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An Algorithm for Autonomous Aerial Navigation using MATLAB® Mapping Tool Box

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***Abstract*—**In the present era of aviation technology, autonomous navigation and control have emerged as a prime area of active research. Owing to the tremendous developments in the field, autonomous controls have led today's engineers to claim that future of aerospace vehicle is unmanned. Development of guidance and navigation algorithms for an unmanned aerial vehicle (UAV) is an extremely challenging task, which requires efforts to meet strict, and at times, conflicting goals of guidance and control. In this paper, aircraft altitude and heading controllers and an efficient algorithm for self-governing navigation using MATLAB® mapping toolbox is presented which also enables loitering of a fixed wing UAV over a specified area. For this purpose, a nonlinear mathematical model of a UAV is used. The nonlinear model is linearized around a stable trim point and decoupled for controller design. The linear controllers are tested on the nonlinear aircraft model and navigation algorithm is subsequently developed for for autonomous flight of the UAV. The results are presented for trajectory controllers and waypoint based navigation. Our investigation reveals that MATLAB® mapping toolbox can be exploited to successfully deliver an efficient algorithm for autonomous aerial navigation for a UAV.

***Keywords*—**navigation; trajectory-control; unmanned aerial vehicle; PID-control; MATLAB® mapping toolbox

I. Introduction

IN modern days, UAVs are finding multiple applications both in military as well as in civil; relevant areas include personnel reconnaissance, security surveillance, fire fighting, agricultural research, meteorological missions and geological explorations etc. [1]. UAVs have proved to be an able alternative in situations where the risk of sending a human piloted aircraft is unacceptable, or the use of a manned flight is impractical. The unchallenged capabilities of UAVs have transformed the future of aviation to be unmanned. Expertise in UAV technology is acquired through the knowledge of areas like aerodynamics, structures, propulsion, communication, controls and navigation. Autopilots are onboard systems to guide the in-flight UAVs with no assistance from human operators. Autopilots were initially developed for missiles in 1920s [1] and later on extended to aircraft and ships. The UAV autopilot contains automatic flight controller which is the main building block of the autopilot. This subsystem controls UAV autonomously by generating control signals for the control surfaces of the aerial vehicle.

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The aircraft autopilot features three design levels, namely, stability augmentation, attitude regulation and trajectory control [2].The literature is replete with various algorithms for aircraft control at all the three levels. These algorithms include schemes based upon proportional-integral-derivative control (PID) [3], fuzzy logic control [4], neural networks [5] and static feedback control augmented with adaptive neural network [6].

Autonomous UAV navigation is an important area in a UAV's design, of which different flight maneuvers like loitering, altitude stabilization, and coordinated turn etc. pose a challenging task for navigation schemes. There are many methods used for the navigation of UAVs like fuzzy logic based UAV navigation, evolutionary algorithm using online/offline path planner [7], 3-D online/offline path planning for UAVs using multi objective evolutionary algorithms [8], vision based aerial navigation [9], combined visual and inertial navigation [10] etc. each having its own advantages and limitations. For example, if compared to the inertial or GPS based waypoint navigation, the online path planner requires more computational power, while the vision based navigation schemes need extra memory for housing the database as compared to the inertial or GPS based way point navigation.

II. UAV Modeling – Nonlinear and Linear Models

In this project an already available model of Aerosonde UAV has been employed using the Aerosim® block set [11] of MATLAB®, for the development of a comprehensive nonlinear mathematical model of an aircraft. The modeling follows the methodology of our earlier work presented in [12], and the model was further refined in light of the results offered in [13].

The Aerosim blockset has been used to develop 6 DOF mathematical model of Aerosonde UAV. The nonlinear model uses various inter-related sub-models as shown in figure 1.

A. Sub-models for the UAV

1) Aerodynamic sub-model uses required aerodynamic forces and moments for control surface loading / deflections.

2) Propulsion model is built to simulate the aircraft's engine and propeller.

3) Inertial model is used to specify the aircraft center of gravity, mass, moments of inertia and product of inertia etc.

4) Atmospheric model simulates the external environmental conditions and is used to model the various operating altitudes of the aircraft and study its effects on the aircraft performance due to varying density and pressure of air.

