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# Extended observer based on adaptive second order sliding mode control for a fixed wing UAV

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A B S T R A C T

This paper addresses the design of attitude and airspeed controllers for a fixed wing unmanned aerial vehicle. An adaptive second order sliding mode control is proposed for improving performance under different operating conditions and is robust in presence of external disturbances. Moreover, this control does not require the knowledge of disturbance bounds and avoids overestimation of the control gains. Furthermore, in order to implement this controller, an extended observer is designed to estimate unmeasurable states as well as external disturbances. Additionally, sufficient conditions are given to guarantee the closed-loop stability of the observer based control. Finally, using a full 6 degree of freedom model, simulation results are obtained where the performance of the proposed method is compared against active disturbance rejection based on sliding mode control.



## 1. Introduction

Fixed wing unmanned aerial vehicles (UAV) have attracted research interest due to its large range of applications such as traffic monitoring, surveillance, weather research, search and rescue of people, mapping, inspection of power lines, and oil pipelines [1]. However, the performance of a fixed wing flight is affected by aerodynamic forces as well as conditions such as altitude, wind payload variation and its resources. Another important challenge for flying small fixed wing UAVs is the presence of external disturbances [2]. Furthermore, the craft has nonlinear and coupled dynamics, therefore the control strategies require robustness against model uncertainties and external disturbances.

In order to tackle the flight control problem, several approaches have been proposed. For instance, linear control methods as in [3] or more recently nonlinear control techniques such as feedback linearization [4], optimal control [5], nonlinear dynamic inversion [6], adaptive backstepping [7], techniques based on invariant manifolds [8], quasi-continuous sliding mode control [9], adaptive flight control [10], and model predictive approaches [11]. Nevertheless, these techniques require knowledge of the exact model and external perturbations to compensate their effects.

On the other hand, to deal with external disturbances and reduced model knowledge, several approaches have been proposed. In [13,14] control schemes for rejecting external disturbances have been reported, where a fuzzy logic method based on backstepping and learning control have been applied to an exoskeleton. Nevertheless, these methods require a training process.

Above controllers assume that all the components of the state vector are available by measurement. However, in practice this is not always possible. Then, in order to implement controllers it is necessary to estimate unmeasurable states. To solve the aforementioned problem, some solutions have been proposed. One of these solutions is the extended state observers, which has a suitable performance to estimate a wide range of disturbances not only those that satisfies matching condition and furthermore do not require an exact model [17]. Under this approach, parametric uncertainties and unmodeled dynamics of the system are considered as an additional state variable, thus the perturbation and unknown dynamics can be compensated by feedback linearization, *i.e.*, active disturbance rejection control scheme ADRC.

Extended state observers have been implemented with several controllers such as classical PID control [18], sliding mode control for providing robustness [15] and adaptive fuzzy control [12], illustrating its advantages according to the application.

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In this work, an adaptive super twisting (AST) controller for flight control of a fixed wing UAV under external disturbances is designed for improving performance under different operating conditions, where the knowledge of disturbances bounds is not required and the control gains are not overestimated. In order to implement this controller, an extended state observer is used to estimate unmeasurable states of the system as well as external disturbances. Furthermore, sufficient conditions are given to guarantee the closed-loop stability of the observer based control scheme.

This paper is organized as follows: In Section 2, a mathematical model including aerodynamics of the fixed wing UAV is presented. An extended observer based on adaptive super twisting control is addressed in Section 3, whereas attitude and airspeed controllers are designed in Section 4. Simulation results illustrating the performance of the proposed observer based control are given in Section 5. Finally, some conclusions are drawn.

## 2. Fixed wing UAV dynamical Model

In this section, the dynamical model of fixed wing UAV moving in the space with the *roll–pitch–yaw* convention by the use of the 3 Euler angles $(\phi,\theta,\psi)\in[-\pi,\pi]$ is introduced.

The control of a fixed-wing UAV is through aileron, elevator and rudders, and the thrust generated by two engines.

