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Wind Estimation by Unmanned Air Vehicle with Delta Wing

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***Abstract*— In this paper, an algorithm to estimate wind direction by using a small and light Unmanned Air Vehicle(UAV) called KITEPLANE was proposed. KITEPLANE had a big main wing which is a kite-like delta shape and, therefore, it was easy to be disturbed by wind. However, this disadvantage implies that the KITEPLANE has an ability to sense wind and that it is expected to use the KITEPLANE as a sensor for wind estimation. In order to achieve this feature, dynamics of the KITEPLANE under wind disturbance were derived and a numerical estimation method was proposed. Devices equipped on board were also developed and the proposed method was implemented. Results of an experiment showed the effectiveness of the proposed method.**

***Index Terms*— KITEPLANE, Unmanned Air Vehicle, Wind disturbance, Estimation.**

I. Introduction

Unmanned Air Vehicle(UAV)s are required in order for observation and rescue activities at dangerous areas such as volcanoes, areas stricken by earthquakes, fires and so on. From practical viewpoints, those UAVs are needed to have enough payload to carry equipments, to be able to fly for an enough time, to be small and light and to be carried easily to the place where they are launched or taken off. Especially, since it is necessary for UAVs to fly at low altitude in order to observe terrain, UAVs are likely to face a danger to fall because of irregular wind or obstacles. Therefore, sophisticated autopilot systems are necessary and UAVs should be less hazardous even if they crashed.

Automatic control for airplanes has a long history and these many control techniques are also able to be applied for autonomous UAVs. Since dynamics of airplanes are nonlinear, controllers based on linear theories are not sufficient for trim conditions which are different from the nominal trim condition. In order to overcome this difficulty, it is common to adopt robust control approaches, gain scheduling techniques and so on. For example, Khammash [1] applied H_∞ approach to control the longitudinal pitch motion under uncertainties of mass and center of gravity. Chu [2] proposed a controller based on gain scheduling for airplanes with multiple engines by using throttles only. Kaminer [3] [4] also proposed a tracking controller by utilizing gain scheduling. Shtessel [5] adopted a sliding mode controller taking bounded inputs into account. Hess [6] and Andrievsky [7] also considered bounded control inputs. Dynamics of UAVs are not only nonlinear but also nonminimum phase. Hauser [8], Benvenutti [9], Koo [10] [11] and Shim [12] have proposed control systems for nonlinear and nonminimum phase systems such as autonomous UAVs by approximate linearlization approach. Al-Hiddabi [13] concentrated to longitudinal maneuver and proposed a nonlinear output tracking method. Intelligent approaches such as artificial neural networks, fuzzy logic controllers [14] have been also utilized. Montgomery [15] proposed a learning method for a fuzzy-neural controller. Fernández-Montesinos [16] utilized fuzzy logic for guidance and control when an airplane was landing under windshear. Vaščák [17] adopted a fuzzy logic controller which was firstly proposed by Mamdani [18]. Sugeno [19] also proposed a fuzzy controller for an autonomous helicopter.

Various structure of UAVs have been also studied. Helicopters have been studied widely(e.g. [19], [15] [10], [20], [11], [12]) in spite of its complex dynamics because it is able to hover or stop in the air. It is also significantly important to make UAVs small and light. Grasmeyer [21] developed a Micro Air Vehicle(MAV) named black widow and Wu [22] proposed a MAV whose wing span was smaller than 4cm. Deng [24] and Schenato [25] studied small MAVs inspired from insects. Micro devices for small UAVs are also important and Lyshvski [26] [27] studied special control surfaces for MAVs.

In this paper, an UAV which is not only small and light but also has large payload is considered. The UAV is named as KITEPLANE [28], [29] because its main wing which is the largest component has a kite-like delta shape (Fig.1). Because the main wing is made of cloth, it is light and flexible. Therefore, the main wing could be large without making the airplane heavy as for rigid fixed wings. This implies that the KITEPLANE is able to be light and to have large payload simultaneously. Owing to the flexibility of the wing, the airplane is rather safe and robust even when it crashed into the ground. The center of the mass locates under the main wing and ailerons attached with dihedral angles. This makes attitude in a trim state rather stable and the motion is well-behaved. Therefore, the airplane may be controlled only by using slow-rate low-cost sensors such as GPS without a full attitude measurement. Nagata [29] proposed a trajectory following controller for the KITEPLANE based on a PID output feedback without attitude information and results of numerical simulations showed the effectiveness of the method under the absence

