Fixed-wing UAVs navigation in the presence of wind: a survey

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Abstract: Innovative organizations have begun to use fixed-wing Unmanned Aerial Vehicles (UAVs) for healthcare delivery since they can fly faster andprovide a proper solution in locations with difficult access or unsafe to human life. Moreover, they assure greater utility and better cost effectiveness than manned aircraft. However, the wind affects both the longitudinal and the lateral variables of the fixed-wing UAV contributing to its nonlinear and due to such external disturbances the UAV can fail its mission. Therefore, this review paper discusses on effects of wind disturbances on navigation of fixed-wing UAV. Full nonlinear equations of motion by including the effects of the wind on the fixed-wing UAV performance are developed. Also an overview of different approaches is presented.
Keywords: Fixed-wing UAV; navigation control; longitudinal, lateral, wind disturbances.

Introduction. Unmanned Aerial Vehicles (UAVs), commonly known as drones are one of the most powerful forms of technology available today because of their various uses and applications, such as surveillance, filming, agriculture, construction, sports, mapping,crop spraying, emergency services,package delivery, photography, etc.[1-3]. UAVs are controlled autonomously by an integrated system called the autopilot[4], which takes full control over the aircraft.

This paper is motivated by a common problem which is very critical to human life especially in Africa; lack adequate access to essential medical products, such as blood and vaccines due to challenging terrain and gaps in infrastructure [5]. Timely delivery of urgently needed medications, blood and vaccines are very critical in healthcare [6]. Thus, innovative organizations such as Zipline have begun to use fixed-wing UAVs for healthcare delivery. However, sometimes during launch process, the wind becomes very strong and this can delay the launch or operators will have to cancel the launch completely. In addition, due to a strong wind the fixed-wing UAV can crush on its way before it delivers the package at the hospital and during all this time the patient waiting for the medication urgently can lose his life. Hence, the general idea of this paper is to discuss on the effects of wind such as wind shear or wind gust on waypoint navigation of fixed-wing UAVs.

Wind effects on fixed-wing UAV motion. Flying in strong winds is one of the great limiting factors of fixed-wing UAVs since wind can cause them to deviate from their desired trajectories, likely leading to crashes. A deviation of a few meters can be tolerable in a sparsely population area, but can imply the big difference between a successful flight and a crush in urban centers.

The most troublesome wind conditions for fixed-wing UAV are gusts of wind. A wind gust is an unexpected, brief increase in the speed of the wind followed by a lull. According to National Weather Service [7] observing practice, gusts are reported when the peak wind speed reaches at least 16 knots (18 mph) and the variation in wind speed between the peaks and lulls is at least 9 knots (10 mph). The duration of a gust is normally less than 20 seconds. Another dangerous wind incident is wind shear, where there is a sudden change in headwind or tailwind resulting in changes in the lift to the aircraft.

When operating autonomous fixed-wing UAV, it is mandatory to deal with the effects of wind that causes the aircraft to deviate in a certain direction and to operate in such environments in a safe and controlled manner [8], it is essential to better understand the varied wind conditions affecting position and trajectory tracking [9]. Here are some cases that can cause the fixed-wing UAV to change the direction under wind disturbances:

- The small size and lightweight of the fixed-wing UAVs make them sensitive to external disturbances.
- Sometimes fixed-wing UAVs controllers don’t have enough information on the actual mode of operation of the wing which can cause tragic losses of control when flying under wind disturbances.

Flying in the presence of wind. The best method to fly in the presence of wind is flying into direction of wind (Fig.1), i.e. when the fuselage is parallel to the wind. Flying into the wind will allow maximum wind speed on leading edge of wing airfoil, as they are designed in such a way [10].

