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AUTOMATIC TAKE-OFF OR LANDING PATH FOLLOWNG IN TURBULENT AIR FOR UAS

AN EKF BASED PROCEDURE

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Abstarct. *By using the Extended Kalman Filter (EKF) an accurate take-off or landing flight path following in turbulent air is performed. The tuned up procedure employs simultaneously two different EKF: the first one estimates gust disturbances, the second one affords to determine the necessary controls displacements for rejecting those ones. In particular, the first filter, by using instrumental measurements gathered in turbulent air, estimates wind components. The second one obtains command laws able to follow the desired flight path. To perform this task aerodynamic coefficients have been modified by adding entirely new derivatives or synthetic increments to basic ones whose might the kind of change required to reject disturbances. Such a procedure leads to a set of unknown stability and control parameters containing the required displacements of the controls. The modified aircraft parameters are determined by augmenting the aircraft's state. The filter estimates the new set of aircraft stability derivatives by using measurements made by the desired take-off or landing flight path parameters. Once the unknown stability and control derivatives have been determined, the obtained control displacements are used to perform an accurate path following in turbulent air. Obviously, the obtained control laws are adaptive since they depend by either the characteristics of the disturbance or the desired flight path. The proposed procedure requires low computational power, therefore it is particularly suited for UAS, besides being simple to implement on board it may be successfully employed on low cost platforms.*

1 INTRODUCTION

As it is well known since 1960 the Extended Kalman Filter has been widely employed in many engineering areas such as, for example, aerospace and aeronautics [1], autonomous or assisted navigation and so on [2]. In particular, it has been used to solve problems related to the filtering of variables corrupted by noise, state variables estimation, disturbance estimation, parameters estimation and so on.

In aerospace application a wide set of applications concerns identification techniques of aircraft's stability and control parameters from flight data in post flight analysis [3-5], on-line estimation of stability derivatives [6-10] and on-line estimation of non-measurable performance parameters of aircraft [11]. For reconfigurable flight control systems, the observer/Kalman filter is also applied for on-line system identification of accurate, locally linear, dynamic models of nonlinear aircrafts [12].

Another set of applications is devoted to the estimation of wind components. Mulgund [13] designs an EKF to estimate state and wind velocity for a subsonic jet transport aircraft in symmetrical flight in wind shear. In Williams [14] estimation of both states and wind intensity is performed for a tethered kite used for wind energy extraction purposes. Alonge et al. [15] design an EKF in order to estimate both longitudinal variables and wind velocities for a non-conventional UAV flying in turbulent air.

In this paper an innovative application of the EKF is proposed. Instead of using the EKF to estimate wind components or aircraft parameters, the EKF is used to achieve an accurate take-off or landing path following. To perform this task aerodynamic coefficients have been expressed by means of a new set of stability and control derivatives. Such a set is formed by entirely new derivatives and by adding synthetic increments to basic ones. These increments contain the required variations of the displacements of the controls to reject the disturbances. Since two EKFs are simultaneously employed. The first one, by using instrumental measurements gathered in turbulent air, estimates both aircraft states and disturbances. The obtained wind velocity components are inserted into the second EKF. The augmented state of such a filter is formed by both the aircraft state in turbulent air and the unknown set of the modified aircraft parameters. The measurements of the second filter are the desired flight path characteristics. In this way the filter is forced to estimate the unknown modified parameters (containing the displacements of the controls) by using the desired outputs. So it is possible to identify both the aircraft modified parameters and the control actions to execute for path tracking.

Therefore, the proposed procedure allows to perform an accurate path following for aircraft flying in turbulent air.

In the present paper only flight paths laying into the vertical plane are taken into account. However the proposed procedure is absolutely general, therefore it may be easily extended to three dimensional take-off or landing procedure.

The present paper is organized as follows. Section 2 explains the proposed procedure to perform the automatic take-off/landing. Section 3 contains the simulation results, which have been obtained by applying the procedure to an UAS. Such section also describes the perturbations that have been injected into the system to test the suggested procedure. Finally a discussion is presented into Section 3. Section 4 concludes the paper and describes the advantages of the tuned up procedure highlighting that such a procedure should be usefully employed to perform a precise path tracking of any Unmanned Vehicles.

