DEVELOPMENT OF POSE ESTIMATION SYSTEM BASED ON DUAL CAMERA TECHNIQUES FOR PARAMETER IDENTIFICATION OF INDOOR MAV

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Abstract

An accurate pose estimation system is determinant to obtain a good parameter identification result. Vision-based measurement is an alternative method for UAV's pose estimation. However, with limited field of view and vision distance, the vision-based measurement is more suitable for a relatively small area or object like indoor MAV.

This work presents development of a vision based measurement system using Dual Camera Technique for 6- DOF pose estimation. The system consists of two outside-in video cameras with 30 fps of frame rate, four onboard markers, an image filtering and Direct Linear Transformation algorithm. The system is simulated using 3D software. A 2D pair images from both video cameras are then processed to reconstruct the position and orientation of the object.

A flight test scenario is virtually simulated to obtain parameters of aerodynamic and moment coefficient of a micro coaxial helicopter. The results show that a vision based measurements offers a relatively straight forward data processing to obtain the defined parameters.

1 Introduction

An accurate pose estimation system is determinant to obtain a good parameter identification result. The limited size, payloads, and the unavailability of global positioning system (GPS) data are the key challenges in indoor UAVs systems [1]. There had been a variety of indoor pose estimation systems developed for aerial vehicles [2]:

- Inertial solution. The most popular technique is the Inertia Measurement Unit (IMU). The IMU measures the accelerations and integrates them over time to obtain the orientation and position. It provides low-noise motion measurements with high sampling rate, but the pose gradually drifts due to the accumulative errors caused by the integration. Even with very light Micro Electro Mechanical Systems (MEMS) inertial sensors, drift-corrected hybrid tracking technology remains unsuitable for the payload for some UAVs.
- Magnetic solutions. The electromagnetic tracking device measures the relative pose of the target very accurately and has been used in many applications. Castillo et al. showed the successful pose estimation and control of a quad-rotor helicopter using an electromagnetic tracking sensor [3]. Electromagnetic has several advantages such as 6-DOF tracking and small sized sensor. However, this type of sensor is highly sensitive to electromagnetic noise, especially when the sensor is very close (typically less than 70cm) to the electric motors in a MAVs.

- Optical solution. Another popular class of the approaches in pose estimation of UAVs is the vision. Having cameras and landmarks on vehicles or on ground, the poses of the vehicles can be estimated. Various optical systems have been designed. Three approaches can be distinguished: (i) the outside-in, where cameras look at targets on the frame of interest, (ii) the inside-out, where the camera is on-board, and (iii) the hybrid based on a pair of ground and onboard cameras. Optical solution, especially the outside-in approach is very suitable for mini-UAVs and MAVs with limited payload because only light markers or Light Emitting Diodes (LED) are required to be mounted onboard.

The paper will discuss on the development of pose estimation system based on dual camera techniques using outside-in approach for identification of parameters of a micro coaxial helicopter. A virtual testing environment as well as helicopter motion will be developed prior to the use of the system.

2 Procedures and Methods

2.1 Pose Estimation Procedure

The pose estimation procedure starts from modeling the object and scenario, image recording, image processing, and finally the reconstruction of position and attitude of the model. In the image processing phase, MATLAB® 2010a software is used to detect and track the markers so that the coordinates of all markers are obtained over the time. The detection and the tracking of the markers is based on image binarization (thresholding) technique. Then by using conversion factor obtained from the calibration, the coordinates of markers in the image plane are converted into the world coordinates. The figure 1 below shows the operation procedures for this research as described above.