The dynamical behavior of a full 6 degree of freedom aircraft model using Newton–Euler convention (see Fig. 1), is given by [3,20]

$$\dot{\mathbf{d}} = \mathbf{R}_1(\boldsymbol{\varphi})\mathbf{v} \tag{1}$$

$$\dot{\boldsymbol{\varphi}} = \mathbf{R}_2^{-1}(\boldsymbol{\varphi})\boldsymbol{\omega} \tag{2}$$

$$\mathbf{F}+\mathbf{T} = m(\dot{\mathbf{v}}+\boldsymbol{\omega}\times\mathbf{v}) - m\mathbf{R}_1^T(\varphi)\mathbf{g} \tag{3}$$

$$\mathbf{M} = \mathbf{J}\dot{\boldsymbol{\omega}}+\boldsymbol{\omega}\times\mathbf{J}\boldsymbol{\omega}, \tag{4}$$

where $\mathbf{d}=[x,y,z]^T\in\mathbb{R}^3$ denotes the inertial position of the aircraft, $\boldsymbol{\varphi}=[\phi,\theta,\psi]^T$ is the attitude described by the set of the Euler angles, $\mathbf{v}=[u,v,w]^T\in\mathbb{R}^3$ corresponds to the non-inertial (body fixed frame coordinates) expression of the linear velocity and $\boldsymbol{\omega}=[p,q,r]^T\in\mathbb{R}^3$ represents the non-inertial expression of the angular velocity (see [20] for more details). Moreover, rotation matrix $\mathbf{R}_1(\boldsymbol{\varphi})\in SO(3)$ maps body axis coordinates to inertial frame coordinates and the operator $\mathbf{R}_2(\boldsymbol{\varphi})\in\mathbb{R}^{3\times3}$ transforms the time derivative of the Euler angles set to the non-inertial expression of the angular velocity. Both matrices are given explicitly by

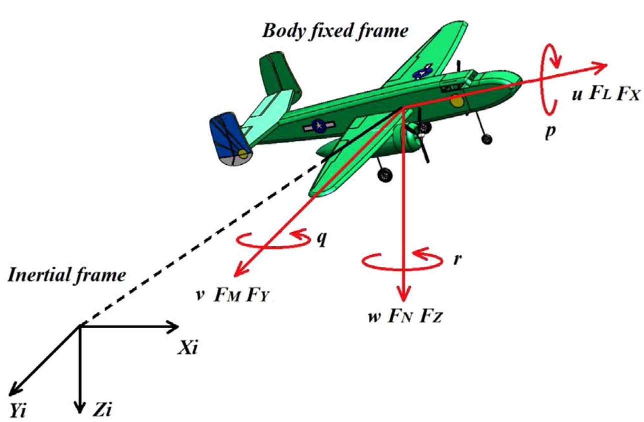


**Fig. 1.** Referential frames configuration.

$$\mathbf{R}_1(\boldsymbol{\varphi}) = \begin{bmatrix} c_\psi c_\theta & -s_\psi s_\phi + c_\psi s_\theta s_\phi & s_\psi s_\phi + c_\psi s_\theta c_\phi \\ s_\psi c_\theta & c_\psi c_\phi + s_\psi s_\theta s_\phi & -c_\psi s_\phi + s_\psi s_\theta c_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{bmatrix}$$

$$\mathbf{R}_2(\boldsymbol{\varphi}) = \begin{bmatrix} 1 & 0 & -s_\psi \\ 0 & c_\psi & c_\theta s_\psi \\ 0 & -s_\theta & c_\theta c_\psi \end{bmatrix},$$

where $s_x$ and $c_y$ stand for the $\sin(x)$ and $\cos(y)$ functions with their corresponding arguments. The extrinsic active forces are given by the propeller thrust, along $x$ body axis, *i.e.*, $\mathbf{T}=[T_x,0,0]^T$. The vector $\mathbf{g}=[0,0,g_z]^T$ denotes the gravity acceleration in inertial coordinates, while the inertia tensor $\mathbf{J}\in\mathbb{R}^{3\times3}$ (with $x$–$z$ plane of symmetry) is constant and expressed in the non-inertial body fixed frame:

$$\mathbf{J} = \begin{bmatrix} J_{xx} & 0 & J_{xz} \\ 0 & J_{yy} & 0 \\ J_{zx} & 0 & J_{zz} \end{bmatrix}. \tag{5}$$