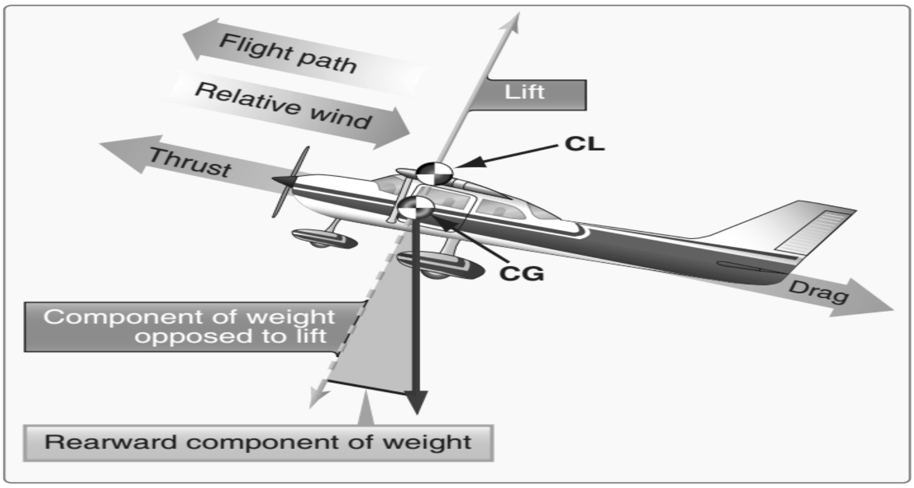

Fig.1. Fixed-wing UAV flying into direction of wind

Full nonlinear fixed-wing UAV equations of motion. The full state model of the fixed-wing UAV consists of 12 coupled nonlinear ordinary differential equations [11], $\dot{X} = [xyzuvw\phi\theta\psi pqr]^T$.

$$\dot{x} = uc\theta c\psi + v(s\phi s\theta c\psi - c\phi s\psi) + w(c\phi s\theta c\psi + s\phi s\psi), \quad (1)$$

$$\dot{y} = uc\theta s\psi + v(s\phi s\theta s\psi + c\phi c\psi) + w(c\phi s\theta s\psi - s\phi c\psi), \quad (2)$$

$$\dot{z} = -us\theta + vs\psi c\theta + wc\psi c\theta, \quad (3)$$

$$\dot{u} = rv - qw - gsin\theta + X_b/m, \quad (4)$$

$$\dot{v} = pw - ru + gcos\theta sin\phi + Y_b/m, \quad (5)$$

$$\dot{w} = qu - pv + gcos\phi cos\theta + Z_b/m, \quad (6)$$

$$\dot{\phi} = p + tan\theta(qsin\phi + rcos\phi), \quad (7)$$

$$\dot{\theta} = qcos\phi - rsin\phi, \quad (8)$$

$$\dot{\psi} = sec\theta(qsin\phi + rcos\phi), \quad (9)$$

$$\dot{p} = (I_{xz}\dot{r} - (I_{zz} - I_{yy})qr + I_{xz}pq + L)/I_{xx}, \quad (10)$$

$$\dot{q} = (-(I_{xx} - I_{zz})rp - I_{xz}(p^2 - r^2) + M)/I_{yy}, \quad (11)$$

$$\dot{r} = (I_{xz}\dot{p} - (I_{yy} - I_{xx})pq - I_{xz}qr + N)/I_{zz}. \quad (12)$$

where $c = cos, s = sin$; x, y and z are positions components in geographical coordinate system; u, v and $w$are velocity components in body frame; p, q and r are rolling, pitching and yawing moments in body frame;ϕ, θ and ψ are the Euler angles including pitch, roll and yaw respectively. X_b, Y_bandZ_b are aerodynamic forces along X, Y and Z axis and L, M and N are moments along X, Y and Z axis. These aerodynamic forces and moments depend on control surfaces; elevator, aileron, rudder and throttle with deflections named $\delta_e, \delta_a, \delta_r, \delta_t$ respectively (Fig. 2). I_{xx}, I_{xz}, I_{yy}andI_{zz} represent products of moment inertia about body fixed X, Y and Z axis; g is acceleration due to gravity in X, Y and Z axis and m is vehicle weight.

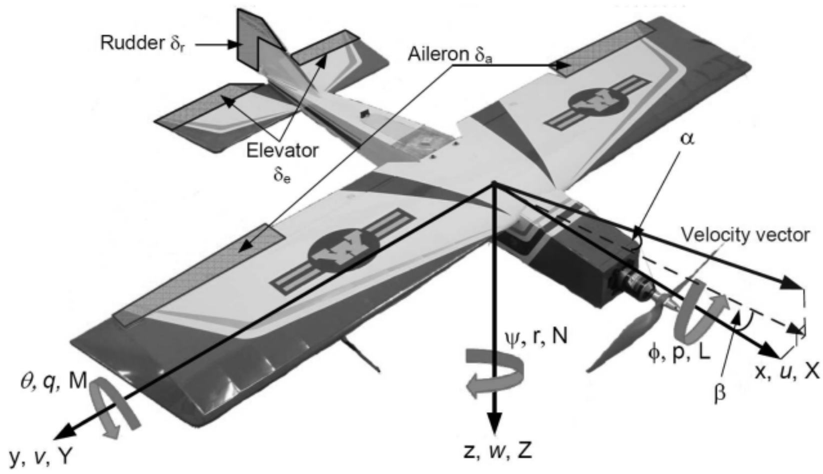

Fig. 2. Fixed-wing UAV velocities, forces, moments, angle rates and control surfaces

Including wind in the fixed-wing UAV equations of motion. In order to describe the behavior of the fixed-wing UAV when flying in windy conditions, the mathematical model needs to be modified so that the wind will be incorporated in the equations of motion.