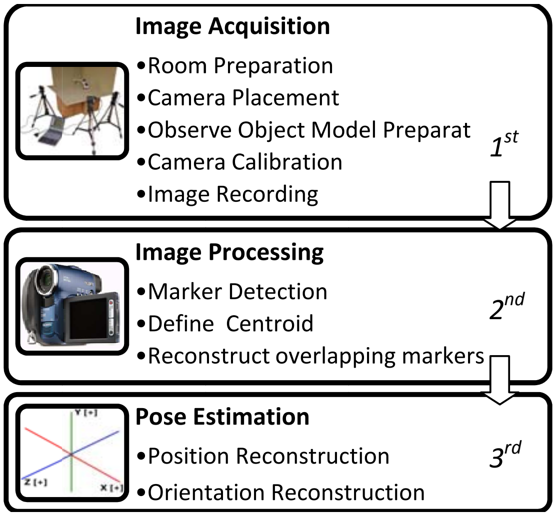


Fig.1 Pose estimation operational procedures

The minimum number of camera required to reconstruct 3D scene from 2D digital image is two [4]. This is due to the nature of the image formation process which consists of a projection from a 3D scene onto a 2D image. During this process the depth information is lost. The 3D point corresponding to a specific image point is constraint to be on the associated line of sight. From a single image it is not possible to determine which point of this line corresponds to the image point. If two (or more) images are available, then the three-dimensional point can be obtained as the intersection of the two lines of sights. This process is called triangulation.

2.2 Direct Linear Transformation (DLT) Method

There are a number of ways to solve the triangulation using either linear or non-linear techniques. The most commonly used camera calibration method is the Direct Linear Transformation (DLT) method originally reported by Abdel-Aziz and Karara (1971) [5]. The DLT method transforms image coordinates into object-space coordinates, as shown in figure 3. It establishes a relationship between digitized coordinates from the two or more camera views and corresponding coordinates in three-dimensional space. This method uses a set of control points whose object space/plane coordinates are already known. The control points are normally fixed to a rigid frame, known as the calibration frame.

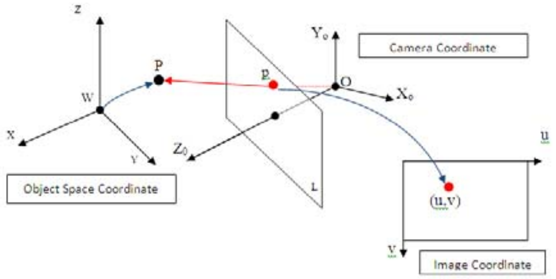


Fig.2 Transformation coordinate from image into object-spaced coordinate

An image defined in the figure above is considered to be a function of two real variables, f(x,y), where x and y are plane coordinates, and the amplitude of f at any pair of coordinates (x,y) is called the intensity or gray level of the image at that point. When x, y, and the amplitude values of f are all finite, discrete quantities, they are so-called a digital image. The amplitude values of each image then processed by sampling and digitization method to get the (u,v) coordinates.

Calibration is an important phase in vision based measurement to determine the accuracy of the measurement results. Several methods for calibration process usually performed using chessboard and the online Matlab® toolbox available from Caltech Institute as done by Tisse [6]. In this research, the DLT method was used for calibration. For 3D analysis, the calibration requires six or more non-collinear control points with known object coordinates.

3 Pose Estimation System

The developed system consists of image recording system, image processing system, and a system to locate the marker into world coordinate. Prior to image recording process, the calibration is conducted to obtain the conversion factor from image coordinate to world coordinate by using Direct Linear Transformation (DLT) method.

All scenarios construction and recording are done virtually using 3D animation software, named Autodesk® 3Ds Max® 2010. A PC with Intel® Core(TM) i5 2.80 GHz, 4 GB RAM, and 200 GB of storage, was used to perform the simulation.

SONY DCR-DVD101E camcorders model is used as virtual camera in this research. Its specification data was used to construct the virtual image. Since the camcorder use the NTSC system, frame rate recording capability was took to be NTSC standard, i.e. 30 fps. The output image is in RGB with 640 × 480 pixel resolution. One more important characteristic is the camera's field of view (FOV). The FOV determines the angular extent of a given scene that is imaged by a camera. It also determines how far the camera should be placed from identification area for capturing images. A camera's FOV can be measured horizontally, vertically, or diagonally. The SONY DCR-DVD101E camcorder lens has 43 mm of diameter. The FOV characteristics of this lens are 53 degrees of FOV in horizontal direction and 41 degrees in vertical direction.