Finally, the fixed-wing UAV aerodynamics are represented by non-inertial expressions of the force vector $\mathbf{F}=[F_X,\ F_Y,\ F_Z]^T\in\mathbb{R}^3$ and the torque vector $\mathbf{M}=[F_L,F_M,F_N]^T\in\mathbb{R}^3$.

### 2.1. Aerodynamics

The aerodynamics forces and torques in (3) and (4) can be calculated by means of aerodynamic coefficients (see for more details [20]), where

$$\boldsymbol{F} = \overline{q}S\mathbf{R}_3(\alpha,\beta)^{-1}[-C_D, C_Y, -C_L]^T$$
$$\boldsymbol{M} = \overline{q}S\left[b\,C_l, \overline{c}\,C_M, b\,C_n\right]^T$$

where $\alpha=\arctan\left(\frac{w}{u}\right)$ and $\beta=\arcsin\left(\frac{u}{v}\right)$ being respectively the angle of attack and the sideslip angle. $C_L$ and $C_D$ represent the drag and lift coefficients for the airplane respectively. The dynamic pressure $\overline{q}=\frac{1}{2}\rho V^2$ is a function of the relative airspeed magnitude $V=\sqrt{u^2+v^2+w^2}$. Furthermore, wing surface area $S$, the wingspan $b$, the mean aerodynamic chord $\overline{c}$ and the air density $\rho$ are considered as constant parameters. The transformation matrix $\mathbf{R}_3(\alpha,\beta)\in SO(3)$ maps body fixed frame coordinates $\Sigma_1$ to a virtual wind frame $\Sigma_w$ defined along the relative velocity of the aircraft is given by [20]:

$$\mathbf{R}_3(\alpha,\beta) = \begin{bmatrix} c_\alpha c_\beta & s_\beta & s_\alpha c_\beta \\ -c_\alpha s_\beta & c_\beta & -s_\alpha s_\beta \\ -s_\alpha & 0 & c_\alpha \end{bmatrix}. \tag{6}$$

The dimensionless coefficients in the force/moment expressions can be decomposed in the following set of equations [20]:

$$\begin{aligned}
C_L &= c_{L0} + C_{L\alpha}\alpha + c_{L\delta e}\delta e + \frac{\overline{c}}{2V}(c_{L\dot\alpha}\dot\alpha + c_{Lq}q) \\
C_D &= c_{D0} + \frac{(c_L - c_{L0})^2}{\pi e AR} + c_{D\delta e}\delta e + c_{D\delta a}\delta a + c_{D\delta r}\delta r \\
C_Y &= c_{y\beta}\beta + (c_{yp}p + C_{yr}r)\frac{b}{2V} + c_{y\delta a}\delta a + c_{y\delta r}\delta r \\
C_l &= c_{l\beta}\beta + (c_{lp}p + c_{lr}r)\frac{b}{2V} + c_{l\delta a}\delta a + c_{l\delta r}\delta r \\
C_M &= c_{m0} + c_{m\alpha}\alpha + c_{m\delta e}\delta e + (c_{mq}q + c_{m\dot\alpha}\dot\alpha)\frac{\overline{c}}{2V} \\
C_n &= c_{n\beta}\beta + (c_{np}p + c_{nr}r)\frac{b}{2V} + c_{n\delta a}\delta a + c_{n\delta r}\delta r,
\end{aligned} \tag{7}$$

where $\delta e$, $\delta a$ and $\delta r$ represents elevator, ailerons and rudder respectively. The above expressions depend on Oswald's efficient number $e$, the Mach number $M$ (due to velocity range of a scale

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