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Modeling and flight simulation of unmanned aerial vehicle enhanced with fine tuning

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A B S T R A C T

This paper focuses on the complete process of building full six-degree-of-freedom, low cost, high fidelity simulation model of a small-unmanned aerial vehicle starting from scratch. The configuration used in this study is currently available propeller-driven radio controlled model airplane. Modeling its six-degree-of-freedom motion includes experimental measurements of geometric and inertia model, modeling of the propulsion system, estimation of the aerodynamic model, and experimental identification of control surfaces actuator model. The complete propulsion simulation model is validated by the wind tunnel test data of the airplane propulsion system. Piloted flight results for the airplane specific longitudinal maneuver with elevator control input are presented to highlight the results of the simulation model. The present work indicates that airplane parameter estimation from flight test data improves the accuracy of the developed flight simulation model.

1. Introduction

Airplane modeling and simulation have a long history in the aerospace industry and are of increasing importance in recent years. A high fidelity six Degrees of Freedom (DoF) simulation model provides engineers with the numerical power to test new airplane designs or any modifications to existing ones in a simulation environment prior to flight tests, saving time and money. It also serves numerous fields such as airplane dynamic and performance analysis, control law design and validation, guidance and trajectory studies, pilot training, airplane design, and air combat investigations. Furthermore, this numerical tool provides a mean to perform virtual testing and analysis, for example testing of different flight phases (take-off, landing... etc.) in presence of gust loads of random magnitude and direction. This enables engineers and researchers to expect the airplane performance in various flight scenarios.

Airplane flight simulation should include five underlying models. These models are dynamic model, aerodynamic model, propulsion model, atmospheric model and actuator model. The accuracy of the airplane simulation depends not only on the mathematical formulation but also on the accuracy of airplane parameters contained inside these models. These parameters can be obtained by theoretical, computational, semi-empirical or experimental methods.

Due to the importance of building flight simulation models for Unmanned Aerial Vehicles (UAVs), several researches have been conducted to discuss such a process. Several efforts have been done to obtain high fidelity aerodynamic models [1–3]. A nonlinear six DoF model for the Rascal 110 airplane is presented by Nidal [4]. The aerodynamic coefficients were estimated using the United State Air Force (USAF) Digital Datcom software. The inertia model was determined experimentally using the pendulum method. The propeller model was developed using software, provided by Jon Becker from Cloud Cap Technologies, based on propeller geometric characteristics and airfoil data. Kargin [5] presented an autonomous landing control algorithm for a fixed-wing UAV. The dynamic model of the UAV is developed in FORTRAN. The aerodynamics of the system is modeled using semi-empirical formulas. The propulsion model consists of an engine model and a propeller model. While the engine data was obtained from the manufacturer, the propeller was modeled using blade element theory. Actuators are approximated as a first order system with time constant 15 rad/s. The dynamics of the engine are added into the engine servo model by selecting a lower time constant $T = 0.5$ rad/s for the engine servo. Inertia properties are obtained using the CATIA CAD program. Mueller [6] presented the nonlinear simulation model for a UAV using Simulink. The aerodynamic derivative lookup tables were obtained from a panel code, LinAir, developed at NASA Ames research centre (ARC). The servo model was iden-

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Nomenclature

b	Wingspan [m]
c	Wing mean aerodynamic chord [m]
C_L, C_D, C_m	Lift, drag, and pitching moment coefficients
C_{Lo}, C_{Do}, C_{mo}	Lift, drag, and pitching moment coefficients at zero values of α, q, δ_e, and $\dot{\alpha}$
$C_{L_\alpha}, C_{L_q}, C_{L_{\delta e}}, C_{L_{\dot{\alpha}}}$	Derivative of lift coefficient w.r.t. α, q, δ_e, and $\dot{\alpha}$ [per degree]
$C_{m_\alpha}, C_{m_q}, C_{m_{\delta e}}, C_{m_{\dot{\alpha}}}$	Derivative of pitching moment coefficient w.r.t. α, q, δ_e, and $\dot{\alpha}$ [per degree]
$C_{D_\alpha}, C_{D_{\delta e}}$	Derivative of drag coefficient w.r.t. α and δ_e [per degree]
C_Y, C_l, C_n	Lateral force, rolling, and yawing moment coefficients
$C_{Y_o}, C_{l_o}, C_{n_o}$	Lateral force, rolling, and yawing moment coefficients at zero values of β, p, r, δ_a, and δ_r
$C_{Y_\beta}, C_{Y_p}, C_{Y_r}, C_{Y_{\delta a}}, C_{Y_{\delta r}}$	Derivative of lateral force coefficient w.r.t. β, p, r, δ_a, and δ_r [per degree]
$C_{l_\beta}, C_{l_p}, C_{l_r}, C_{l_{\delta a}}, C_{l_{\delta r}}$	Derivative of rolling moment coefficient w.r.t. β, p, r, δ_a, and δ_r [per degree]
$C_{n_\beta}, C_{n_p}, C_{n_r}, C_{n_{\delta a}}, C_{n_{\delta r}}$	Derivative of yawing moment coefficient w.r.t. β, p, r, δ_a, and δ_r [per degree]
C_T, C_q, C_p	The propeller thrust, torque, and power coefficients
$\vec{F}_B$	Resultant external force vector applied on the airplane in body axes [N]
$\vec{g}_o$	Gravity acceleration vector [m/s^2]
J	Propeller advance ratio
$\vec{M}_B$	Resultant external moment vector, about the mass center [N m]
m	Airplane mass
p, q, r	Scalar components of airplane angular velocity in body axes [rad/s]
S	Wing area [m^2]
u, v, w	Scalar components of airplane linear velocity in body axes [m/s]
$\vec{V}_B$	Airplane velocity vector expressed in the body-fixed reference frame [m/s]
V_T	Total velocity [m/s]
x, y, z	Components of airplane trajectory [m]
ρ	Air density [kg/m^3]
δ_{th}	Airplane propulsion throttle position
ϕ, θ, ψ	Roll, pitch and yaw angle (Euler angles) [degree]
$\vec{\omega}_B$	Airplane angular velocity vector in body axes [rad/s]