There are several aspects for acceptable camera vision that affect camera placement. The aspects are resolution, focal length (f), FOV, visibility, angle of view, and prohibited regions [7]. The virtual flight test was simulated to be conducted inside a meeting room at Faculty of Mechanical and Aerospace Engineering building. The room dimension is 10 meter length, 7 meter wide, and 3 meter height.

Several studies were conducted to identify the best camera placement for minimizing error in the case of two view cameras method. According to Amat et al.[8], the error is a function of the angle between two cameras and the distance to the center point of identifying object. The minimum error is obtained when the angle between two cameras is 90 degrees.
Camera placement in the virtual environment is illustrated in figure 3. Study of the accuracy of the camera placement can be found in [9].

Following a study conducted by Gui et al [10], four marker will be used to obtain the model position and attitude information. The observed model will be modeled to have four 5 cm ball markers with four different colors. The four markers are placed in one square plane with 45 cm side.

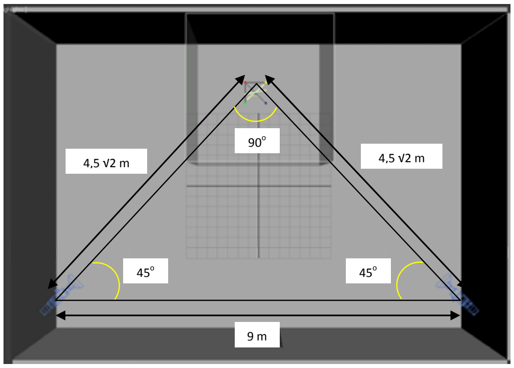


Fig.3 Camera placement in the virtual environment

Figure 4 below illustrates the observed object model.

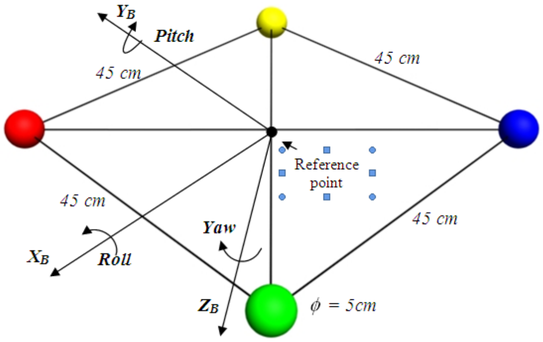


Fig.4 Observed object model

By obtaining the position of four markers, the reference point position as well as the model attitude with respect to inertial reference can be computed, *i.e.* X, Y, Z and ϕ, θ, ψ.

For a dynamic mathematical model, velocity and angular rate with respect to the body fixed reference will be needed. Hence, a transformation between inertial reference frame and body fixed reference frame is needed [10]. The transformation matrix of a translation and angular motion is defined below

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = R(n) \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{1a}$$

$$\Re(\eta) = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \tag{1b}$$

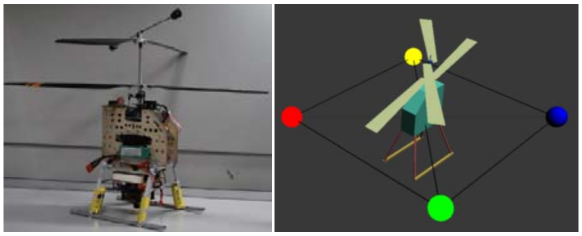
$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \Re_{2JB} \cdot \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{1c}$$

In which
$$\begin{aligned} -\pi &< \psi < \pi \\ -\pi/2 &< \theta < \pi/2 \\ -\pi &< \phi < \pi \end{aligned}$$

4 Simulated Flight Test for Parameter Identification

4.1 Simulated Model

The model used is a modified Lama 400D RC coaxial helicopter with a rotor diameter of 50 cm and weight of 800 gram. It has two counter rotating rotor located one above another and separated at a distance of 80 mm. On the lower rotor, a swash-plate system is used to control the pitch and roll of the helicopter through the mechanical linkages with the servo system. On the upper rotor, a fly-bar is attached to the rotor shaft, and driven at the same speed as the upper rotor but with 45 deg phase lead. The fly-bar acts as a second swash-plate.