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5) Earth model simulates the performance of the model in earth's environment. It uses the mathematical models WGS-84, EGM-96 and WMM-2000 to calculate earth radius and gravity, sea-level altitude and earth magnetic field components at current aircraft position.

6) The 6 Degree-of-Freedom (6-DoF) equations of motions are implemented in the aircraft body axes. These equations constitute the basic mathematical model of the aircraft on which the entire system performance relies.

B. Linear Model for the UAV

Once the non-linear model has been developed, linearization of the nonlinear model is performed around a stable trim point for steady-state wing level flight. The linearization facilitates the analysis of various aircraft's natural modes of motion and their subsequent control using linear controllers [14]. The designed controllers successfully work for a nonlinear model, if the perturbation around the stable equilibrium point is small (within certain range of linear operation) [15]. The linearization of the nonlinear aircraft model has been used to develop a simplified state space based model of the UAV.

It can be seen that for a steady state wing level flight with approximately zero side slip angle, the system matrix 'A' of the linear model has negligible cross diagonal terms [16], thus resulting into easy decoupling of system into longitudinal and lateral sub-models. The typical state space system's realization for a decoupled sub-model is given as:-

$$\dot{x} = Ax + Bu \tag{1}$$

Where x is the state vector, $\dot{x}$ is the time derivative of state vector, u is control input vector, A is the decoupled system matrix and B is the decoupled input matrix for the respective sub-model (longitudinal or lateral). In this case [v q θ h] is the decoupled longitudinal state vector; where v is the velocity along body x-axis, q is the pitch rate, θ is pitch angle and h is the altitude of the UAV. For the inputs, δ_e is elevator deflection angle in degrees and δ_t is the throttle input in percentage advance. The state space representation of longitudinal sub-model is given in (2).

$$\begin{bmatrix} \dot{v} \\ \dot{q} \\ \dot{\theta} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} X_u & X_q & X_\theta & -g_0\cos\theta \\ Z_u & Z_q & Z_\theta & -g_0\sin\theta \\ M_u & M_q & M_\theta & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} v \\ q \\ \theta \\ h \end{bmatrix} = \begin{bmatrix} X_{\delta e} & X_{\delta e} \\ Z_{\delta e} & Z_{\delta e} \\ M_{\delta e} & M_{\delta e} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} \tag{2}$$

Similarly, the state space representation of lateral sub-model is given in (3). The decoupled lateral state vector is [β p ψ φ] where β is the sideslip angle, p is the roll rate, ψ is the heading angle and φ is the bank angle.

The elements of the system matrices and input matrices in (2) and (3) are in concise representation form of control derivatives and stability derivatives in the aircraft body axis and are discussed in detail in[18].

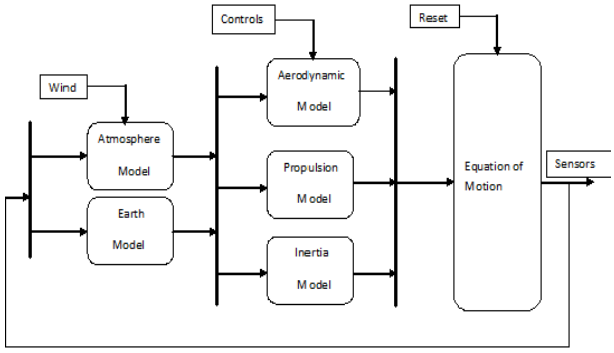


Fig. 1 Non-linear mathematical model

$$\begin{bmatrix} \dot{\beta} \\ \dot{p} \\ \dot{j} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} Y_v & -U_0 & V_0 & -g_0\cos\theta \\ N_v & N_r & N_p & 0 \\ L_v & L_r & L_p & 0 \\ 0 & \tan\theta_0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ p \\ j \\ \psi \end{bmatrix} = \begin{bmatrix} Y_{\delta a} & Y_{\delta r} \\ N_{\delta a} & N_{\delta r} \\ L_{\delta a} & L_{\delta r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \tag{3}$$