tified based on experimental measurements using Matlab System Identification Toolbox.

A 6-DoF nonlinear model for the Yak-54 Remotely Controlled (RC) airplane was obtained using different techniques [7,8]. The Aerospace Blockset was used by Leong et al. [7]. The Advanced Airplane Analysis software (AAA) was used to obtain the aerodynamic derivatives. The linear component build-up method was used to generate the aerodynamic forces and moments. The actuator dynamics was modeled by a first order system. A servo delay tester was used to measure the response time. The engine dynamics was simplified by using first order time delay. The thrust force was calculated based on the propeller dynamic characteristics, which were estimated using a computer program called JavaProp. The moment of inertia was computed analytically. Jager [8] used two generic modeling and simulation packages, which were included in the flight control system (Piccolo II). The first package was the Standard Cloud Cap Simulation model (SCCS) which internally estimates the aerodynamic parameters using geometric data. The second was Athena Vortex Lattice (AVL) based on airplane modeling tool. In the two packages, a simple power vs. rpm look up table was used to determine the engine power. The simulator assumes a linear relationship between throttle movement and power generation. The moments of inertia were calculated analytically.

The Aerosonde UAV, provided by AeroSim Blockset, was adopted to model the Ultrastick UAV by Paw [9]. The aerodynamic coefficients were approximated by parameter tuning approach using pilot-in-the-loop simulator. The inertia model was determined experimentally using pendulum method. The motor performance data was obtained from MotorCalc commercial software and the propeller characteristics was approximated from a published database for propellers. The actuator model was simplified by a first order system. The time delay for the servo actuator dynamics was approximated from a single period of Pulse Width Modulation (PWM) input signal operating at 45 Hz frequency. Modeling the ARF60 UAV was presented by Al-Radaideh et al. [10]. Most subsystems of the nonlinear model were built using the Aerosim and Aerospace toolboxes. Airplane aerodynamic data was modeled using linear estimated coefficients based on airplane geometry. The propulsion system model (engine and propeller) was identified experimentally as a black box in static conditions only by relating the engine response to throttle command assuming all other inputs constant. Then, by measuring engine thrust and rpm, the transfer functions relating throttle command to engine rpm and propeller thrust force were obtained. The actuator model was identified experimentally as a first order model. The inertia was measured experimentally.

Edwards [11] presented a nonlinear six DoF airplane simulator for the X-2C Xawk UAV. The simulator was constructed by using the readymade MATLAB Aerospace Blockset. Tornado was used for computing the aerodynamic data. The aerodynamic loads were calculated using component linear build-up method. The propulsion system (a propeller driven by reciprocating engine) was modeled using the "Turbofan Engine System" block from the Aerospace Blockset. The thrust curve was approximated without having any test data from the actual engine. A simple lag filter was used to simulate the response dynamics of the engine. The moments of inertia were calculated analytically. Airplane actuators' dynamics were not taken into consideration.

This paper presents the building of the six-degree-of-freedom simulation model of a small-unmanned aerial vehicle. The test bed used was the Tiger–Trainer airplane. In the next section, the mathematical model is presented. Section 3, is devoted to develop the airplane geometric data, moments-of-inertia, propulsion, aerodynamic, actuator models, and finally the complete six DoF nonlinear simulation model. Verification of the developed six DoF nonlinear simulation model through the correct operation and flight-testing was discussed. Finally, airplane model tuning using flight test data was presented.

2. Airplane mathematical modeling

The first step to develop a six-DoF nonlinear flight simulation model of an airplane is to develop the mathematical model that describes the airplane dynamics and its surroundings. It includes the development of the airplane equations of motion (dynamic model), and the mathematical representation for the aerodynamic forces and moments.