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Nonlinear Adaptive Observer for Unmanned Aerial Vehicle without GPS measurements.

Khadija Benzemrane, Gilney Damm and G.L Santosuosso

Abstract—The present work deals with the classical problem of speed estimation for a small 4 rotors helicopter drone based on acceleration, rotation angles and angular speed measurements only. This problem concerns indoors applications as well as outdoors applications close-by large structures. Small Unmanned Air Vehicles (UAV) are commonly used for inspection applications such as beneath bridges, water dams, industrial facilities and interior of large structures and pipes. An observer is designed based on nonlinear adaptive techniques providing a global exponential solution to this problem when exact measurements are available. Simulation results illustrate the observer performance and suggest that the estimator presents good robustness in the more realistic case of noisy acceleration measurements.

I. INTRODUCTION

This work addresses problem of speed estimation of a six degrees of freedom vehicle when only accelerations, angular speeds and angles are available for measurement. This problem appears in several applications of robotics and vehicle control. In most vehicle control applications, this problem may be solved by coupling GPS measurements to a Kalman Filter integration for short time periods. The resulting estimation works well as far as GPS precision and sample rate are acceptable for the proposed application. This is usually true when large size vehicles are considered, but not for small unmanned air vehicles (UAV). In the same way, this technique can't be used in indoors applications or even just close-by large structures. In both cases GPS signal is not available and the system must rely only on its local measurements. Even in the cases when GPS is available, the produced error may reach many meters and the sample rate may easily be around 1-2 Hz. While not critical when dealing with large airships, using GPS measurements is not acceptable in the stabilization of small drones less than 1 meter wide. In some cases, a solution may be provided using D-GPS measurements. This has some drawbacks since such devices are in general very expensive; large and heavy; only available around a small region about 500

meters radius, and for these reasons this technique is not considered in this work.

An other well known approach is the use of vision based controllers [5]. The main drawback of this method is the large amount of computer resources needed. It is not possible to run such vision algorithms in the very small micro-controllers used in small UAVs. One solution could be to use remote computers at a land base to perform part of the algorithms. This solution is usually not applied first by the time delay associated to this procedure, remote computing and communication, and second by the danger of losing the contact and as a consequence losing stability. Vision can be used for path planning, in a hierarchical display where a slow controller gives path planning references to a fast stabilizing one.

The recent results in non-linear observers have made possible to apply those techniques to small UAVs. The increasing interest in such techniques is well illustrated by the large number of recent works in this field as (see [4], [11] and [12]). The present work follows this way mainly based in the recent theoretical results presented in [9]. These observer's design strategies based on nonlinear adaptive control were used in some previous results where different observers were proposed to deal with the speed estimation problem [3]. Those algorithms are very interesting but may be complicated to implement in small microcontroller. This was the main motivation to develop more simple observer. Furthermore, the present observer is also faster and simpler to tune.

The proposed scheme is applied to a 4 rotors helicopter robot shown in Fig. 1 - produced to operate in an urban environment at the Laboratoire IBISC - CNRS, Université d'Evry, which is not equipped with GPS related devices and relies on the Inertial Measurement Unit only that provides accelerations, angles and angular speeds of the drone.

The simulation results obtained on the model of the drone -even in the presence of noise- are very promising, and will be soon implemented on the physical prototype. It is important to notice that the proposed scheme is very simple to implement and represents light computation burden. This will be very important for the following implementation steps. The proposed algorithm must be able to run in rather small micro-controllers such as allow a stabilizing controller based only on local measurements.

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Section II states the problem and describes the drone model. Section III introduces the observer scheme as well as a sketch of estimation convergence proof. In section IV some simulations are presented to illustrate the observer performances, indicating good robustness toward measurement noise, and to compare it with an Extended Kalman Filter. Finally in section V conclusion remarks and future steps of this work will be presented.