III. Trajectory Controllers And Navigation

A. Controller Design

In the process of trajectory controllers design, control responses and stability is used to analyze linear dynamics of the closed-loop system [17], i.e. settling time and overshoot have been considered as the conclusive time-response specifications. The flight parameters of altitude and heading are controlled using a Phase Lead Compensator and a Proportional Integral Differential (PID) controller respectively. The design details and affirmative results for altitude acquire-and-hold were presented in our earlier work [18]. For heading acquire-and-hold, a PID controller is used with inputs as the aircraft actual heading and the reference heading. This reference (desired) heading is provided by the navigation algorithm and the subsequent heading error is used to determine the minimum heading angle difference between the two inputs to the controller. The structure of PID controller is also discussed in detail in [18]. The PID based heading controller uses gain values of K_p=0.218 (proportional gain), K_i=0.0001 (integral gain) and K_d=0.0523 (differential gain). The output of this PID controller is added to the current bank angle of the aircraft and applied to the stability augmentation controller (Proportional Integral PI controller) for the stabilization of lateral dynamics. The resultant output is applied as the control surface input (aileron deflection angle). The closed-loop representation of heading controller is shown in figure 2.

B. Autonomous Navigation

A self-governing navigation algorithm is developed using the MATLAB® mapping toolbox [19] that offers two techniques for course-plotting. For small aerial distances i.e. for inter-regional flights, "rhumb-line" based navigation [20] is realized assuming a flat earth model. Whereas, for long aerial distances i.e. intra-regional flights, "great-circle" based routing is employed that is based on spherical geometry instead of planar geometry and therefore, an oblate earth model is used in this navigation scheme [20].

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The developed navigation algorithm calculates the azimuth between the current aircraft position and the destination, and thus provides the UAV heading controller with a set-point (reference input) for the desired destination. This algorithm further calculates the elevation to the next waypoint, and therefore, presents the altitude controller with a set-point for the desired waypoint. Finally, the current distance between present position and the destination is provided by the algorithm.

The great circle distance and azimuth are computed using the mathematical relations shown in (4) and (5).

$$Great\,Circle\,Distance = \sin^2((lat2-lat1)/2) + \cos(lat1)* \cos(lat2)*\sin^2((lon2-lon1)/2) \quad (4)$$

$$Azimuth = a\tan 2(\cos(lat2)*\sin(lon2-lon1), \cos(lat1)*\sin(lat2)-\sin(lat1)*\cos(lat2)*\cos*(lon2-lon1)) \quad (5)$$

Where *lat1* and *lon1* are latitude and longitude of the initial point, *lat2* and *lon2* are the latitude and longitude of the destination respectively. The latitude and longitude are provided in radians.

The rhumb line navigation algorithm uses equations (6) to (9) for distanced and azimuth calculation.

If dlonW < dlonE, then:

$$Distance = \sqrt{f^2 * dlonW^2 + (lat2-lat1)^2}, \quad (6)$$

$$Azimuth = \mathrm{mod}(a\tan 2(-dlonW, dphi), 2\pi) \quad (7)$$

If dlonW > dlonE, then:

$$Distance = \sqrt{f^2 * dlonW^2 + (lat2-lat1)^2} \quad (8)$$

$$Azimuth = \mathrm{mod}(a\tan 2(dlonE, dphi), 2\pi) \quad (9)$$

$$where,\ f = \cos(lat1);\ \text{if}\ (abs(lat2-lat1) < \sqrt{TOL})$$

$$f = (lat2-lat1)/dphi\ ;\ \text{otherwise}$$

$$dlonW = \mathrm{mod}(lon2-lon1, 2\pi)$$

$$dlonE = \mathrm{mod}(lon1-lon2, 2\pi)$$

$$dphi = \log(\tan(lat2/2+\pi/4)/\tan(lat1/2+\pi/4))$$

TOL = small number of order machine precision (e.g. 1e-05)

The navigation scheme further offers coordinated turn based loiter maneuvering over a target area. An aircraft is said to perform a coordinated turn if it meets the trimming requirements and the lateral component (along body frame y-axis) of aerodynamic forces is equal to zero [21]. Most of the fixed wing aircraft lack hover capability and therefore, the autonomous loiter maneuver becomes a valuable feature in the UAV's navigation system. In our work this feature is accomplished with a PI controller implemented with the feedback of aircraft's roll angle.

