UAV stability derivatives estimation for hardware-in-the-loop simulation of Piccolo autopilot by qualitative flight testing

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Abstract — This article summarizes the modelling of a UAV with an unconventional configuration in the context of a commercial project, aiming to integrate an off-the-shelf autopilot unit to the UAV in the minimum amount of time. Hardware-in-the-loop simulation is used to setup the flight system. The use of a vortex-lattice aerodynamic code and manual methods for the estimation of stability derivatives and qualitative flight testing for the determination of the final values is presented. Preliminary results are obtained by successfully applying the method to a conventional configuration aircraft. Upon successful implementation, the process is then used to integrate the autopilot to an inverted V-tail full size UAV.

I. INTRODUCTION

AeroDreams is the Argentinean leading company in the development of unmanned aerial vehicles (UAVs) for surveillance, reconnaissance and aerial mapping. Among the developed products and projects is the ADS-101 Strix, a fully tested medium-sized multipurpose UAV platform of up to 4 hour endurance and 5 kg payload capacity, in production since 2006. A stretched improved version of the Strix, with 6+ hours endurance and 8 kg payload capacity is under development and in the initial flight testing phase.

Fig. 1: Strix UAV landing approach
The Strix can be equipped with a wide range of EO/IR and electronic sensors, including stabilized camera gimbals and aerial photogrammetry platforms for high resolution imagery. Communications to ground control station (GCS) can be via UHF or satellite data link.

Other AeroDreams projects include the ADS-201 Petrel Jet, a high speed jet-powered aerial target with a 20 kg payload capacity and 650 km/h maximum airspeed and its propeller-powered version, the ADS-202 Petrel Prop. This version has a maximum speed of 370 km/h but a greater flight time (4 hours against 1 for the jet-powered) with the same payload capacity. The ADS-301 Ñancú is a short-range portable UAV specially designed as a tactical observation platform. Hand-launched, light-weight and electric-powered, the Ñancú UAV is suitable for over-the-hill or complex urban scenario observation with 15 km of operational range and 1 hour endurance. And at the strategic level, the ADS-401 is a long-range, twin engine UAV project specially designed for coastline search & rescue and surveillance, equipped with FLIR, SAR, SLAR and other payloads, and broad band satellite communications.
The Piccolo Plus autopilots provide a complete integrated avionics system including the core autopilot, flight sensors, navigation, wireless communication and payload interface. A broad range of fixed wing vehicle configurations have been supported and its simulation and control flexibility makes it a straightforward process to integrate the Piccolo into the system, as we will see further on. The Strix UAV is also equipped with a Piccolo II autopilot with Iridium satellite communications.

II. OBJECTIVE

The purpose of this assignment is to successfully integrate Piccolo Plus autopilot unit from CloudCap Technologies to a full size 30 kg UAV in the minimum amount of time. The Piccolo flight control system is based on PID controllers and, besides physical integration of the unit to the aircraft, the most important step is to tune the autopilot gains. Hardware-in-the-loop (HIL) simulation is the key to minimize the cost and time required to reach a successful first autonomous flight.

HIL simulation of the Piccolo autopilot system requires a detailed dynamic model of the aircraft involved in the simulation. The model represents the way the aircraft will react in terms of aerodynamics, propulsion and inertia effects. It is the key element to take advantage of the powerful potential of the simulation tool.
The model consists of two parts. One is the representation of the propulsion generated by the aircraft’s powerplant, and the other describes the flying qualities and additional data regarding geometrical and mass properties. When dealing with internal combustion engines, propulsion can be difficult to represent. Fortunately, the success of the simulation isn’t strongly linked to the accuracy of this part of the model, and hence a moderate amount of effort is sufficient.

The aerodynamics model is considerably more complex. Estimating stability derivatives with precision is an important task that can be carried out in one of two ways with the tools provided by CloudCap. The first option involves utilizing a conventional aircraft model as a basis for introducing parameters and allowing the simulator calculate the different aerodynamic contributions. The second and more advanced option is to make use of a vortex lattice code to calculate the aerodynamic characteristics of any aircraft configuration. This code is a customized version of the MIT’s open-source AVL code [11].

The objective was to test the second option procedure on a conventional RC aircraft and to use qualitative flight testing to check and eventually correct the model. Experience acquired from the test was then used on a second configuration, consisting of an inverted V-tail full size ADS-101 Strix UAV.