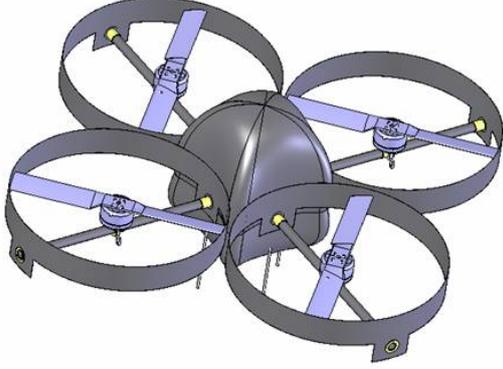


Fig. 1. Representation of the UAV

II. PROBLEM FORMULATION

The motion of a four rotor aerial robot can be described by the following equations (see [1]).

$$\begin{aligned}
\dot{x} &= \cos\theta \cos\psi u \\
&\quad + (\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi) v \\
&\quad + (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) w \\
\dot{y} &= \cos\theta \sin\psi u \\
&\quad + (\sin\phi \sin\theta \sin\psi + \cos\phi \cos\psi) v \\
&\quad + (\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi) w \\
\dot{z} &= -\sin\theta u + \sin\phi \cos\theta v + \cos\phi \cos\theta w
\end{aligned} \tag{1}$$

$$\begin{aligned}
\dot{\phi} &= p + (\sin(\phi) q + \cos(\phi) r) \tan(\theta) \\
\dot{\theta} &= \cos(\phi) q - \sin(\phi) r \\
\dot{\psi} &= (\sin(\phi) q + \cos(\phi) r) \cos(\theta)^{-1}
\end{aligned} \tag{2}$$

$$\begin{aligned}
I_{xx}\dot{p} &= l_b k_T (\omega_1^2 \cos\beta_1 - \omega_3^2 \cos\beta_3) \\
&\quad - q I_r (\omega_1 \cos\beta_1 + \omega_2 + \omega_3 \cos\beta_3 + \omega_4) \\
&\quad - k_M (\omega_1^2 \sin\beta_1 + \omega_3^2 \sin\beta_3) - (I_{zz} - I_{yy}) r q \\
I_{yy}\dot{q} &= -(I_{xx} - I_{zz}) p r - r I_r (\omega_1 \sin\beta_1 + \omega_3 \sin\beta_3) \\
&\quad + p I_r (\omega_1 \cos\beta_1 + \omega_2 + \omega_3 \cos\beta_3 + \omega_4) \\
&\quad + l_b k_T (\omega_2^2 - \omega_4^2) + u_G k_T (-\omega_1^2 \sin\beta_1 + \omega_3^2 \sin\beta_3) \\
I_{zz}\dot{r} &= -(I_{yy} - I_{xx}) p q - l_b k_T (\omega_1^2 \sin\beta_1 - \omega_3^2 \sin\beta_3) \\
&\quad + k_M (\omega_1^2 \cos\beta_1 - \omega_2^2 + \omega_3^2 \cos\beta_3 - \omega_4^2) \\
&\quad + q I_r (\omega_1 \sin\beta_1 + \omega_3 \sin\beta_3)
\end{aligned} \tag{3}$$

$$\begin{aligned}
\dot{u} &= -q w + r v - g \sin\theta \\
&\quad - \frac{k_T}{m} (\omega_1^2 \sin\beta_1 + \omega_3^2 \sin\beta_3) \\
\dot{v} &= -r u + p w + g \sin\phi \cos\theta \\
\dot{w} &= -p v + q u + g \cos\phi \cos\theta \\
&\quad - \frac{k_T}{m} (\omega_1^2 \cos\beta_1 + \omega_2^2 + \omega_3^2 \cos\beta_3 + \omega_4^2)
\end{aligned} \tag{4}$$

where $\eta_1 \triangleq [x \ y \ z]^T$ is the position vector represented in the global reference frame, $\eta_2 \triangleq [\phi \ \theta \ \psi]^T$ is the Euler angles vector represented in the global reference frame (roll pitch and yaw respectively), $\nu_1 \triangleq [u \ v \ w]^T$ is the speed vector represented in the local reference frame (surge, sway and heave respectively) and $\nu_2 \triangleq [p \ q \ r]^T$ is the angular speed vector represented in the local reference frame. In this model, the control input vector is $\Omega = [\omega_1 \ \omega_2 \ \omega_3 \ \omega_4 \ \beta_1 \ \beta_3]^T$ where ω_i , $i = 1 \dots 4$, are the angular speed of the 4 rotors, and β_1 and β_3 represent the orientation of the rotors 1 and 3.