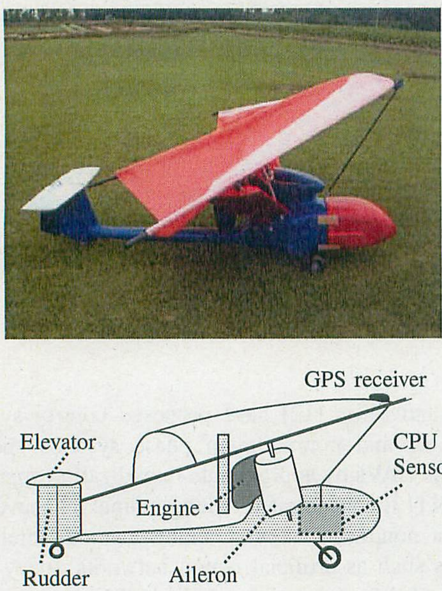


Fig. 1. KITEPLANE

of wind disturbance.

However, wind disturbance significantly deteriorates the performance of the path following of the KITEPLANE because of its large main wing. On the contrary, this implies that the KITEPLANE is sensitive to wind and it is able to be utilized to observe wind direction. Once the wind information is available, the performance of the autopilot system will be able to be improved. Furthermore, autonomous path planning taking wind into account will also be able to make efficient flight. Information about wind itself is also required by many applications such as a weather forecast, estimating the diffusion of pollution, preventing a fire and so on. Therefore, a method to estimate wind, especially its direction was considered in this paper. To this end, dynamics of the KITEPLANE under wind disturbance was derived first, and then a method to estimate parameters of wind was proposed which was the main contribution of this paper. For a small UAVs, Wu modeled the dynamics as ARX model and identified those parameters using measured results of flight test [23]. The model used in this paper was a nonlinear system and parameters were estimated online by solving an algebraic equation using measured data.

In order to show the validity of the proposed method, results of experiments were shown. For experiments, a small all-in-one computer system was developed. Results showed the effectiveness of the proposed method.

This paper is organized as follows. In the next section(Sec.II), the KITEPLANE and the computer system are shown and dynamics of the system is derived in the section III. The method to estimate wind is proposed in the section IV and results of experiments are shown in Sec.V. Then, conclusion follows (Sec. VI).

II. KITEPLANE

KITEPLANE is introduced briefly in this section. It's full length, wing span and height are $2,280$mm, $2,780$mm and $1,130$mm respectively. Weight is about 20kg. Payload of a KITEPLANE is more than 6kg. It is able to take off from a runway or a flat field, to fly more than $3,000$m above sea level and to land on the ground. The airplane has five wings, *i.e.* a delta-shaped main wing, a couple of ailerons, an elevator and a rudder. The main wing is fixed to the body. Servo motors are attached to ailerons, the elevator and the rudder as control surface actuators. The engine is installed in the center of the body and a servo motor controls its throttle.

An on-board computer system which will be referred as CPU is a PC/104 IBM-PC compatible embedded PC unit(Advantech, PCM-3370) and connected to A/D unit(Advantech, PCM-3718HG), GPS(Furuno Electric Co., GN-79) and FPGA system for a servo signal generator/receiver unit. Sensor unit connected to A/D unit consists of three accelerometers(Crossbow, CX02LF3), three gyroscopes(Murata Manufacturing Co., ENV-05F-03), a magnetometer(AP1 System, AM-21M) for an azimuth angle and two inclination-meter(Midori Precisions, UV-00H) for roll and pitch angles. All servo motors are controlled manually via radio control in manual mode, or automatically by an on-board computer system in auto mode. A block diagram of the system is shown in Fig. 2.