(a) (b)

Fig.5 Micro coaxial helicopter (a) simulated model (b)

The mathematical model of coaxial helicopter is derived in [11] by combining rigid body dynamics and rotor dynamics which includes the flybar dynamics. The inputs-outputs of the equations of motion are:

- Inputs: rotor rotational speed for upper and lower rotor (ω_u, ω_l), and deflection angles of swash-plate for longitudinal motion and lateral motion $(\delta_{lon}, \delta_{lat})$.

- Outputs: velocity in body fixed reference frame *(u, v, w)*, angular rates in body fixed reference frame *(p, q, r)*, lower rotor and fly-bar flapping angles $(\alpha_l, \beta_l, \alpha_f, \beta_f)$, Euler angles (ϕ, θ, ψ), and position (x, y, z).

In this paper, estimation of linear parametric of aerodynamic forces and moment model in longitudinal mode will be described. For idealized longitudinal motion, the condition $\phi = 0$, $p = 0$ and $r = 0$ should be applied.

Equations of motion of the helicopter in longitudinal motion is given by [10]:

$$\dot{u} = a_x - qw - g\sin\theta$$

$$\dot{w} = a_z + qu + g\cos\theta$$

$$\dot{q} = \frac{M}{I_{yy}}$$

$$\dot{\alpha}_l = -\frac{\alpha_l}{\tau_{f,l}} + \frac{K_b}{\tau_{f,l}}\delta_{lon} - q$$

$$\dot{\alpha}_f = -\frac{\alpha_f}{\tau_{f,f}} - q$$

$$\dot{Z} = -\dot{z} = u\sin\theta - w\cos\theta \qquad (2)$$

α_x, α_z are the helicopter acceleration in body axis. M, I_{yy} represent the pitching moment and helicopter Inertia moment in Y axis. α_l, α_f are the lower rotor and flybar longitudinal flapping angle. $\tau_{f,l}$, $\tau_{f,f}$ are flapping time constant of lower rotor and flybar, where as K_b represents mechanical linkage factor of lower rotor to the swash plate.

A linearize longitudinal aerodynamic force and moment can be modeled in terms of the helicopter's state and control inputs, *i.e.*, angular velocity *(q)*, rotor flapping angle, (α_u, α_l), active control input, (δ_{lon}) and propulsion (T_c) as follows :

$$C_X = C_{X_0} + C_{X_{\alpha_u}}\alpha_u + C_{X_{\alpha_l}}\alpha_l + C_{X_q}q + C_{X_{\delta_{lon}}}\delta_{lon} + C_{X_{T_c}}T_c$$

$$C_Z = C_{Z_0} + C_{Z_{\alpha_u}}\alpha_u + C_{Z_{\alpha_l}}\alpha_l + C_{Z_q}q + C_{Z_{\delta_{lon}}}\delta_{lon} + C_{Z_{T_c}}T_c$$

$$C_m = C_{m_0} + C_{m_{\alpha_u}}\alpha_u + C_{m_{\alpha_l}}\alpha_l + C_{m_q}q + C_{m_{\delta_{lon}}}\delta_{lon} + C_{m_{T_c}}T_c \qquad (3)$$

Where C_X and C_Z denote the coefficients of the aerodynamic-propulsion forces along the X and Z axes, and C_m denotes the pitching moment coefficients about the Y axis. $C_{X_q}, C_{X_{\alpha_u}}, C_{X_{\alpha_l}}, C_{X_{\delta_{lon}}}, C_{X_{T_c}}, C_{Z_{\alpha_u}}, C_{Z_{\alpha_l}}, C_{Z_q}, C_{Z_{\delta_{lon}}}, C_{Z_{T_c}}$, $C_{m_{\alpha_u}}, C_{m_{\alpha_l}}$ $C_{m_q}, C_{m_{\delta_{lon}}}, C_{m_{T_c}}$ are the constant model parameters to be determined.