2 PROPOSED PROCEDURE

As stated previously, the aim of present work is to perform a precise flight path on vertical plane, so only longitudinal equations of motion are considered. In the used 3 DoF model, the controls are elevator (δ_e) and throttle (δ_{th}) displacement.

The proposed on-line procedure, to perform the path following in turbulent air, is formed by the following steps:

1. Estimation of disturbances via a first EKF (wind components determination);
2. Insertion of the estimated wind components into the predictor of a second EKF;
3. Estimation, by using the second EKF, of modified aircraft parameters;
4. Determination (by means of modified parameters) of both the elevator and throttle positions;
5. Application of the determined control action to the aircraft.

The schematic block of the outlined procedure is shown in Figure 1.

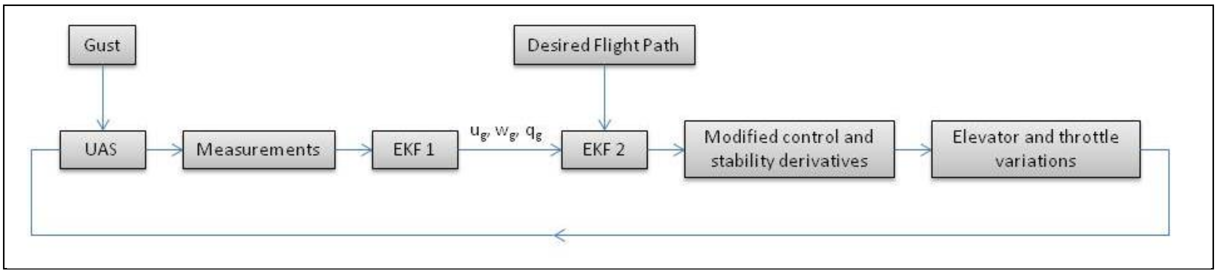

Figure 1: Schematic block of the proposed procedure

As formerly outlined, the first step of the flight path following procedure is the estimation of the disturbances. An EKF has been tuned up to determine the wind components.

As it is well known the structure of the EKF is formed by a predictor and a corrector. These ones work as shown in Figure 2.

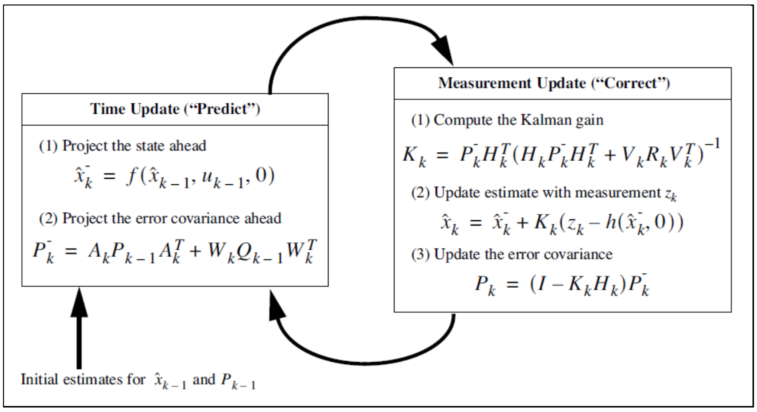

Figure 2: Operations of the Extended Kalman Filter from [16]

The corrector of such a filter employs a set of measurements gathered in turbulent air. The selected measured variables are:

$$Z = [V, q, \vartheta, x_E, h]^T$$

where V is the airspeed, q is the pitch rate, ϑ is the angle of elevation, x_E is the spatial coordinate of the center of mass and h is the altitude of the aircraft.

Obviously:

$$\begin{gathered} V = \sqrt{\left(u + u_g\right)^2 + \left(w + w_g\right)^2} \\ \alpha = atan \frac{w + w_g}{u + u_g} \\ q = q + q_q \end{gathered} \tag{1}$$

with - (u_g, w_g, q_g) unknown wind components in body axes.