The constants k_T and k_M respectively are the constants relating rotor speeds to resulting thrust and torque, l_B is the length of each drone's arm, and I_r is the rotor's inertia moment constant.

This vehicle is only equipped with an Inertial Measurement Unit (IMU) which provides the orientation, angular velocities and acceleration of the drone. In this context, defining the system state vector $X = [\phi, \theta, \psi, p, q, r, u, v, w]^T$ and the measurement output $y = [\phi, \theta, \psi, p, q, r, \dot{u}, \dot{v}, \dot{w}]^T$, equations (3)-(5) can be rewritten as :

$$\begin{cases} \dot{X} = f(X, \Omega), & X \in \mathbb{R}^9 \\ y = h(X, \Omega), & y \in \mathbb{R}^6 \end{cases} \tag{5}$$

where $f : \mathbb{R}^9 \times \mathbb{R}^6 \rightarrow \mathbb{R}^9$ and $h : \mathbb{R}^9 \times \mathbb{R}^6 \rightarrow \mathbb{R}^6$ are smooth functions depending on the states and the control input $\Omega = [\omega_1, \omega_2, \omega_3, \omega_4, \beta_1, \beta_3]^T$. The measured accelerations \dot{u} , \dot{v} , \dot{w} are expressed as functions of X and Ω via (5).

Definition 1: Let G denote the set of all finite linear combinations of the Lie derivatives of h_1, \dots, h_p with respect to f for various values of $u = \text{constant}$. Let dG denote the set of all their gradients. If we can find n linearly independent vectors within dG , then the system is **locally observable**.

If one can find n linearly independent vectors within dG , then the nonlinear system is said to be **locally observable** ; the observability matrix is given by :

$$\vartheta = \begin{pmatrix} L_f^0 h \\ \dots \\ L_f^{p-1} h \end{pmatrix}$$

The system is locally observable if ϑ has full rank.

In the case of system we consider, the observability matrix has full rank if and only if $(p(t), q(t), r(t))^T$ are not identically equal to $(0, 0, 0)^T$. In the case of $p(t), q(t)$ and $r(t)$ equal to zero, $\text{rank}(\vartheta)$ is 6 and the system is not observable anymore.

As a consequence, the control algorithm that the angular speeds $[p, q, r]^T$ has to track bounded and non vanishing reference trajectories to guarantee the observability of system 5

The paper objective may be stated as : to present an observer designed to provide an estimation of the unmeasurable state variable ν_1 , based on the measurable variables $\eta_2, \dot{\nu}_1$ and given by the standard sensors embeded in the drone. The proposed algorithm will be compared to an extended Kalman filter. In section IV, simulation results illustrate the performances of the proposed observer.

III. OBSERVER DESIGN

In this section, we study the observability of the system described by equations (3) - (5). We also describe the estimation strategy following the techniques presented in [8] and [9] as well as an outline of its stability proof.

We now consider the system (5). It can be rewritten as :

$$\dot{\nu}_1(t) = A(t)\nu_1(t) + b(t) \quad (6)$$

where A, b and y are defined by

$$A(t) = \begin{bmatrix} 0 & r & -q \\ -r & 0 & p \\ q & -p & 0 \end{bmatrix} \quad (7)$$

$$b(t) = \begin{bmatrix} -g \sin\theta - \frac{k_T}{m}(\omega_1^2 \sin\beta_1 + \omega_2^2 \sin\beta_3) \\ g \sin\phi \cos\theta \\ g \cos\phi \cos\theta - \frac{k_T}{m}(\omega_1^2 \cos\beta_1 + \omega_2^2 + \omega_3^2 \cos\beta_3 + \omega_4^2) \end{bmatrix}$$

We introduce an estimate of the linear velocity

$$\hat{\nu}_1 = \begin{bmatrix} \hat{u} \\ \hat{v} \\ \hat{w} \end{bmatrix}$$

along with a filter vector state $\zeta \in \mathbb{R}^3$ that satisfy the differential equations :

$$\dot{\zeta} = -c\zeta + \underbrace{[\dot{\nu}_1 - b(t)]}_{A\nu_1} - A\hat{\nu}_1 \quad (8)$$

and

$$\dot{\hat{\nu}}_1 = \hat{\nu}_1 + \Lambda A^T \zeta \quad (9)$$

where $c > 0$ and Λ is the (diagonal) adaptive gain.