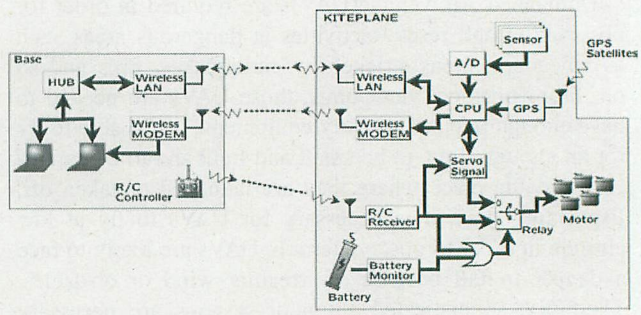


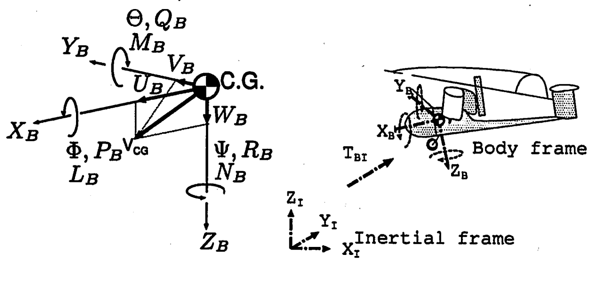
Fig. 2. Overview of KITEPLANE System

ART-Linux [30] which was a real time operating system based on Linux was used and the proposed system was implemented as a realtime task. GPS information was available once per a second and other sensory information were sampled each 50msec. GUI monitoring system which informs operators the stat of the airplane. TELNET protocol was used for forking tasks on CPU and FTP was used for transferring data among CPU and base computers as they were used in usual LAN.

III. Dynamics of KITEPLANE

Though the complete dynamics of the KITEPLANE are extensively complex, a simple rigid body model is useful which is shown in this section.

Let "body frame" be the Cartesian coordinate system which is attached to the airplane and whose origin is located at the center of the gravity (Fig. 3). X axis is aligned to the front of the body and Z axis is aligned to down when the airplane stays on the ground. Y axis is chosen as the body frame becomes right-hand. Let "inertial frame" be the Cartesian coordinate system which is fixed on the ground. X axis and Y axis of the inertial frame are aligned to East and North respectively. Z axis is toward perpendicular upright direction. Denote the velocity of



(a) Body Frame (b) Coordinate Transformation

Fig. 3. Body Frame and Inertial Frame

the airplane as $\boldsymbol{V_{CG}}$ and let U_B, V_B and W_B represent elements of $\boldsymbol{V_{CG}}$ with respect to the body frame. P_B, Q_B and R_B represent angular velocities with respect to the body frame. F_{XB}, F_{YB}, F_{ZB}, L_B, M_B and N_B denote aerodynamic forces and moments. Define Z-Y-X Euler angle from the inertial frame to the body frame as Φ, Θ, Ψ and denote a transformation matrix from the inertial frame to the body frame as $\boldsymbol{T_{BI}}(\Phi, \Theta, \Psi)$ or $\boldsymbol{T_{BI}}$ in short. It is easy to show that there exists an inverse of $\boldsymbol{T_{BI}}$, which will be denoted as $\boldsymbol{T_{IB}}$, as far as $\Theta \neq \pm\frac{\pi}{2}$. Denote m and $\boldsymbol{I}$ as mass of the airplane and an inertia matrix respectively. The position of the center of the gravity is denoted by X_I, Y_I, Z_I with respect to the inertial frame. Let $\boldsymbol{\lambda_B} = [U_B, V_B, W_B]^T$ and $\boldsymbol{\xi_B} = [P_B, Q_B, R_B]^T$.

Assume the wind effect can be modeled as forces and moments added to the system. Denote them as $\boldsymbol{\delta\omega_{FB}}$ or $\boldsymbol{\delta\omega_{RB}}$ respectively. Then, by using above notations, dynamics of the KITEPLANE can be given as follows:

$$m\frac{d}{dt}\boldsymbol{\lambda_B} + \boldsymbol{\xi_B} \otimes \boldsymbol{\lambda_B} = \boldsymbol{T_{BI}}\,[0, 0, mg]^T + [F_{XB}, F_{YB}, F_{ZB}]^T + \boldsymbol{\delta\omega_{FB}} \quad (1)$$

$$\boldsymbol{I}\frac{d}{dt}\boldsymbol{\xi_B} + \boldsymbol{\xi_B} \otimes \boldsymbol{I\xi_B} = [L_B, M_B, N_B]^T + \boldsymbol{\delta\omega_{RB}} \quad (2)$$