C_X, C_Z and C_m are defined as :

$$C_X = \frac{m.a_X}{1/2\ \rho\pi R^4\omega^2}$$

$$C_Z = \frac{m.a_Z}{1/2\ \rho\pi R^4\omega^2}$$

$$C_m = \frac{q.I_{yy}}{1/2\ \rho\pi R^5\omega^2} \qquad (4)$$

Where m is the helicopter mass. ρ is the air density, R is the rotor radius dan ω is the average rotor angular velocity.

During hover flight, aerodynamic thrust generated by the upper and lower rotors could be defined as

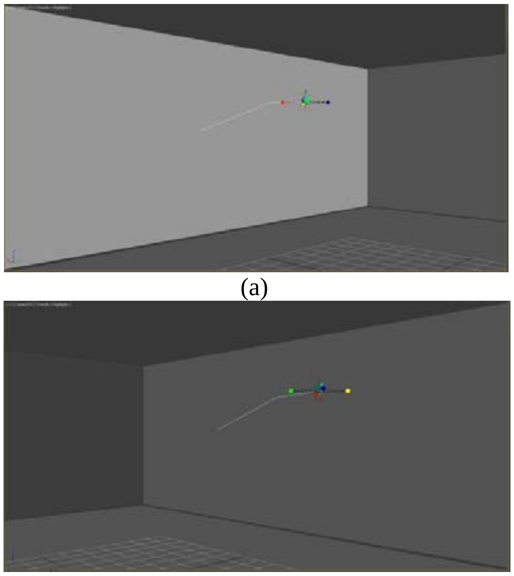
$$T_c = C_{T_u}\rho\pi R^4\omega_u^2 + C_{T_l}\rho\pi R^4\omega_l^2 \qquad (5)$$

Where ω_u, ω_l are the upper and lower rotor rotational speed. C_{T_u}, C_{T_l} are the thrust coefficient of upper and lower rotor considered to be constant.

4.2 Test Scenario

Following a flight test procedure to a typical UAV proposed in [10], a scenario was made After a 2 seconds hover flight, a doublet longitudinal deflection of lower swash plate angle is given (δ_{lon}). The deflection magnitude is set to 5 degree for 1 second down followed by 1 second up. The rotor speed of upper and lower rotor angle are set to be constant, and lateral swash plate angle is set to be zero.

The motion of the simulated model is defined using simulation results. The output of model position and attitude is used to construct a movie illustrating the motion. The test will last 10 seconds, thus generating 300 pictures for each camera. The translation path can be seen in figure 6 below.


(a)

(b)

Fig.6 The motion path for observed object model represented with white line. Image (a) taken from camera1; image (b) taken from camera2.

4.3 Camera Calibration

In this experiment, six markers are used as control point and placed at known position. The calibration frame formed into a 3 m cube with each marker at its vertices.

This data would be used to calculate the DLT parameters. The DLT parameters define calibration, position and orientation of camera. It is the parameters that reflect relationship between the image reference frames and object reference frame.

There are 11 DLT parameters obtained and are shown in table 1 below.