The estimation error $\tilde{\nu}_1 \triangleq \nu_1 - \hat{\nu}_1$ then satisfies the following equation :

$$\dot{\tilde{\nu}}_1 = -\Lambda A^T \zeta \quad (10)$$

The observer described by the following equations :

$$\begin{cases} \dot{\zeta} &= -c\zeta + A\tilde{\nu}_1 \\ \dot{\tilde{\nu}}_1 &= -\Lambda A^T \zeta \end{cases}$$

guarantees exponential convergence to zero of estimation error under some conditions on matrix A that will be discussed.

Proof:

The stability proof is standard and follows Lyapunov techniques. Consider the Lyapunov function :

$$V = \frac{1}{2}\zeta^T \zeta + \frac{1}{2}\tilde{\nu}_1^T \Lambda^{-1} \tilde{\nu}_1 \quad (11)$$

$$(12)$$

By computing the time derivative of V , we have :

$$\begin{aligned} \dot{V} &= -c\|\zeta\|^2 + \zeta^T A\tilde{\nu}_1 + \tilde{\nu}_1^T \Lambda^{-1} (-\Lambda A^T \zeta) \\ &= -c\|\zeta\|^2 + \tilde{\nu}_1^T A^T \zeta + \tilde{\nu}_1^T A^T \zeta \\ \dot{V} &= -c\|\zeta\|^2 \end{aligned} \quad (13)$$

The previous equations imply that $\|\zeta\|$ and $\|\tilde{\nu}_1\|$ are bounded. As a consequence, ζ is also bounded, and then

$$\ddot{V} = -c\zeta \dot{\zeta}$$

is bounded. As a consequence \dot{V} is uniformly continuous, and according to Barbalat's Lemma, since $V \geq 0$, \dot{V} tends to zero.

This in turns implies, from (13), that ζ also converges to zero. Then, according to (10) and the convergence of ζ to zero, results that $\dot{\tilde{\nu}}_1$ also converges to zero. Now, stating the assumption that \dot{A} is also bounded, it is shown using the equation:

$$\ddot{\tilde{\nu}}_1 = \Lambda(A^T \dot{\zeta} + \dot{A}^T \zeta)$$

that $\ddot{\tilde{\nu}}_1$ is also bounded and then $\dot{\tilde{\nu}}_1$ is uniformly continuous. As a consequence it can now be stated that $\tilde{\nu}_1$ converges to a constant, since $\dot{\tilde{\nu}}_1$ converges to zero.

From (8), since ζ converges to zero, and its forcing term $A\tilde{\nu}_1$ is uniformly continuous:

$$A\tilde{\nu}_1 = 0 \quad (14)$$

It was shown that $\tilde{\nu}_1$ converges to a constant, and as a consequence this equation has a unique zero solution if and only if the matrix $A(t)$ satisfies the persistency of excitation condition, which means that there exist

strictly positive constants α and T such that such that for any $t > t_0$:

$$\int_t^{t+T} A(\tau)A^T(\tau)d\tau \geq kI \quad (15)$$

where $k > 0$

Condition (15) implies that the only solution of equation (14) is $\tilde{v}_1 = 0$ ■

Previous arguments can ne summarized in the following

Proposition 1: The UAV described by (3)-(5) with output measurement satisfies the following conditions :

- 1) The matrix A given by (7) is bounded.
- 2) The matrix \dot{A} given by

$$A(t) = \begin{bmatrix} 0 & \dot{r} & -\dot{q} \\ -\dot{r} & 0 & \dot{p} \\ \dot{q} & -\dot{p} & 0 \end{bmatrix},$$

where $[\dot{p}, \dot{q}, \dot{r}]^T$ are defined in (4), is also bounded.

