Optimal Control Strategies for a Ducted RUAV

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ABSTRACT

A comparison has been made between four control strategies for a mini ducted rotary UAV (RUAV). The design and the manufacturing of this ducted RUAV will be explained and presented. The maximum dimension of this UAV is 700 mm and its mass reaches about 10 kg in its final version.

The control strategies have been applied to a split control process of the RUAV : a first one for the altitude and the yaw control of the vehicle and a second one for the attitude and the horizontal position of the vehicle.

The four control strategies that have been examined and compared are :

- *PID (Proportional Integral Derivative) and LQR (Linear-Quadratic Regulation)*

- *PID and cascade saturations*

- *Backstepping*

- *Backstepping with integration.*

1.0 INTRODUCTION

The principal foundations for this Rotary UAV (RUAV) design incorporate safety and operational definitions. The most important are :

- A ducted rotor to reduce risk of injury during deployment, to protect the rotor from hitting obstacles when approaching objects (e.g. when flying close to trees, improving camouflage), to improve power consumption, to enhance hover qualities;

- No rotating anti-torque blades;

- Battery equipped, to reduce IR signature, to avoid smoke production, which would be the case when using an internal combustion engine, making the UAV more detectable and possibly hindering camera sight (e.g. oil deposition on lens), to reduce acoustical footprint and vibrations;

- Deployable at 2500 m in ISA +20°C conditions;

- A powerful camera with outstanding optical zoom, allowing to inspect a larger area when flying a fixed pattern, permitting to inspect targets more carefully when observing a stakeout from a fixed altitude, i.e. during hover or when landed temporarily on a building or similar;

- Use of a classic swash plate to control the rotor, avoiding the need for a complex flight control system and still allowing upgrades with piezo-electrics, possibly reducing weight.

A typical military mission is shown on Figure 1 and a civil application is presented on Figure 2.
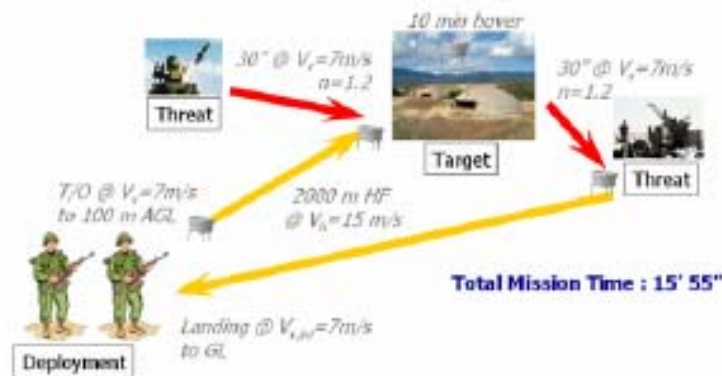

Figure 1: Military or (battlefield) surveillance RUAV mission profile

Five different flight conditions are considered :

- Vertical take off (T/O) to 100 m AGL @ 7m/s

- Horizontal flight (HF), 2 km @ 15m/s

- Manoeuvres for 30s with vertical speed of 7m/s and load factor of 1.2 g

- Hover, 10min @ 100 m AGL

- Vertical landing

All flight conditions are examined during the aerodynamics assessment, which will give an output for the average energy consumption.

Figure 2: Civil application, anti-terror or traffic monitoring mission profile

2.0   RUAV DESIGN

Figure 3 represents simplified the iteration scheme that was used to mainly determine the platform weight, battery choice and gearbox reduction.
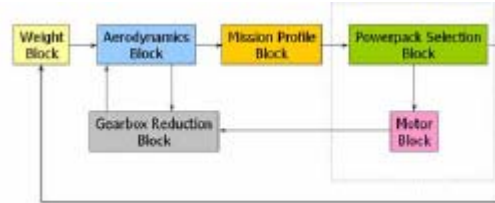

Figure 3: Simplified iterative design process

The iteration starts with an estimation of the platform's weight. This will allow an optimum rotor blade to be calculated in the aerodynamics block, releasing figures of power required in function of the flight conditions for a minimum blade RPM. The data is then applied in the mission profile block, which calculates an average power consumption. The power pack selection block takes this data into account as well as the maximum power required during the mission. This data, along with ambient conditions and several losses serve to determine the required engine power, thus also the engine, as well as the engine RPM. The RPM serves to determine the gearbox reduction. The resulting mass breakdown is presented in Figure 4.
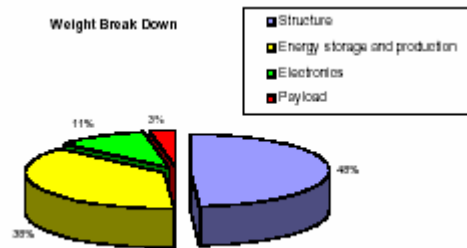