The predictor is constituted of an accurate non-linear mathematical model of the aircraft flying in turbulent air. The classical rigid body equations of motion in body axes have been used [17] by inserting the wind components into the aerodynamic forces and moments.

The state of the system is constituted by the six aircraft state variables in body axes and the wind components:

$$X = \left[u, w, q, \vartheta, x_E, h, u_g, w_g, q_g\right]^T \tag{2}$$

To estimate the disturbance the following equations are inserted into the predictor:

$$\begin{gathered} \dot{u}_g = 0 \\ \dot{w}_g = 0 \\ \dot{q}_g = 0 \end{gathered} \tag{3}$$

In this way no hypothesis has been made about wind dynamics and the filter is forced to estimate disturbances by using measurements.

The first EKF estimates the wind components. These ones, by using Eq. (1), are inserted into the predictor of the second EKF.

The corrector of such a filter uses, as measurements, the desired values of the state variables (characteristic variables of the desired flight path).

$$Z_d = \left[V_d, q_d, \vartheta_d, x_{E_d}, h_d\right]^T$$

In order to estimate the control action, the aircraft parameters have been modified by imposing:

$$\Delta\delta_e = k_1\alpha + k_2 q \tag{4}$$

$$\Delta\delta_{th} = k_3 h \tag{5}$$

In this way, the modified aircraft parameters are:

$$C_{L_{\alpha m}} = C_{L_\alpha} + C_{L_{\delta_e}} k_1 \tag{6}$$

$$C_{L_{qm}} = C_{L_q} + C_{L_{\delta_e}} k_2 \tag{7}$$

$$C_{M_{\alpha m}} = C_{M_\alpha} + C_{M_{\delta_e}} k_1 \tag{8}$$

$$\mathrm{C_{M_{qm}}} = \mathrm{C_{M_q}} + \mathrm{C_{M_{\delta_e}} k_2} \tag{9}$$

Since a completely new control derivative has been postulated:

$$C_{T_h} = C_{T_{\delta_{th}}} k_3 \tag{10}$$

Eqs. (6-10) represent a set of aircraft unknown parameters. In such a way the aircraft unknown augmented state vector is:

$$X = \left[u, w, q, \vartheta, x, h, c_{L_{\alpha m}}, c_{M_{\alpha m}}, c_{L_{qm}}, c_{M_{qm}}, \mathrm{c_{T_h}}\right]^T$$

To estimate the modified aircraft parameters, the following equations has been inserted into the predictor:

$$\begin{gathered} \dot{C}_{L_{\alpha m}} = 0 \\ \dot{C}_{M_{\alpha m}} = 0 \\ \dot{C}_{L_{qm}} = 0 \\ \dot{C}_{M_{qm}} = 0 \\ \dot{\mathrm{C}}_{\mathrm{T_h}} = 0 \end{gathered} \tag{11}$$

Because the modified aircraft parameters contain the elevator deflections and the throttle positions (Eqs. 4-10), the estimated values of these ones allow to determine the control laws.

It is noticeable that once the modified aircraft parameter have been determined, an adaptive control law has been obtained. In fact no hypothesis has been made about the modified parameters dynamics.

The filter is forced to determine these ones by using the desired values of the flight path characteristics which constitute the measurements data set.

Obviously the modified parameters are strictly related to both the desired flight path and the estimated wind components. In this way obtained control laws are adapted to either the desired flight path or the disturbances.

3 RESULTS AND DISCUSSION

The proposed procedure has been applied to an UAS that is a 1:5 scale model of the ultra-light aircraft N3-PUP.

Geometric characteristics and aerodynamic derivatives of the studied aircraft are showed into Table 1 and Table 2.