If the atmosphere is at rest, the ground speed V_g is equal to the airspeed V_a [12]. But, aircraft generally fly in the presence of wind; hence, this lead to the following equation

$$V_g = V_a + V_w,$$

where V_w is the wind velocity vector.

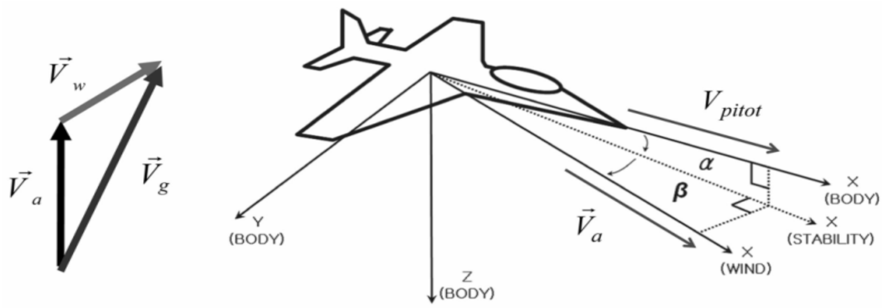

Fig. 3. Aircraft axes and angles

The aerodynamic forces and moments acting on the aircraft are dependent mainly on airspeed V_a, angle of attack α and side slip angle β (Fig.3). This implies that

$$V_a = \sqrt{u^2 + v^2 + w^2};$$

$$\alpha = arctan\frac{w}{u};$$

$$\beta = arcsin\frac{v}{V_a}.$$

The wind affects both the longitudinal and the lateral variables of the fixed-wing UAV contributing to its nonlinear, coupled and complex dynamics and due to such external disturbances the UAV can fail its mission. Hence, the equations of motion can be separated into a longitudinal and a lateral-directional.

Longitudinal variables. Restricting the flight path to the vertical plane by setting the lateral-directional motions to zero, the longitudinal variables are represented by $\dot{X}_{long} = [x, z, u, w, \theta, q]^T$.

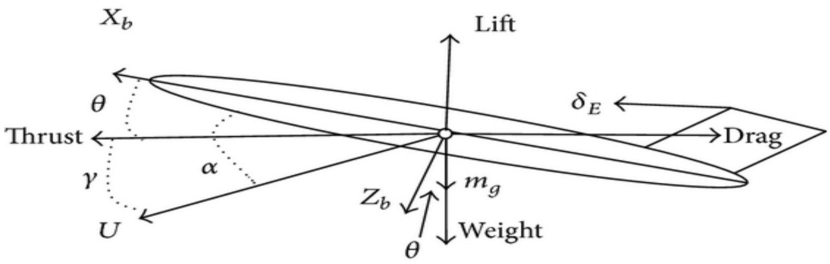

Fig. 4. Fixed-wing UAV longitudinal dynamics

The equations (1, 2, 4, 6, 8 and11) can be further transformed by replacing the body components of the velocity (u, w) by polar inertial components (V_a, γ) and by expressing the forces in the wind axes direction, (T, D, L) instead of (X_b, Z_b). Moreover, neglecting the range and the altitude and replacing the pitch angle by the angle of attack from the relationship $\alpha = \theta - \gamma$ (Fig.4), it gives

$$\dot{x} = V_a cos\psi cos\gamma + w_x,$$

$$\dot{z} = V_a sin\gamma + w_z,$$

$$\dot{V}_a = \frac{1}{m}[Tcos\alpha - D - mgsin\gamma],$$

$$\dot{\gamma} = \frac{1}{mV_a}[Tsin\alpha + L - mgcos\gamma],$$

$$\dot{\alpha} = \dot{\theta} - \dot{\gamma} = q - \frac{1}{mV_a}[Tsin\alpha + L - mgcos\gamma],$$

$$\dot{q} = \frac{M(\delta_e)}{I_{yy}},$$

where$\gamma$is the air mass referenced flight path angle; w_x and w_z are the north and altitude components of the wind.