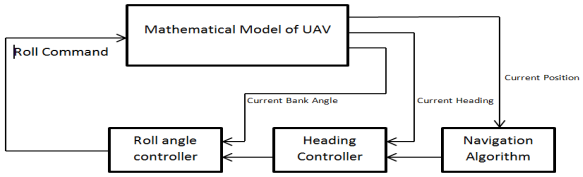


Fig. 2 Closed loop configuration with Heading Controller

Once engaged in the loiter mode, the algorithm uses the information of aircraft speed and bank angle, and returns the reference heading for coordinated turn while maintaining altitude of the aircraft.

The coordinated turn rate and the radius of turn can be realized with the mathematical expressions given in (10) and (11) below:

$$Rate\ of\ Turn = (g*\tan\phi)/TAS \quad (10)$$

$$Radius = (TAS)^2/(g*\tan\phi) \quad (11)$$

Where, g is acceleration due to gravity, Φ is bank angle, and TAS is true airspeed of the UAV.

IV. Simulation Results

MATLAB/Simulink® is used for the nonlinear simulation of the UAV flight. Simulation sampling period is set to 0.02 sec. which is corresponding to the operating frequency (50 Hz) of the actuators used in Aerosonde. The continuous time models of controllers and navigation block were discretized (for ease of implementation on hardware) in MATLAB® and controller gains were fine-tuned for desired performance.

A. Navigation and Loiter Maneuver

The navigation algorithm, as well as, the trajectory controllers (altitude and heading controllers) were tested for the nonlinear UAV model. The result of the navigation algorithm is presented in figure 3. Along x and y axes longitude and latitude in degrees are presented respectively and altitude is plotted in meters along z-axis. The figure 3 shows initially the climb of UAV from 1000m to 1100m (using altitude controller), followed by a loiter maneuver while holding altitude at 1100m (using navigation algorithm) and finally the exit of UAV from the loiter maneuver and moving towards the next waypoint (using heading controller).

V. Conclusion

In this paper, a non-linear UAV model is used for design of trajectory controllers and development of an efficient aerial navigation scheme. Aircraft altitude and heading controllers are used with the developed navigation algorithm for autonomous flight. The preliminary results for altitude and heading control were verified and subsequently MATLAB® mapping toolbox was used to build the navigation sub-system. The developed algorithm was tested for various flight phases including climb, descent, waypoint based navigation and coordinated turn based loiter maneuver. Successful results were presented for both trajectory controllers and the navigation algorithm. The promising results of nonlinear simulations are suggestive of successful implementation of this complete design on an embedded platform (e.g. embedded computer PC-104) for hardware-in-loop simulation and autonomous flight testing.

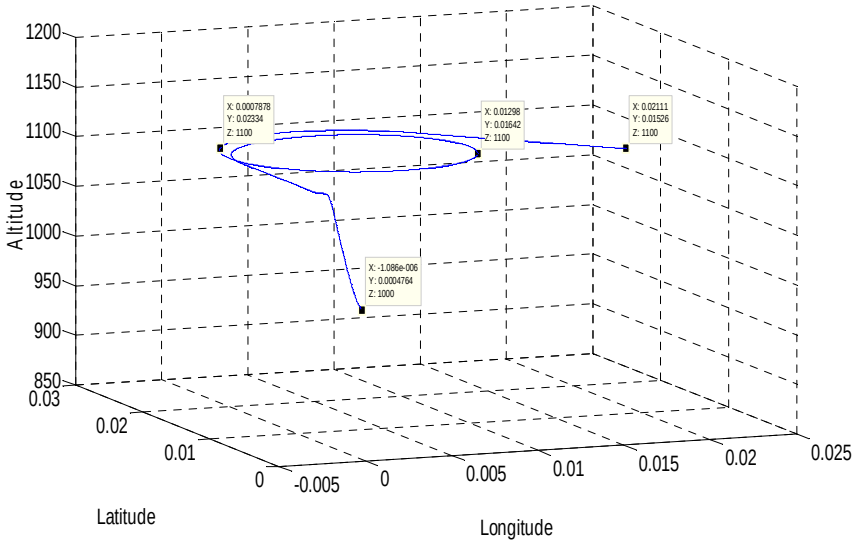


Fig. 3 Trajectory plot for loiter maneuver and steady wing level flight

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