$$\frac{d}{dt}[X_I, Y_I, Z_I]^T = \boldsymbol{T_{IB}\lambda_B} \quad (3)$$

$$\frac{d}{dt}\begin{bmatrix} \Phi \\ \Theta \\ \Psi \end{bmatrix} = \begin{bmatrix} \frac{C_\Psi}{C_\Theta} & \frac{S_\Psi}{C_\Theta} & 0 \\ -S_\Psi & C_\Psi & 0 \\ C_\Psi\frac{S_\Theta}{C_\Theta} & S_\Psi\frac{S_\Theta}{C_\Theta} & 1 \end{bmatrix} \boldsymbol{T_{IB}\xi_B} \quad (4)$$

where C_Ψ, S_Ψ, C_Θ, S_Θ, and g represent $\cos\Psi$, $\sin\Psi$, $\cos\Theta$, $\sin\Theta$ and a gravitational acceleration. $\otimes$ denotes outer product. Since aerodynamic forces and moments are mainly caused by wings, $F_{XB}, F_{YB}, F_{ZB}, L_B, M_B$ and N_B are not only functions of the state of the airplane but also functions of control inputs which is denoted as $\boldsymbol{u}$. Refer [28], [29], [31] for further details.

The dynamics (1),(2),(3) and (4) are able to be summarized in a general nonlinear form:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{u}) + \boldsymbol{\delta w_B} \\ \boldsymbol{y} &= \boldsymbol{h}(\boldsymbol{x}), \end{aligned} \quad (5)$$

where $\boldsymbol{x} = [U_B, V_B, W_B, P_B, Q_B, R_B, X_I, Y_I, Z_I, \Phi, \Theta, \Psi]^T$, $\boldsymbol{y}$ are measurable outputs such as the position (X_I, Y_I, Z_I). $\boldsymbol{\delta w_B}$ represents wind disturbances with respect to the body frame. Since "wind frame" is omitted in the above modeling, the effect of attack of angle caused by wind is also included in $\boldsymbol{\delta w_B}$.

IV. Wind Estimation

The KITEPLANE is able to observe angular velocities, accelerations with respect to the body frame, and roll and pitch angles with respect to the inertial frame. X_B component of dynamics (5) can be written as

$$a_{XB}(t) = \boldsymbol{\Gamma}_0(\boldsymbol{x}(t))\boldsymbol{\Lambda}_0 + \delta w_{XB}(t), \quad (6)$$

where a_{XB}, $\boldsymbol{\Gamma}_0(\boldsymbol{x})$ and $\boldsymbol{\Lambda}_0$ represent the acceleration in X_B direction, a row vector of known nonlinear functions and a column vector of unknown parameters respectively. Denote the number of unknown parameters as r. Assume that constant wind is blowing only in the horizontal plane. $\boldsymbol{\delta w_B}$ can be approximated as

$$\boldsymbol{\delta w_B} = \boldsymbol{T_{BI}}(\boldsymbol{x}) \begin{bmatrix} w_X \\ w_Y \\ 0 \end{bmatrix}, \quad (7)$$

where w_X and w_Y are constant parameters. Let

$$\boldsymbol{\Gamma}(\boldsymbol{x}) = [\boldsymbol{\Gamma}_0(\boldsymbol{x}), T_{BI11}(\boldsymbol{x}), T_{BI12}(\boldsymbol{x})],$$

where T_{BIij} represents i, j element of $\boldsymbol{T_{BI}}$ and let

$$\boldsymbol{\Lambda} = \left[\boldsymbol{\Lambda}_0^T, w_X, w_Y\right]^T.$$

Then, (6) can be expressed as follows:

$$a_{XB}(t) = \boldsymbol{\Gamma}(\boldsymbol{x}(t))\boldsymbol{\Lambda}. \quad (8)$$

Though (6) gives an algebraic relation between the observed information and unknown parameters, it is not possible to solve $\boldsymbol{\Lambda}$ since (6) is under-determined.