Mean chord **c**	0.24 m	Inertia moment $\mathbf{I_x}$	0.2369 kg m^2
Wing span **b**	1.86 m	Inertia moment $\mathbf{I_y}$	0.1080 kg m^2
Wing area **S**	0.4464 m^2	Inertia moment $\mathbf{I_z}$	0.3330 kg m^2
Mass **W/g**	2.5 kg	Inertia moment $\mathbf{I_{xy}}$	-0.0086 kg m^2

Table 1: Geometric characteristics

$C_{L_V} = C_{D_V} = C_{M_V}$	0
$C_{D_{\dot{\alpha}}} = C_{D_{\delta_e}} = C_{D_q}$	0
C_{L_α}	3.9984
C_{M_α}	-0.9196
$C_{L_{\dot{\alpha}}}$	1.3689
$C_{M_{\dot{\alpha}}}$	-3.4263
C_{L_q}	5.9449
C_{M_q}	-10.2831
C_{T_V}	-0.0988
$C_{L_{\delta_e}}$	0.1554
$C_{M_{\delta_e}}$	0.4029
$C_{T_{\delta_{th}}}$	1.5635*10^{-4}

Table 2: Aerodynamic derivatives

The following equation has been used to model the aircraft drag polar:

$$C_D = C_{D_0} + 0.007446\, C_L + 0.30061\, C_L^2 + 0.001625\, C_L^3$$

with $C_{D_0} = 0.049607$.

Before implementing the proposed procedure on board of the studied UAS, it has been tested in simulation environment. Various simulations have been performed in MatLab environment.

An accurate 3-DoF non-linear model of selected UAS has been built.

The model has been used:

1. as predictor into both the tuned up EKF;
2. to determine the aircraft state in turbulent air which constitutes the measurement set of the first EKF in simulation environment;
3. to test the goodness of the obtained control laws;

Obviously, once the procedure will be implemented on-board, following the scheme in Figure 1, the designed model will be employed simply to perform the item 1.

A take-off path has been chosen as desired path to obtain the measurement set for the second EKF. At the beginning of the simulation UAS is considered already at take-off speed. Then it flies until regular obstacle height with a climb composed by a flare (until the climb angle reach 0.1 rad) and a rectilinear climb until the cruise height of 32m.

Besides it has been imposed that:

- $V_{TO}=V_{cruise}$
- V=24.63m/s during the whole flight path

The desired flight path is shown in Figure 3.

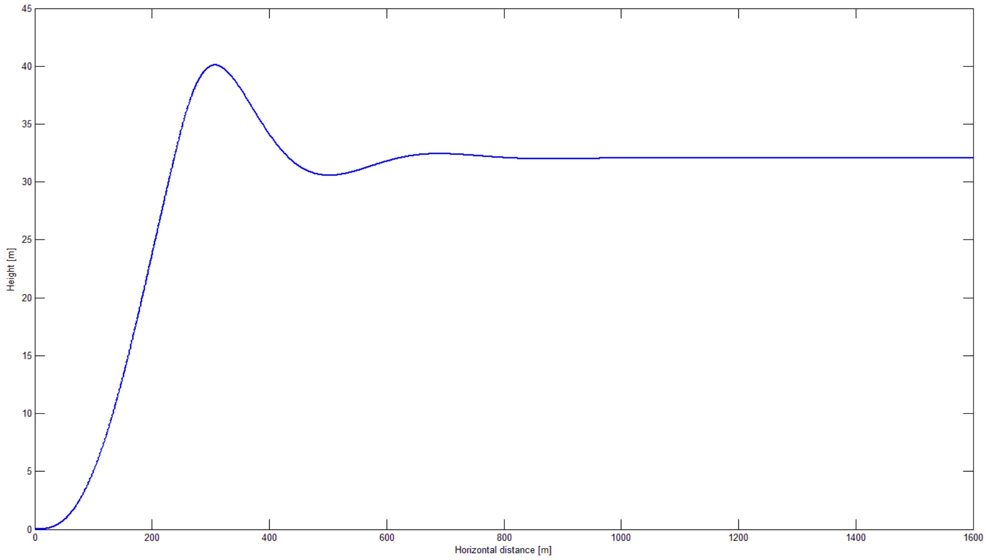

Figure 3: Desired take-off path

Many simulations have been performed by modifying wind speed components. In particular finite and infinite step components, harmonic disturbances, random disturbances have been injected into the UAS model.