III. CONVENTIONAL AIRCRAFT

The aircraft used for the first test is a conventional RC model airplane commonly preferred for training purposes. It was chosen mainly because of its simplicity and conventionality. In addition, it was also considered as a secure platform to test the system.

- Wingspan: 1.51 m
- Wing Area: 0.408 m²
- CAM: 0.27 m
- Dihedral: 2°
- Taper ratio: 1
- Empty weight: 3.6 kg
- Engine: OS-61FX
- Propeller: 12 x 6

The input geometry for the CloudCap-modified version of the AVL vortex lattice code can be seen in Figure 1. The XML output was then put together with the inertia and engine models as inputs for the hardware-in-the-loop simulator [2]. Two experienced UAV pilots who have flown the aircraft previously performed the first qualitative check and, together with engineers, arrived to the conclusion that corrections in drag, lateral dynamics and control power derivatives should be made.

The first step was to re-calculate the involved derivatives with alternative methods like those proposed by Roskam [4], Perkins [6], Etkins [5] or by the ones proposed by NACA, Datcom, or ESDU.
The first noticeable difference was in the amount of power available. The AVL outputs a $C_{D_0}$ of about 100 drag counts, which is a very low value for this conventional configuration. The drag polar was re-calculated [1] taking into account effects from the landing gear, surface roughness, protuberances like antennas, battery pod, servos and power plant installation, which were not taken into account in the AVL code and resulted in a 280 drag counts increment. This value proved to be reasonable compared to the previous estimation and so it was introduced in the $C_{Dvis}$ field of the XML file.

The second problem was a clear difference between the simulation and the actual aircraft response sensitivity to manual inputs in both roll and yaw axis. The lateral-directional damping and control derivatives were also re-calculated with the proposed alternative methods and replaced in the AVL output. The ruling task was matching the aircraft response characteristics in the simulator with the real response in the same control deflection conditions. Achieving this is the key to obtain a suitable gain set for the autopilot.

<table>
<thead>
<tr>
<th></th>
<th>AVL</th>
<th>Roskam</th>
<th>Etkin</th>
<th>Perkins</th>
<th>Chosen value</th>
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<tr>
<td>$C_{lp}$</td>
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<td>0.51</td>
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<td>0.53</td>
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<td>$C_{nr}$</td>
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<td>0.095</td>
<td>0.14</td>
<td>0.10</td>
<td>0.13</td>
</tr>
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</table>

**TABLE I: LATERAL-DIRECTIONAL DAMPING DERIVATIVES - TRAINER**

By introducing these values, the responsiveness was improved but there was still an excess of control power in the roll and pitch axis. Assuming the longitudinal stability was estimated correctly by the code, the longitudinal and lateral control derivatives were explored.

Having done the derivatives re-calculation did not guarantee that the model was correct since, after all, the alternative methods are a second theory. Therefore, the next important step was to put the enhanced (modified) model to the test again in a trial and error process that included a human pilot in the loop. The control derivatives were modified within the limits of the calculated values and tested in the simulator. While the exact solution may not be found, if the pilot senses that a certain value corresponds to the actual aircraft response, then that value becomes a highly eligible parameter to be included in the simulator. Though qualitative in nature, this flight testing procedure allowed for the determination of valuable information in the minimum amount of time. Since pilot sensation may introduce a considerable amount of error, the simulator was setup for an on-site operation with the real aircraft, for continuous comparison purposes. Both aircrafts (real and simulated) were configured with the same deflection angle limits. The comparison was successfully completed in two flights and the behavior of the real and simulated aircraft were matched with considerable similarity according to the pilots.

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<tr>
<td>$C_{l_{\alpha}}$</td>
<td>0.303</td>
<td>0.178</td>
<td>0.210</td>
<td>0.140</td>
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<tr>
<td>$C_{m_{\alpha}}$</td>
<td>0.571</td>
<td>0.613</td>
<td>0.491</td>
<td>0.456</td>
</tr>
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</table>

**TABLE II: LATERAL-DIRECTIONAL CONTROL DERIVATIVES – TRAINER**

Once satisfied with the behavior of the model, the next step was to adjust the autopilot gains and obtain at least 10 hours of simulator training. This can be easily completed following the Aircraft Integration Guidelines [9] provided by CloudCap. The rest of the integration steps are described in the Steps to Autonomous Flight document [7]. After completing all the steps and checks, a first autonomous flight was carried out. With the aircraft in level flight and at a secure altitude the trims were captured and, following immediately, the entire autopilot system was engaged at once. No initial perturbation was
observed and all the flight test cards [8] were performed with minor modifications of the gains. No further modifications were needed.