Define a matrix $\boldsymbol{\Pi}$ which contains a time series of $\boldsymbol{\Gamma}$ as

$$\boldsymbol{\Pi}(t) = \begin{bmatrix} \boldsymbol{\Gamma}(\boldsymbol{x}(t-(n-1)T_S)) \\ \boldsymbol{\Gamma}(\boldsymbol{x}(t-(n-2)T_S)) \\ \vdots \\ \boldsymbol{\Gamma}(\boldsymbol{x}(t-T_S)) \\ \boldsymbol{\Gamma}(\boldsymbol{x}(t)) \end{bmatrix}, \quad (9)$$

where T_S represents the sampling period and n represents the number of sampled data. Similarly, define a vector $\boldsymbol{\Upsilon}$ which contains a time series of acceleration a_{XB} as

$$\boldsymbol{\Upsilon}(t) = \begin{bmatrix} a_{XB}(t-(n-1)T_S) \\ a_{XB}(t-(n-2)T_S) \\ \vdots \\ a_{XB}(t-T_S) \\ a_{XB}(t) \end{bmatrix}. \quad (10)$$

From (8), (9) and (10), the following holds.

$$\Upsilon(t) = \Pi(t)\Lambda. \quad (11)$$

If the rank of Π is r, Λ can be solved and wind parameters (w_X, w_Y) are able to be estimated. When $n = r$, Π is a square matrix and the estimated vector of Λ at time t, which is denoted as $\hat{\Lambda}$ can be computed by

$$\hat{\Lambda}(t) = \Pi^{-1}(t)\Upsilon(t)$$

as far as Π is not singular.

However it is not appropriate to use only r points since the assumption that Π is not singular is easily violated in practical situations. And because current computers even for embedded applications have rich computational resources, the number of stored sampled data can be increased more than r so as to make Π contain r linearly independent vectors. In this case, (11) becomes over-determined and only the optimal solution which makes the difference of left and right hand sides of (11) be minimum can be obtained. To this end, an iterative optimization method will be adopted below. Consider the error vector $E_\Lambda(t)$ which is defined as

$$E_\Lambda(t) = \Upsilon(t) - \Pi(t)\hat{\Lambda}(t). \quad (12)$$

$\hat{\Lambda}$ is updated by the following updating law,

$$\hat{\Lambda}(t+T_S) := \alpha\hat{\Lambda}(t) + \beta(t)E_\Lambda^T(t)\Pi(t)^T, \quad (13)$$

where α is a constant ($\alpha \leq 1$) and

$$\beta(t) = \beta_0 \frac{E_\Lambda^T(t)\Pi(t)^T\hat{\Lambda}(t)}{\|\Pi(t)^T\hat{\Lambda}(t)\|^2 + \delta} \quad (0 < \beta_0),$$

where δ is a small positive constant. The updating law(13) only guarantees the convergence of $\hat{\Lambda}$ to a some optimal solution when Υ and Π are constant vectors. However, by taking the number of stored data, or n, sufficiently large and if $x(t)$ varies '*enough*', $\hat{\Lambda}$ can be expected to converge to Λ. In order to avoid the divergence of $\hat{\Lambda}$, α and β_0 should be chosen appropriately.

V. Experimental Results

The proposed method was implemented on CPU which was introduced in Sec. II. The PID based autonomous autopilot system [29] was also implemented and the wind direction was estimated during the autopilot mode. Parameters used by the proposed method are summarized in Table.I.

TABLE I

Parameters of the Proposed Method

$n = 100$	$\alpha = 0.9995$	$\beta_0 = 0.95$	$T_S = 1$[sec]	$\delta = 0.001$

At the experiment, the airplane was taken off in the manual mode and then the autopilot system was turned on. After the automatic flight for about 10 minutes, it turned back to the manual mode and guided to land on the runway. Fig.4 shows hourly wind data measured by AMeDAS(Automated Meteorological Data Acquisition System) of Japan Meteorological Agency [32]. The experiment began at 12:37 noon when the wind was blowing from South-West at 4[m/sec] on the ground.