Table.1 DLT parameter values

DLT Parameters	Camera 1	Camera 2
L1	-106,7667	-35,5769
L2	-35,6386	106,7356
L3	0,0880	0,0572
L4	320,4361	320,4868
L5	-26,7309	26,7668
L6	26,7541	26,7286
L7	-100,6446	-100,6437
L8	391,5768	391,5773
L9	-0,1110	0,1111
L10	0,1109	0,1109
L11	0,0001	0,0002

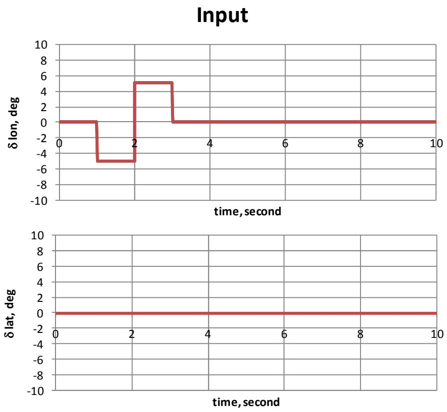
4 Results and Discussions

4.1 Tracking of Observed Object Model

Using the constant value as described in table 2, and the input as described in figure 7, the state of the virtual coaxial helicopter can be obtained.

Table.2 Contant value

Parameter	Value	Unit
ρ	1.14	[kg/m^3]
g	9.804	[m/s^2]
m	0.8	[kg]
R	0.25	[m]
I_{yy}	6.26E-03	[kg.m^2]
C_{T_u}	7.18E-03	[rad^{-1}]
C_{T_l}	4.98E-03	[rad^{-1}]
$\tau_{f,l}$	0.05	[s]
$\tau_{f,f}$	3.0	[s]
K_b	0.91	[-]



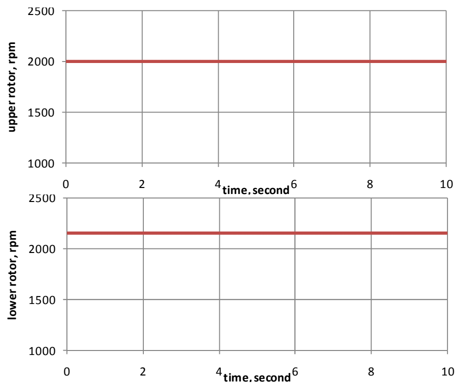


Fig.7 Inputs for the flight test

The position and attitude as well as the velocity and angular rate of the helicopter are shown in figure 8, 9, 10 and 11 below. Original data response represents information generated from helicopter simulation based on mathematical model and reconstruction result are obtained using image processing based on simulated scenario.