IV. INVERTED V-TAIL UAV

The aircraft for which the fast autopilot integration procedure presented herein was conceived can be seen in Fig 6. This unconventional aircraft configuration makes good use of the AVL tool and the previous experience in modeling and tuning.

- Wingspan: 3.6 m
- Wing Area: 1.12 m²
- CAM: 0.349 m
- AR: 11.6
- Empty weight: 25 kg
- Engine: 3W-56iB2
- Propeller: 22 x 10
- Control surface gap: 4 mm

As was done with the conventional configuration, the geometry was modeled in AVL and the results put together with the engine and inertia models. Drag, lift and pitching moment characteristics were obtained from CFD results, and respective AVL outputs were replaced with them. Once the model was completed, simulation and qualitative flight testing for comparison was done.

As with the RC aircraft, two pilots with experience flying the Strix UAV reached the conclusion that the lateral dynamics and excess of control power were the issues, and so the respective derivatives were re-calculated.
Again, the objective was to match the responsiveness of the model to the feeling of the human pilot. Perhaps an important point to mention at this stage when using the simulator is that the AVL output has a linear behavior at high control surface deflection angles so it is only valid for small deflection angles. Starting from the AVL values, systematic reduction of them was performed until the pilots were satisfied with the aircraft’s responsiveness.

Regarding control derivatives, an important factor is the control surface gap which seriously affects the efficiency of the control power (this problem was solved in the upgraded version of the Strix). Given the construction of the Strix UAV control surfaces (Figure 7), the gap effect on the 3D lift slope can be calculated as efficiency by methods like ESDU [10]. For the geometrical data given in Table III, the control power with the unsealed gap is found to be 74% of the sealed gap case. With this efficiency in mind, the chosen values for the lateral-directional control derivatives were reduced from the theoretical values.

With these changes made on the model, a suitable gain set was found and the autopilot training was carried out in order to perform a successful first flight. The first autonomous flight was carried out flawlessly with nearly undetectable visual perturbation when the autopilot was engaged and minor corrections were applied to the gain set. The only major correction was the engine gain which was slightly elevated.

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<td>$C_{Yb}$</td>
<td>0.23</td>
<td>0.55</td>
<td>0.55</td>
<td>-</td>
</tr>
<tr>
<td>$C_{lp}$</td>
<td>0.41</td>
<td>0.56</td>
<td>0.57</td>
<td>0.59</td>
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</table>

TABLE III: LATERAL-DIRECTIONAL DERIVATIVES – STRIX UAV

![Fig. 7: Strix UAV control surface](image-url)

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<th>Chosen value</th>
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<td>$C_{l0a}$</td>
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<td>-0.105</td>
<td>-0.120</td>
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<tr>
<td>$C_{m0e}$</td>
<td>-0.493</td>
<td>-0.431</td>
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<td>$C_{n0e}$</td>
<td>-0.0329</td>
<td>-0.0291</td>
<td>-0.0284</td>
</tr>
</tbody>
</table>

TABLE II: LATERAL-DIRECTIONAL CONTROL DERIVATIVES – STRIX UAV
V. CONCLUSIONS

The procedure of using a vortex-lattice code to obtain a suitable model for hardware-in-the-loop simulation was applied successfully twice, resulting in correct-from-first-flight autopilot gain set. The AVL output was modified in both cases, mainly regarding lateral dynamics and control power derivatives. The control power derivative changes were the most influential in the model. The Strix UAV seems to have less control efficiency than theory predicts and a factor that may be affecting this efficiency is the gap in control surfaces that has not yet been properly taken into account in the AVL implementation. Nevertheless, the corrections were within normal limits according to alternative derivatives and control surface efficiency calculation methods and the final models were not only able to satisfy the human pilot expectations but also were good enough to produce two correct gain sets from first flight.

Future work on the subject may include the detailed modeling of the control surface gap effect directly in the vortex lattice code and the correction of the linear behavior of the AVL output regarding high deflection angles of the control surfaces so it can be used in the complete range of movement.

Piccolo autopilot system provides the possibility of using a doublet command in every axis and saving the corresponding response at a fast rate. Reducing data from these maneuvers could be an even faster and more efficient way to achieve a suitable aircraft model for the simulator. Given the quantitative nature of the data reduction procedure, a complete set of tools should be generated to perform the task. This composes the next step to obtain an advanced and time-efficient autopilot integration procedure.

REFERENCES