- 3) The persistency of excitation condition given by (15) is satisfied.

Then the observer (8), (9), (10) assures global asymptotical estimation of the unmeasurable states representing the linear velocities of the considered UAV.

Remark 1: Conditions 1, 2, 3 are easily satisfied since the controller assures the boundness of the angular speeds $[p, q, r]^T$ with bounded control magnitude.

Remark 2: Conditions 3 reflects the observability study presented in section II. As presented before, it can be easily verified since $[p, q, r]^T$ are not identically equal to zero in the considered time period. For instance, a small periodic orbit around the desired trajectory assures the persistency of excitation condition.

IV. SIMULATION RESULTS

In this section we illustrate the performances of the observer designed above to estimate the linear velocity of an UAV based on the measurable states (angles and angular velocities) and on the linear accelerations.

In all simulations, the estimations have initial conditions set to zero, while the desired states are time varying (and different from zero at $t = 0$). We have used the following parameters values:

TABLE I
SIMULATION PARAMETERS

| | |
|--------------------------------|--------------------------------|
| $m = 2.500Kg$ | $l_b = 23cm$ |
| $I_R = 10010^{-7}Kg m^2$ | $I_{xx} = 22493110^{-7}Kg m^2$ |
| $I_{yy} = 22261110^{-7}Kg m^2$ | $I_{zz} = 32513010^{-7}Kg m^2$ |
| $k_T = 10^{-5}N.s^2$ | $k_M = 910^{-5}N.s^2m$ |

I_R is the inertia moment of the rotating elements in the rotors, while I_{xx} , I_{yy} and I_{zz} are the diagonal terms of the body's inertia tensor. Finally k_T represents a coefficient related to the lift torque ($F \triangleq k_T\omega^2$) and k_M is the coefficient related to the drag torque ($M_D \triangleq k_M\omega^2$).

In Fig. 2 the orientations, angular speeds, and accelerations of the UAV are plotted. Small periodic orbits were considered in order to satisfy the persistency of excitation condition. To guarantee the stability of the physical system, some constraints must be satisfied: the angles have to be less than 0,1 rad (about 6 degrees) and the frequency of the needed oscilations must be less than 1Hz.

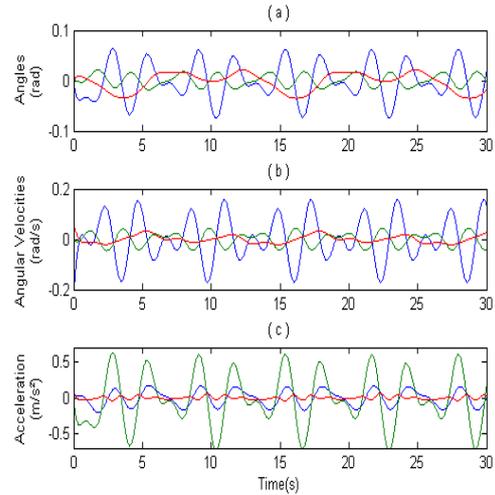


Fig. 2. (a) Angles (b) Angular Speed., (c) Acceleration

The time history of the three speeds to be observed is shown in Fig. 3a, and observer estimates in Fig. 3b, while estimation errors going exponentially to zero are shown in Fig. 3c.