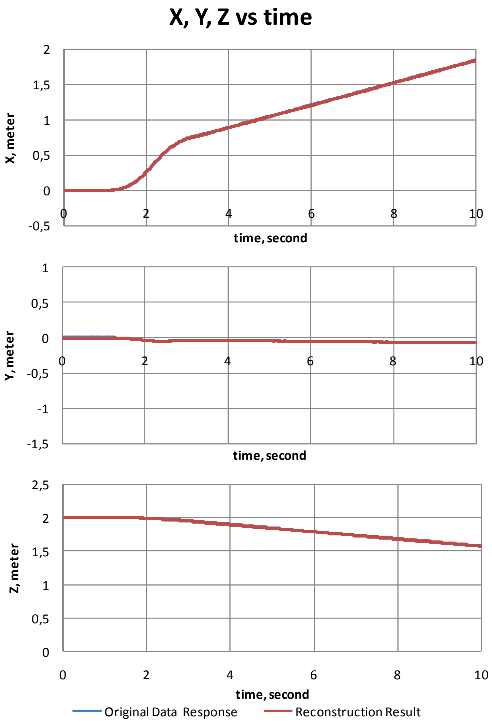


Fig.8 Helicopter position

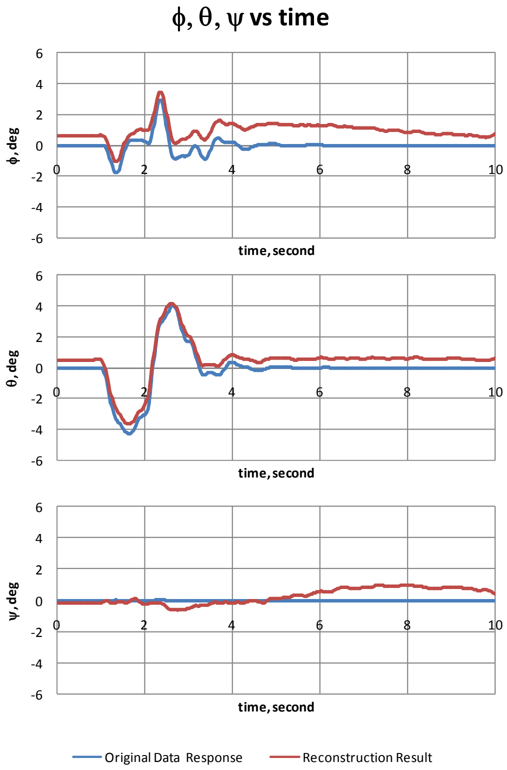


Fig.9 Helicopter attitude

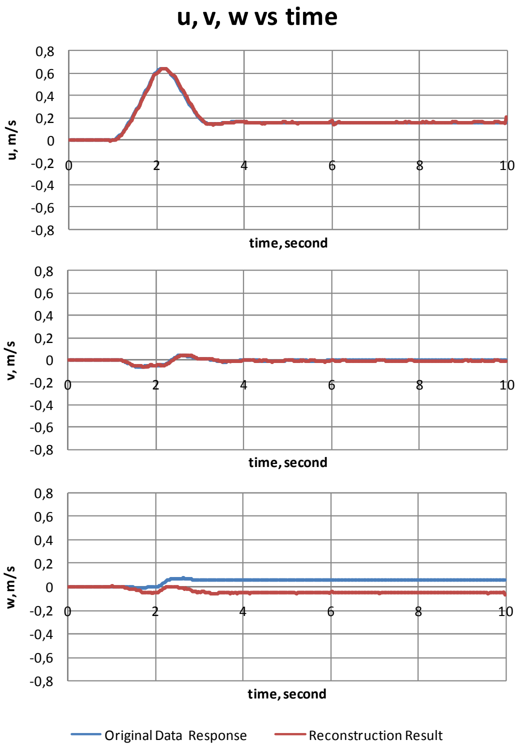


Fig.10 Helicopter velocity

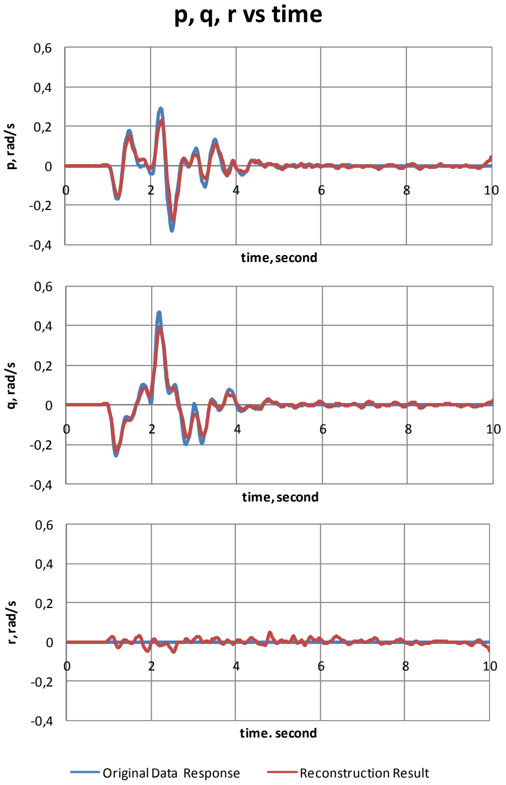


Fig.11 Helicopter angular rate

4.2 Parameter identification process

The values of C_X, C_Z, C_m can be computed by using equation (2) and (4). By knowing the values of C_X, C_Z, C_m, and the values of independent variables $q, \alpha_u, \alpha_l, \delta_{lon}, T_c$, the parameters in equation (3) can be estimated using regression method. A Total Least Square (TLS) method will be used. A study by H. Muhammad *et al.* [12] on estimation of aerodynamic parameter of Micro Aerial Vehicle using TLS, showed that TLS could give consistent estimation of the parameters in the presence of noise in the measured data.

