzy PD	3099	5.33×10^4	1.32	1.91	0.0	1.8	STF-PID	1074	1.42×10^5	15.7	23.6
Fuzzy PD+I	604.2	4.79×10^4	1.1	1.54	0.0	0.02	STF-PID	1032	1.38×10^5	12.4	54.3
FLSMAC	212.5	2.63×10^4	0.76	0.87	0.0	0.012	STF-PID	1046	1.41×10^5	11.8	52.72

Figure 9. Various UAV airspeeds with PI and AI-based controllers.

$\dot{\lambda}(t) = -\vartheta \cdot s(t) \cdot \int^t V^*(t) - V(t) dt$, where ϑ is a constant. To test disturbance, i.e., air density rejection and effect of mass uncertainty on speed and altitude performance of UAV using FLSMAC with constant λ and then with time varying sliding surface parameter $\lambda(t)$, a +100 air density at $t = 60$ s and +10,000 kg mass at $t=80$ s, -12,500 kg mass at $t=81$ s and 0 kg mass at $t=82$ s is applied and the effect on response of speed and altitude with constant λ and then with time varying $\lambda(t)$ of FLSMAC is represented in figures 10 (a) and (b). In figures 10 (a) and (b) both disturbances due to air density as well as mass uncertainty is taken into consideration. From figure 10 (a) it is clearly seen that the effect of air density and mass uncertainty on air speed with FLSMAC using constant λ is more as compared to FLSMAC with time varying $\lambda(t)$.

The FLSMAC with $\lambda(t)$ gives small 5.7% OS and nearly 0.9 s settling time. These disturbances are not affecting the altitude performance because STF-PID controller is used as altitude controller as seen from figure 10(b). Hence, the autopilot system for UAV using FLSMAC with time varying λ gives robust and adaptive performance.

Due to the significant steady state error in air speed using AI-based control technique, the kinetic energy may not be accurately balanced and this is reflected as minor deviation in specific

Figure 10. Response with constant and time varying λ of FLSMAC (a) speed, (b) altitude.

Figure 11. Response of specific energy rate per velocity.

energy rate per velocity for short duration in UAV as seen in figure 11 and that may be neglected as it is minor deviation in energy level and within the limits.

As seen from figure 11, specific energy rate per velocity is finally zero for a specified flight path when autopilot system is activated between the interval of 10 s to the 1400 s, with constant air speed of 100 m/s throughout the path. During the transients, the controller regulates the kinetic energy well and the potential energy is expected to rise. The plot is drawn using (37) ' $\sin \gamma + \dot{V}/g$ ' for specific energy rate per velocity as shown in figure 11. As can be seen, the total energy is balanced at fast rate after every transient hence the energy control efficiency is achieved. The objective of the analysis is to verify the robustness of the proposed closed-loop autopilot system against various flight conditions and to investigate the conformity of the closed-loop system responses. In the present work, the main concern is the effect on the aircraft energy management by controlling the aircraft speed and altitude and the analysis of transient and steady-state response for various control strategies on closed-loop system during the transient period, to investigate the rise time, the settling time and the air speed responses. According to proper balance in time domain, IEPI and energy control of autopilot system for UAV with FLSMAC as speed controller and STF-PID as altitude give the best control performance.

6. Conclusion

In this paper, the design of autopilot system for longitudinal motion of UAV is presented. The AI-based STF-PID controller as altitude control and FLSMAC as speed control are designed to improve the UAV performance and also to reduce the controller tuning time effectively, hence replacing conventional PI controller where a large time is required for tuning. The conventional PI and AI-based controllers are applied to control the speed and altitude by mixing appropriate amount of air mass to the fuel mass through throttle valve of autopilot system for nonlinear UAV. The results show that AI-based controller give better performance results in comparison to conventional PI controllers considered for inner and outer loops in UAV control. Since the maximum overshoot and settling time in achieving the desired speed being the least with AI-based controller, hence the current and torque of the motor to control the same will also be optimized with the desired throttle position of ETCS through DC servo motor which ensures better fuel economy and efficiency. AI-based control technique may also be applied to other similar nonlinear systems for performance optimization. Since the air mass flow to the fuel mass is dependent on throttle position and the ratio of the same decides the energy efficiency, fuel economy and pollution, it may be concluded that UAV along with AI-based control of ETCS is effectively controlled for variable speed operation of the same.

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