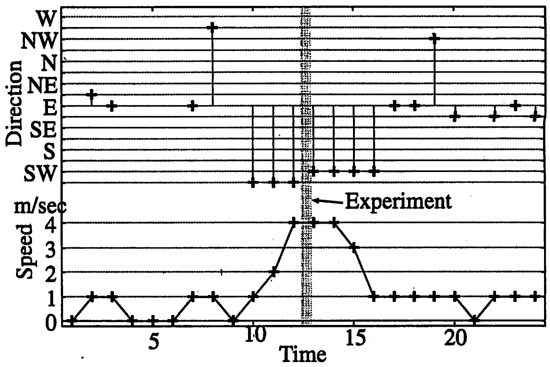


Fig. 4. Hourly Wind Data

Fig. 5 shows the flight path of the KITEPLANE. In Fig.5(a), top of the figure is North and right is East. The airplane flew around with following circles as normal flights though the flight path itself was not important for the proposed wind estimation method. In Fig.5(b), altitude of the airplane is shown. The airplane took off from the altitude 720m above sea level and it flew up to 925m. Velocities U_B, V_B and W_B which were required by wind estimation were computed as the difference of this GPS signal.

Sensory information used by the proposed method are shown in Fig.6. Fig.6(a) shows the acceleration a_{XB} and angular velocities of roll, pitch and yaw are shown in Fig.6(b),(c) and (d) respectively. Fig.6(e) and (f) show roll and pitch angles of the airplane measured by inclination-meters. Though all those signals were sampled at every 50msec, the method sampled signals once a second synchronizing to GPS signal.

Estimated results are shown in Fig.7. Parameters of wind, w_X and w_Y are estimated as shown in Fig.7(a) which shows both parameters were kept bounded and one converged to almost 0.5 and the other varied slowly. The estimated wind direction which was shown in Fig.7(b) converged to West South-West which corresponded to the direction reported by AMeDAS. Fig.7(c) shows that the residual, or the magnitude of the error vector E_Λ was kept small except two peaks at 200[sec] and 420[sec] when the airplane took off and landed. From above, it can be concluded that the proposed method worked well for this experiment.

VI. Conclusion

In this paper, the small UAV called KITEPLANE was utilized to estimate wind direction. Because the KITEPLANE has a large main wing, it has a disadvantage such that it is easily disturbed by wind. In this paper, this disadvantage was utilized in order to estimate wind