Figure 4: Platform mass breakdown

The rotor blades were iteratively designed using a modified blade element momentum theory completed with data obtained from X-foil©. The blades are non symmetric and have a washout. Depending on the flight and atmospheric conditions, the rotor can run up to 5.000 RPM. In order to reduce parasite rotor drag and to protect the rotor from dust and filth, the rotor is equipped with a rotor hub fairing. Unconventionally, the RUAV uses anti-torque vanes and blades to compensate for the rotor torque. Three fixed (stator vanes) and three (blades) movable "wings" are installed in the downwash of the rotor. The vanes are asymmetric, the blades are symmetric.
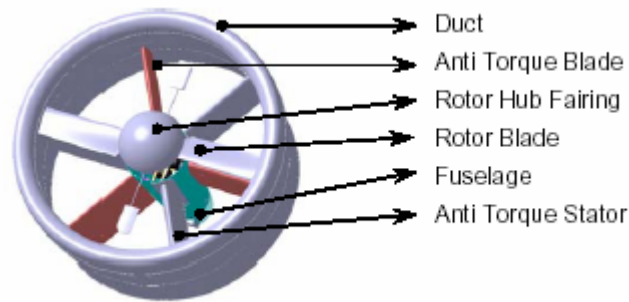This is shown on Figures 5 and 6.

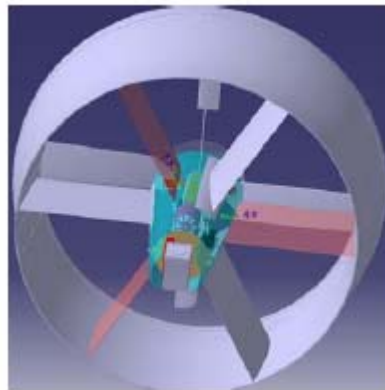**Figure 5: RUAV main components and their designation**

Figure 6: Blades for the anti-torque system and their high speed servo control

3.0   RUAV AERODYNAMICS

Rotor blade assessment : Before making moulds to produce the rotor blades, which is costly, one should verify the characteristics of the blade. Making a mould for an asymmetric evolutive blade requires many man-hours and is labour-intensive. Any modification on the blade that is pushed forward after examination of the wind tunnel results, requires the mould to be reconstructed or to be adjusted if possible, draining your budget and possibly endangering the project. Therefore, one decided to construct the first blade prototypes via stereo-lithography, using Optoform B material. Because of safety reasons, the blades of this brittle, stiff and strong material could not turn at RPM values higher than approximately 2500. Figure 7 reflects the results obtained with the rotor blades installed in the duct, in hover. At 300 rad/s and a pitch angle of 20°, the ducted rotor seems to produce enough thrust to lift the platform. The calculated blade profile was accepted and released for production.

The anti-torque system could not really be evaluated on beforehand. This because of the hard-to predict downwash velocities. Stators and blades were dimensioned from an estimated velocity field below the rotor. The airfoils for the wind tunnel application, were made from polystyrene foam wrapped in a glass fibre skin. Figure 7 shows that the blades need to deflect by approximately 1° in order to counteract all torque produced by the rotor. In fact, the stators absorb the biggest part of the torque, while the blades take only what is left (residual torque). If the residual torque were 0 Nm at 0° pitch angle, then, the optimum would be obtained. However, since the error of the measured blade pitch angle amounts to 1°, no changes were made to the configuration. The "excess" of torque is used for yaw control. Remark that the slope of the curves steepens with rotor pulsation, meaning that the directional responsiveness of the platform increases with rotor RPM.
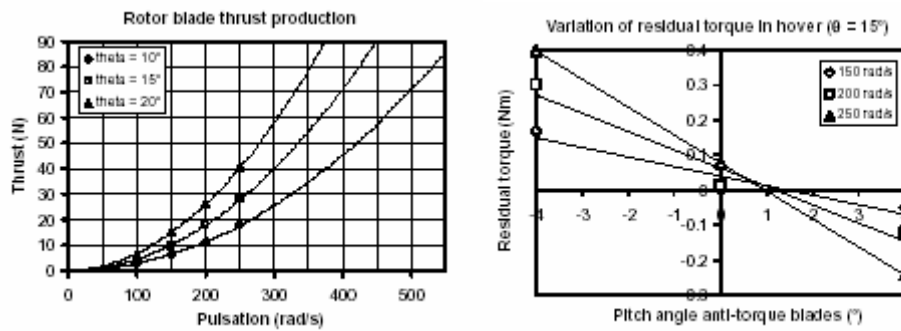
Figure 7: Experimental rotor thrust of a ducted system and anti-torque

Five duct shapes were examined. The ducts differed from each other by length, lip radius and divergence angle. During the tests, smoke helped to identify flow behaviour around the inlet. Figure 8.a shows, for the examined configuration, that the airflow remains attached to the lips, when accelerating. