AUTOPilot INTEGRATION FOR A FLYING WING UAV

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Abstract
This study focuses on the technical challenges of integrating an autopilot/GPS system onto an existing flying wing UAV without adequate contractor's aerodynamic, propulsion and stability data. A fair amount of reverse engineering is needed to derive the flying characteristics of the aircraft. The paper describes the CFD estimation of the aerodynamic forces and stability derivatives for the flight dynamics and control model. In addition, the estimation of autopilot gains for the non-conventional configuration is presented. This paper will also give an insight on the application of optimization on the derivation of the best PID gains for the autopilot loops to minimize the delay time and achieve steady state. Finally the study shows how the autopilot/GPS is integrated with the existing UAV.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Sideslip angle</td>
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<tr>
<td>$\delta a$</td>
<td>Aileron deflection angle</td>
</tr>
<tr>
<td>$\delta e$</td>
<td>Elevator deflection angle</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Pitch angle</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Roll angle</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Yaw angle</td>
</tr>
<tr>
<td>$c$</td>
<td>Mean aerodynamic chord</td>
</tr>
<tr>
<td>$C_y$</td>
<td>Function of chord length with respect to Y coordinate</td>
</tr>
<tr>
<td>$L$</td>
<td>Rolling moment</td>
</tr>
<tr>
<td>$M$</td>
<td>Pitching moment</td>
</tr>
<tr>
<td>$N$</td>
<td>Yawing moment</td>
</tr>
<tr>
<td>$S$</td>
<td>Wing area</td>
</tr>
<tr>
<td>$U$</td>
<td>Indicated airspeed</td>
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Introduction

With growing interest in stealth technology and the increasing usage of UAVs in military operations, the flying wing configuration of the Stealth Fighter is gaining popularity in the aircraft industry, as well as in the UAV community. This is especially vital where Uninhibited Combat Aerial Vehicles (UCAVs) are concerned, as they have to have stealth capabilities to be able to attack without being seen by the enemy.

The flying wing configuration is a combination of all the usual parts of an aircraft into just an extended wing, and instead of having separate elevators and ailerons to control the pitch and roll of the aircraft, a single set of control surfaces called elevons are used, usually near the wingtips to control the pitch and roll. Rudders may or may not be present.

The usual method of developing an aircraft is to decide what the mission requirements of the new aircraft are, finding an aerfoil shape specific to it by testing, do a sizing and performance optimization and integrate it together with the other parts of the aircraft, i.e. controls, propulsion systems, payloads etc.

For this project, an autopilot system is required to be integrated into a given rudderless flying wing Unmanned Aerial Vehicle (UAV) to enable it to move from waypoint to waypoint using GPS navigation. However, only a physical model of the UAV was given without adequate contractor’s aerodynamic propulsion and stability data. This breaks the chain of development and it is required therefore to do a fair amount of reverse engineering to determine a good estimate of these required data.

Moreover, conventional methods of testing and analysis may not apply to this UAV as it is much smaller and slower than normal aircraft. New methods may have to be developed by trial and evaluation.
Description of the UAV

The UAV given is almost a flying wing, but unlike a real flying wing, it is equipped with a fuselage to store the electrical systems and the payload.

Effectively, there are only two control surfaces on the UAV. These are the elevons found at the ends of the wing. These elevons control the pitching and rolling of the aircraft. No rudders have been installed on this UAV.

Furthermore, the ends of the wing where the elevons are situated are angled upwards at about 30 degrees to the horizontal to compensate for the lack of the rudder surfaces, acting as a pair of winglets to provide stability to the aircraft. Even then, the lack of real rudder surfaces on the UAV may make the control of the lateral movements of the UAV harder to stabilize as any adverse yaw due to the rolling motion of the UAV might not be cancelled out.
The wing is also highly curved, forming a horizontally extended ‘M’ shape, looking from the back of the UAV. This makes the mathematical modeling of the UAV more difficult as the shape is rather unconventional.

**Autopilot control**

![Figure 3. The Micropilot™ control card](image)

To provide autopilot control to the UAV, a Micropilot™ control card was provided and is required to be integrated into the UAV. It consists of an on-board GPS, gyro unit as well as an air data unit. From these units, the UAV flight data i.e. position, turn rate, pitch and roll angles, airspeed, altitude etc are determined and sent into the corresponding control loops to determine what corrective actions need to be taken to take it to its determined waypoint at a given speed and altitude. It is thus required to find the appropriate Proportional, Integral and Derivative (PID) gains and input them into the program provided with the autopilot card to determine the appropriate amount the control surfaces would correct each situation by to prevent over or under-correction, which may lead to instability in flight. Finding these gains would thus be the main aim of this project.

To control the aircraft using the autopilot, it is necessary to know which feedback loops are involved before we are able to find the appropriate gains for each of them. For the Micropilot™ card, as there is no rudder on this UAV platform, only the feedback loops involving the aileron and elevators are considered.
The loops therefore are the Aileron-from-roll loop and the Elevator-from-pitch loop. Calculation of the gains for both the loops would give a relatively good estimate of the actual gain required as corrections still need to be made due to changes in atmospheric and environmental conditions.

To determine the gains, a mathematical model of the UAV would have to be found to enable calculations to be done. This mathematical model would thus be determined using the Equations of Motions (EOM) for an aircraft.

As there was only a physical model of the UAV given, there was therefore inadequate information to fully derive the EOM of the UAV. All of the aerodynamic coefficients inside the EOM have to be found by means of reverse engineering.

**Estimation of aerodynamic forces and stability derivatives**

![Figure 4. CAD model of the UAV](image)

To derive the aerodynamic derivatives, a CAD model of the UAV would first have to be made. Each of the components i.e. the wings, fuselage, elevons were modeled separately.

To model the wings, the shape of the aerofoil, taken from the fuselage end of the wing, was plotted out on paper and the coordinates taken and plotted onto Solidworks™. To model the curvature of the wing, coordinates were taken of a few points and joined together to form a guide curve, which was used to loft the aerofoil shape out to the winglet end, assuming that the shape of the aerofoil is constant throughout the wing. This is repeated for the winglet,
with the exception that instead of a guide curve in this case, a straight line was used to loft the winglet up to the tip. The elevons were modeled separately and assumed to be flat rectangular pieces.

The fuselage was assumed to be a box with a rectangular-base and a top that followed the curvature of the top of the wing closest to the fuselage. The nose was modeled using curves.

The final CAD part was converted into a STEP file and meshed using GAMBIT™ to be used for Computational Fluid Dynamic (CFD) calculations in FLUENT™ to find the required aerodynamic derivatives.

![Figure 5. Mesh of the UAV used in FLUENT](image)

In FLUENT™, runs were done to estimate how the UAV reacted to changes in speed, angle of attack, sideslip, control surfaces etc.

In the FLUENT™ computations, it was assumed that the flow over the UAV was laminar. This is due to the fact that the UAV is small in size, and thus would cause to a low Reynolds Number flow over the airfoil. Also it was assumed that the density and viscosity of air was constant.

From these runs, coefficients of forces in the X, Y and Z directions (as defined in the stability axes model), as well as the moments about these axes (L, M and N) with respect to different values of the relevant parameters are found.
Using these values, graphs were plotted to find out each parameter affected the respective forces and moments. The relationships were assumed to be roughly linear, and thus the relevant aerodynamic coefficients were defined as the slope the linear portion of each graph.

![Graph of Total Force (Z-Dirn) vs Angle of Attack](image1)

Figure 6. Graph of Total Force (Z-Dirn) vs Angle of Attack

![Graph of Total Force (Y-Dirn) vs Sideslip Angle](image2)

Figure 7. Graph of Total Force (Y-Dirn) vs Sideslip Angle

However, only the coefficients of the force and moments with respect to the change in speed, angle of attack, sideslip, and deflection of control surfaces were obtainable from such runs. The coefficients due to the pitch, roll and yaw could not be derived. Thus, a semi-empirical method of solution as defined in Cook was used for these derivatives.
To derive these coefficients semi-empirically, certain other values (function of the chord length with respect to Y \((C_y)\), wing area \((S)\), mean aerodynamic chord \((\overline{c})\) etc.) need to be found.

To determine \(C_y\), three coordinate points were taken from the original wing. The curve was assumed to be quadratic and using the three points, an estimated curve equation was derived.

By integrating \(C_y\), the wing area was derived.

From the results of these semi-empirical formulations, the coefficients of the pitch, roll and yaw rates were derived.

**Optimisation of Transfer functions**

The coefficients were put into the equations of motions of the aircraft, and the transfer functions of the UAV were then to be derived.

To derive the transfer functions, the equations of motions affecting the longitudinal and lateral stability of the UAV were separated. The components of the forces and moments due to the control surfaces were then put on one side of the equation.

Laplace transform was taken on all the equations. A matrix was then used to separate the coefficients from the disturbance parameters.

**Longitudinal:**

\[
\begin{bmatrix}
ms - c_{xx} & -c_{xa} & mg \cos \theta_e - c_{aq} s \\
-c_{za} & mu_s - c_{za} & mg \sin \theta_e - (c_{za} + mu_e) s \\
-c_{mu} & -c_{ma} & I_s s^2 - c_{mq} s \\
\end{bmatrix}
\begin{bmatrix}
u \\
\alpha \\
\theta \\
\end{bmatrix}
\times
\begin{bmatrix}
c_{\alpha \delta_e} \\
c_{\theta \delta_e} \\
c_{m \delta_e} \\
\end{bmatrix}
\times
\begin{bmatrix}
\delta_e \\
\end{bmatrix}
\]

**Lateral:**

\[
\begin{bmatrix}
mu_s - c_{\beta \delta_e} & -c_{\beta p} - mg & mu_s - c_{\beta s} \\
-c_{\beta \delta_e} & I_s s^2 - c_{\beta p} s & -I_{xz} s^2 - c_{\beta s} s \\
-c_{\alpha \delta_e} & -I_{xz} s^2 - c_{\alpha p} s & I_s s^2 - c_{\alpha s} s \\
\end{bmatrix}
\begin{bmatrix}
\beta \\
\phi \\
\psi \\
\end{bmatrix}
\times
\begin{bmatrix}
c_{\gamma \delta_e} \\
c_{\delta \delta_e} \\
c_{\alpha \delta_e} \\
\end{bmatrix}
\times
\begin{bmatrix}
\delta_e \\
\end{bmatrix}
\]
The equations were then divided throughout by the effect of the control surfaces, giving the response of the individual parameters due to the control surfaces.

Longitudinal:

\[
\begin{bmatrix}
\frac{u}{\delta_e} \\
\frac{\alpha}{\delta_e} \\
\frac{\beta}{\delta_e} \\
\frac{\phi}{\delta_e}
\end{bmatrix} = \begin{bmatrix}
ms - c_{xa} & -c_{xa} & mg \cos \theta_e - c_{eq} s \\
-c_{za} & mu s - c_{xa} & mg \sin \theta_e - (c_{za} + mu_e) s \\
-c_{ma} & -c_{ma} & I_x s^2 - c_{mq} s \\
\end{bmatrix}^{-1} \begin{bmatrix}
c_{ve} \\
c_{ze} \\
c_{me}
\end{bmatrix}
\]

Lateral:

\[
\begin{bmatrix}
\frac{\rho}{\delta_e} \\
\frac{\phi}{\delta_e} \\
\frac{\psi}{\delta_e} \\
\frac{\beta}{\delta_e}
\end{bmatrix} = \begin{bmatrix}
mu s - c_{y\beta} & -c_{yp} s - mg & mu_e - c_{yr} s \\
-c_{y\beta} & I_x s^2 - c_{yp} s & -I_{xz} s^2 - c_{yb} s \\
-c_{n\beta} & -I_{xz} s^2 - c_{np} s & I_z s^2 - c_{nr} s \\
\end{bmatrix}^{-1} \begin{bmatrix}
c_{y\delta} \\
c_{l\delta} \\
c_{n\delta}
\end{bmatrix}
\]

Since we only needed to solve for the gains of the elevator-from-pitch and the aileron-from-roll loops, only the solutions of \(\frac{\rho}{\delta_e}\) and \(\frac{\phi}{\delta_e}\) would be used.

The above solutions would thus be the transfer functions of their respective loops.

To derive the PID gains for the UAV, an optimization would have to be done to find the optimal gains for the UAV. MATLAB™ was used to find the gains, using the transfer functions that were derived previously as the “Plant” of the loop used for optimization.

![Figure 9. Block diagram of the loop used for optimization](image-url)
To optimize for the gains, the objective function of the above model was optimized to get the minimum sum-squared value of the error with respect to the step input provided using the Complex RF method\(^5\), which is similar to the Neadler-Mead Simplex method.

In the Complex RF method used, it takes \(2n\) number of random combination of values of P, I and D gains, with \(n\) being the number of variables involved (in this case, there are three variables, thus six combinations of values are taken), from the range of values given and finds each of their function evaluations. The combination with the worst evaluation would be set aside and a triangulation would be done for the remaining evaluations to give a centroid. The combination giving the lowest evaluation value would be reflected through the centroid to give another combination. Once again a function evaluation is done for this value and a comparison is done to eliminate the worst function evaluation. The process goes on until the difference between the function evaluations are below a certain prescribed value. The results from this optimization would give the optimal gains for the respective feedback loop to achieve a response with sufficient damping, minimal overshoot and shortest response time.
**Flight Testing**

As the computations given above merely serves to derive an estimate of the flying characteristics of the UAV, actual flight test would have to be done to find the correct gains to allow the UAV to fly the way it is supposed to autonomously.

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References