Lateral-directional variables. The lateral-directional vector is also composed of six variables $X_{lat} = [y, v, \phi, \psi, p, r]^T$. With this, by introducing the wind parameters in equations (3, 5, 7, 9, 10, and 12) and by replacing the body components of the velocity v by polar inertial component β, it yields

$$\dot{y} = V_a sin\psi cos\gamma + w_y, \qquad \dot{\psi} = \frac{g}{V_a} tan\phi,$$

$$\dot{\beta} = -r + \frac{1}{Va}[gsin\phi cos\theta + \frac{Y_b}{m}], \qquad \dot{p} = \frac{I_{zz}\bar{L}}{I_{xx}I_{zz} - I_{xz}^2}(\delta_a),$$

$$\dot{\phi} = p + rtan\theta cos\phi, \qquad \dot{r} = \frac{I_{xx}N}{I_{xx}I_{zz} - I_{xz}^2}(\delta_r),$$

wherew_y is wind direction; Y_b ,$\bar{L}$ and$N$ are the aerodynamic side force, rolling, and yawing moment respectively. The aerodynamic forces and moments are computed through their non-dimensional coefficients as

$$Y_b = \frac{1}{2}\rho V^2 SC_y; \ \bar{L} = \frac{1}{2}\rho V^2 SbC_l; \ \ N = \frac{1}{2}\rho V^2 SbC_n.$$

where, ρ is the air density; S is the reference wing area; b is the wing span; and C_y,C_l and C_n are sideforce, rolling and yawing moment coefficients respectively.

The results of experimental studies. The problem of fixed-wing UAVs navigation in the presence of wind has been widely studied. Different approaches can be seen in the literature such as backstepping[13], nonlinear model predictive control (NMPC) [14], sliding modes control (SMC) [15], nested saturation [16], fuzzy control [17], H∞ control [18], dynamic inversion based control [19], etc.

In [20], authors have proposed a method to estimate wind velocity from the vehicle response and a path following controller in order to evaluate the effectiveness of this approach. In [21], Seleck et al. have suggested a novel method for trajectory planning for fixed-wing UAVs in the presence of wind, based on a modified Accelerated A* algorithm. In [22], authors have suggested a method to generate smooth trajectories that prioritize the wind energy harvesting for different cases of wind fields. They extended a nonlinear guidance method based on a look-ahead vector, particularly suitable for fixed-wing UAVs (Fig. 5). In [23], Kohno et al. have proposed a dynamic inversion method. A robust controller was applied to the linearized system and to suppress the influence of disturbance such as a gust of wind. Moreover, disturbance accommodating control (DAC) method and the Extended Kalman Filter (EKF) were employed to estimate nonlinear terms.

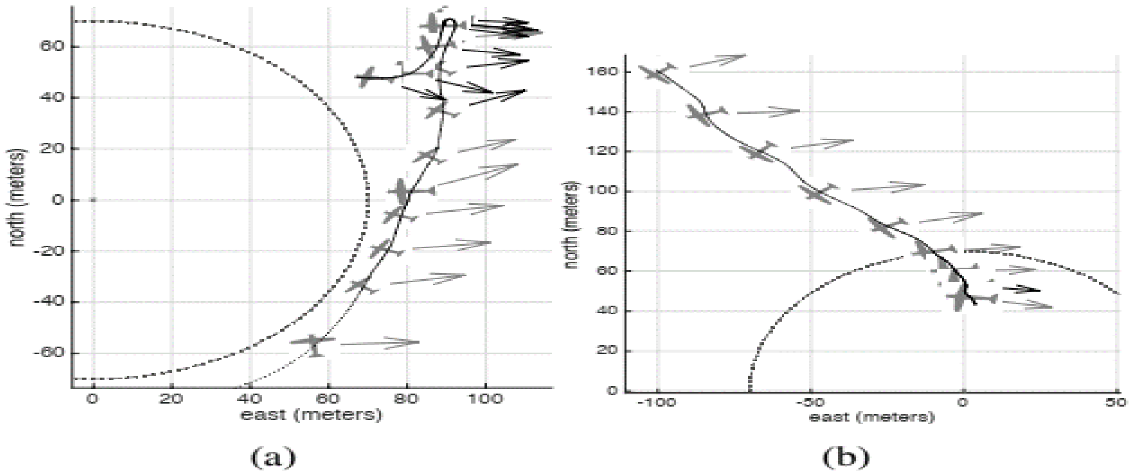

Fig. 5. Windy flight experiments [22]

Conclusion and future work. In conclusion, the paper presents a review on fixed-wing UAVs in the presence of external disturbances such as wind gust and wind shear. The theoretical aspects of a nonlinear model derivation for a fixed-wing UAV flying in the presence of wind are provided. An analysis of how wind affects the dynamics of flight has been presented. Furthermore, the nonlinear equations of the fixed-wing UAV have been extended so that the effects of the wind on the UAV performance were incorporated. Different approaches from other authors and their results have been presented.

Future work will develop a navigation control for a fixed-wing UAV using Analytical Design of Aggregated Regulators (ADAR) method and approaches of Synergetic Control Theory in order to accomplish different missions in presence of wind. Lastly, obtained results using ADAR method will be compared to different methods we mentioned in this article.

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