In Figures 4-7 are reported, as example, obtained results with a finite step gust with the following characteristics:

$$u_{gust}=5m/s, \text{ duration } 3.5 \text{ sec.}$$

$$w_{gust}=1m/s, \text{ duration } 3.5 \text{ sec.}$$

The gust is inserted at the beginning of the flare.

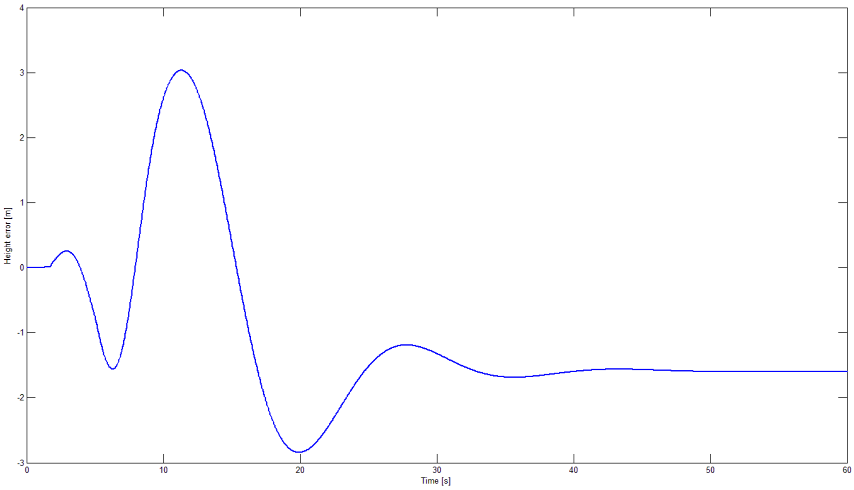

Figure 4: Height error

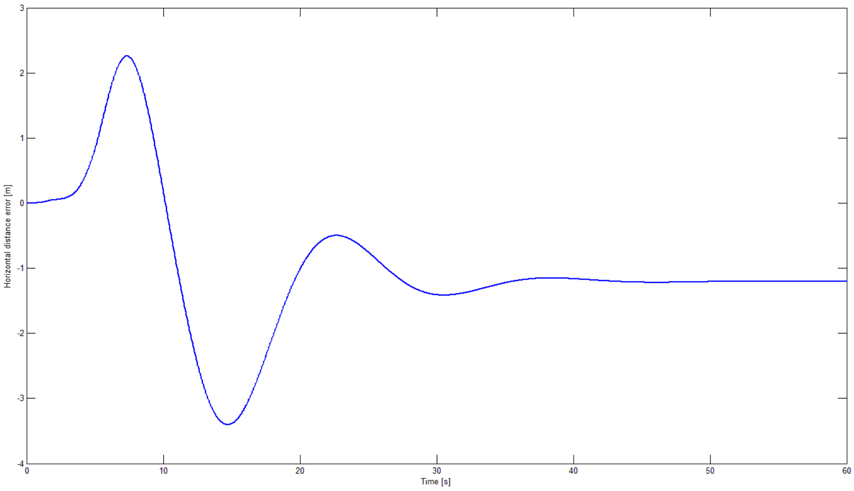

Figure 5: Horizontal distance error

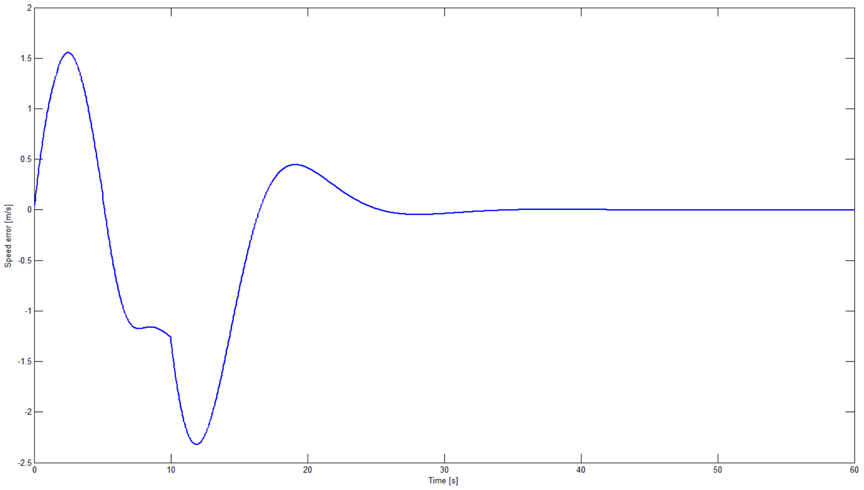

Figure 6: Speed error

Figures 4-5 show that the implemented methodology afford to perform the desired take-off path with a good precision even if in presence of noticeable wind gust. In fact the mean horizontal error is 1m during a 1600 m trajectory. At the same time, the mean height error in 1.10 m on a total height variation of 32 m.

Besides the speed constrain is perfectly verified, in fact, as shown in Figure 6, the mean speed error is 0.11 m/s.

Finally in Figure 7 is showed the comparison between the desired take-off path and the controlled one. In spite of the high values of the wind components ($u_g=20\%\ u_{UAS}$ and $w_g \cong w_{UAS}$), the path during flare is exactly flown, there is a small height error (1.5 m, less than 5%) at cruise height.

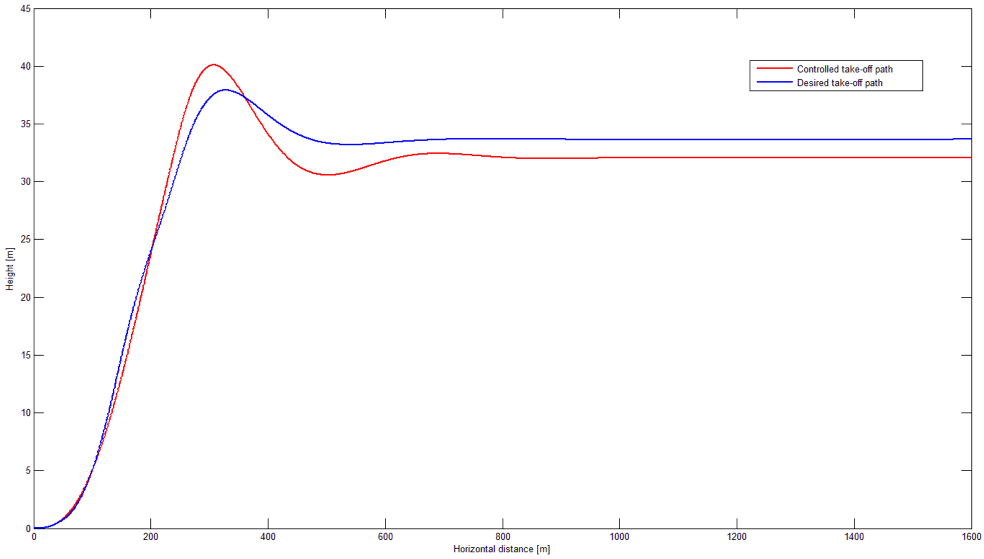

Figure 7: Desired VS controlled flight path

It is noticeable that the high precision of the take-off path has been obtained despite the injection of the disturbance at the beginning of the flare maneuver.

4 CONCLUSIONS

The present work has shown that, by an innovative employment of the EKF, it is possible to achieve both a precise flight path following and an adequate disturbance rejection in turbulent air.

The proposed approach requires low computational power, therefore it is particularly suited for UAS; besides being simple to implement on board. So it allows to design a fully automatic take-off/landing control system able to efficiently perform the guidance of UAS in turbulent air.

Finally, it is noticeable that the obtained control laws are automatically modified by changing either the desired flight path or the disturbance characteristics.

Because of the total generality of the discussed procedure, it may be applied to various kinds of Unmanned Systems in order to perform a precise path tracking.

Further development of the present paper is the extension of the proposed method to the six DoF model of aircraft.

At the present such a procedure is implementing on-board of a Remote Piloted Research Vehicle.

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