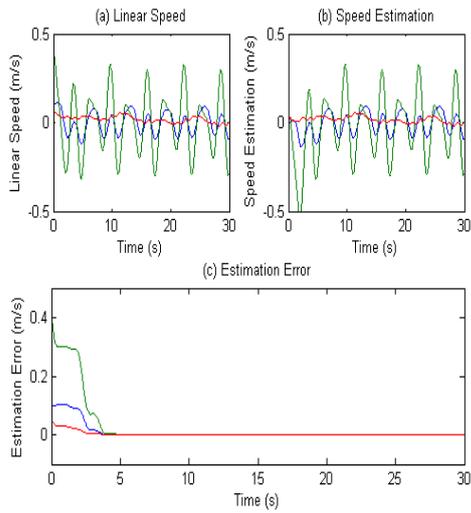


Fig. 3. (a) Linear Speed, (b) Speed Estimation, (c) Estimation Error

We have considered the observer in the case of additive measurement noise. The measured acceleration is presented in Fig. 4 where the noise μ is 10 percent of the measured acceleration. One may see in Fig. 5a the velocity estimated by the observer, while Fig. 5b describes the estimation time history, and Fig. 5c illustrates the observation error going exponentially to a residual set given by the noise amplitude.

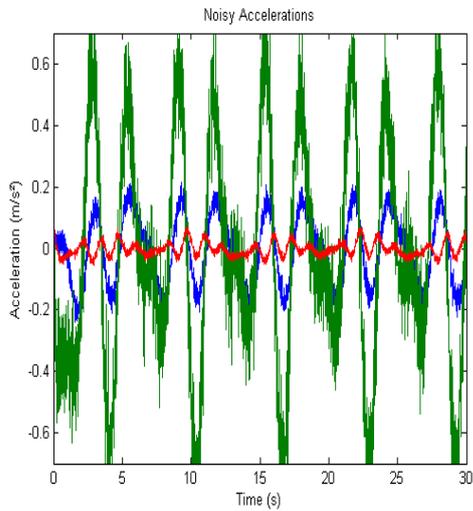


Fig. 4. Noisy acceleration

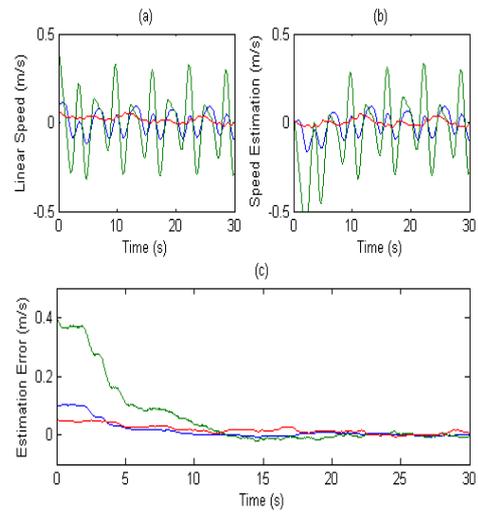


Fig. 5. (a) Angles (b) Angular Speed, (c) Acceleration

In order to evaluate the performances of the proposed observer, it has been compared to an EKF, an commonly used technique in the field of estimators.

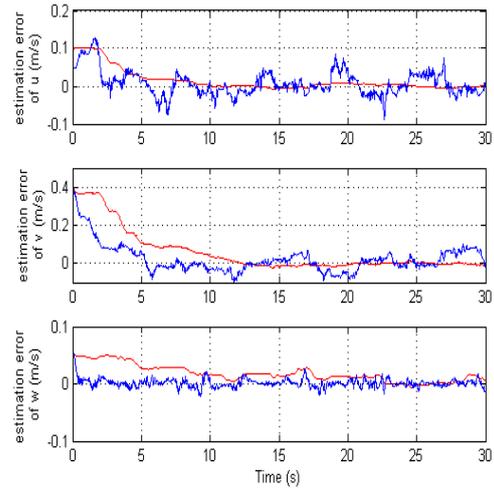


Fig. 6. Comparison of both observer

On Fig. 6, the estimation given by the adaptive observer is equivalent to the one given by Kalman filter estimation for the noisy acceleration considered in this section.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper the proposed observer scheme, based only on linear acceleration and angular measurements, assures global exponential estimation of the linear velocity of the UAV. This theoretical result is illustrated by computer simulations and presents good behaviour even in the presence of measurement noise. This good performance as well as the small size of the algorithm reinforces the idea of implementing it in the considered drone. In the following it will be studied the coupling of this observer with a control system in order to stabilize the drone and to perform tracking. Finally, the considered algorithms will be implemented in the 4-rotors drone available at IBISC laboratory.

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