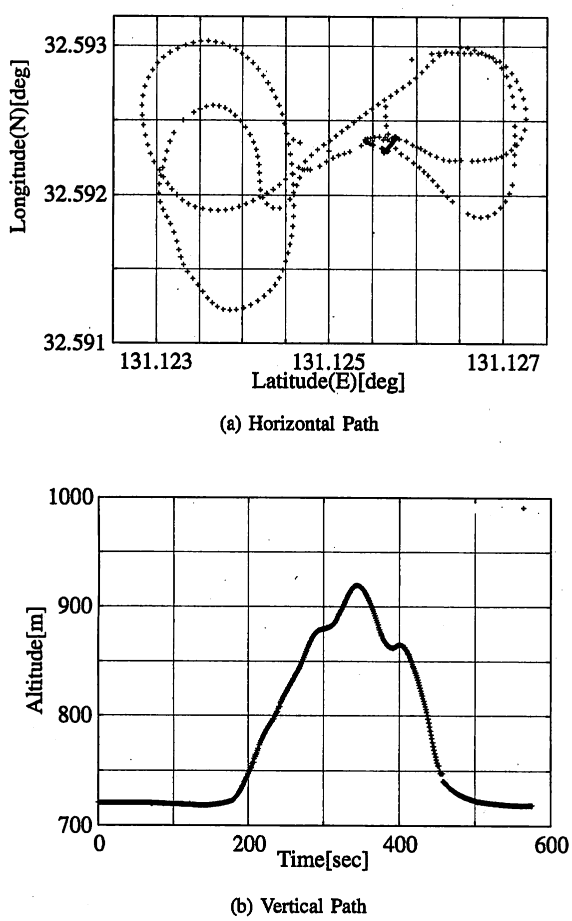


Fig. 5. Flight Path

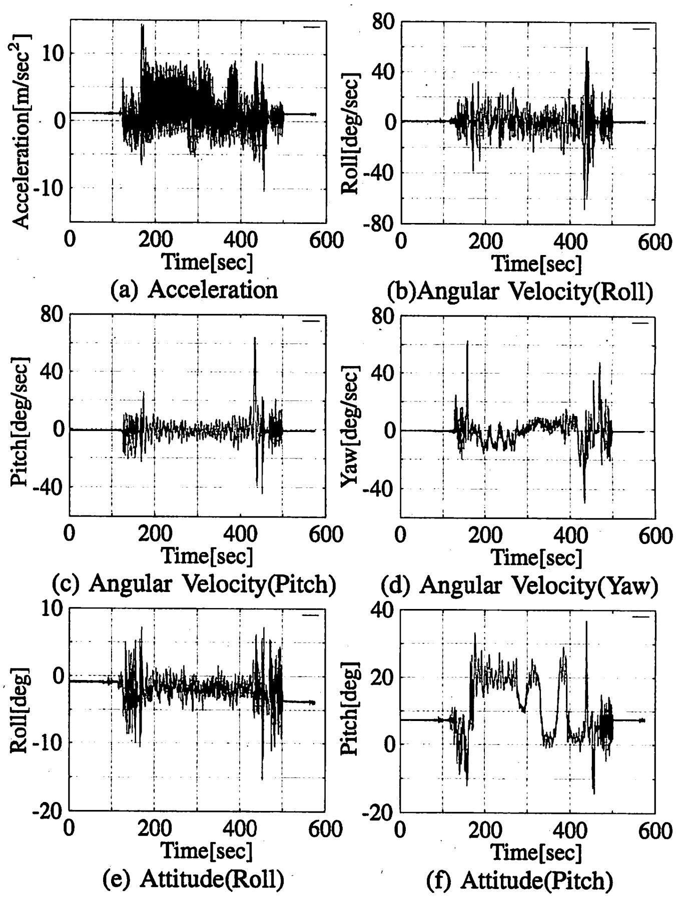


Fig. 6. Sensory Information

direction since this disadvantage could be interpreted as the KITEPLANE was sensitive to wind. For the wind estimation, the dynamical model was derived and the computational approach was proposed. Devices for experiments were also developed and the proposed method was implemented on the developed system. The result of an experiment showed the validity of the proposed approach.

For future works, autopilot system by utilizing the information about wind should was able to be estimated is needed to be developed, since the effect of wind is critical for practical uses of the KITEPLANE.

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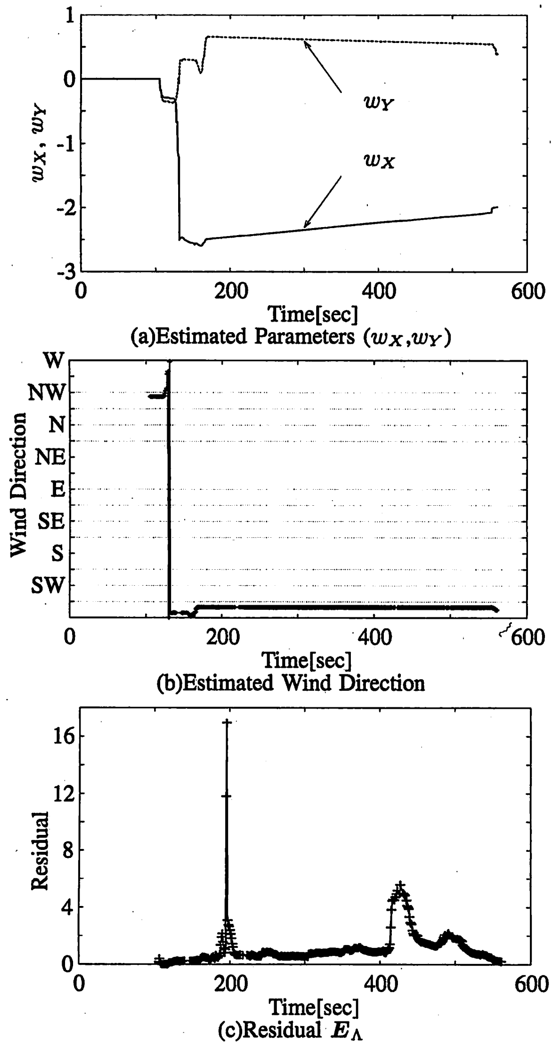

Fig. 7. Wind Estimation

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