The value of parameters obtained by implementing TLS are presented in table 3. The comparison between aerodynamic force and coefficient obtained by direct calculation to those obtained using identified parameters presented in figure 12 shows good approximation. Maximum residual for C_X is 0.0018 , C_Z is 0.00055 and C_m is 0.0047.

Table 3. Values of identified parameters

Parameter	Value	Parameter	Value
C_{X_0}	0.0015	$C_{Z_{\delta_{lon}}}$	0.0003
$C_{X_{\alpha_u}}$	0.0050	$C_{Z_{T_l}}$	-0.0000
$C_{X_{\alpha_l}}$	-0.0006	$C_{Z_{T_u}}$	0.0057
C_{X_q}	-0.0003	C_{m_0}	-0.1423
$C_{X_{\delta_{lon}}}$	0.0155	$C_{m_{\alpha_u}}$	-1.0544
$C_{X_{T_l}}$	0.0000	$C_{m_{\alpha_l}}$	-0.0984
$C_{X_{T_u}}$	-0.0002	C_{m_q}	0.0060
C_{Z_0}	-0.0505	$C_{m_{\delta_{Lon}}}$	-0.0109
$C_{Z_{\alpha_u}}$	-0.0014	$C_{m_{T_l}}$	-0.0074
$C_{Z_{\alpha_l}}$	0.0002	$C_{m_{Tu}}$	0.0379
C_{Z_q}	-0.0000		

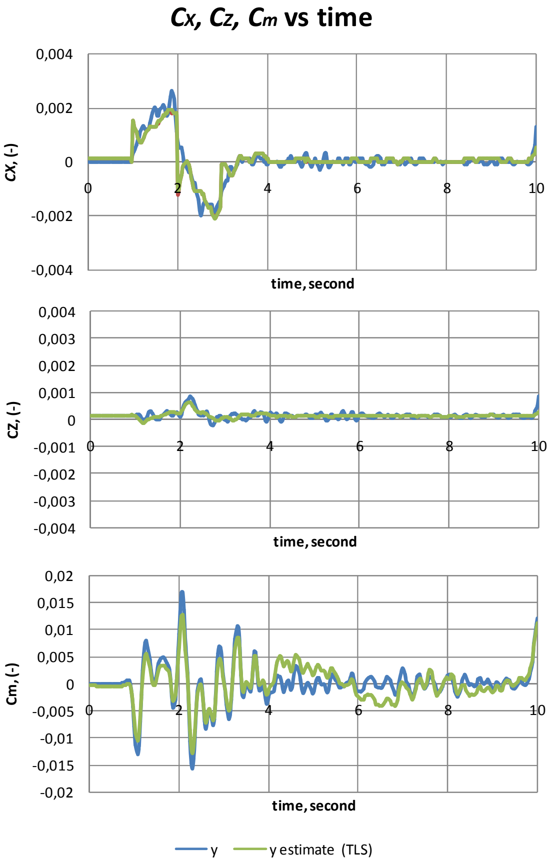


Fig.12 Estimation of aerodynamic coefficient using TLS

5 Conclusions

Several conclusions can be obtained from this research:

- A pose estimation system based on dual camera technique has been developed. The system can be used in estimating the position and attitude of virtual coaxial helicopter.
- The process of obtaining values of linearized parameter of aerodynamic force and moment coefficient is relatively straight forward by applying matrix transformation and differentiating the position and attitude of the object taken from the image.
- The parameter obtained by identification process produce a good correlation with the value of aerodynamic force and moment obtained by direct calculation.

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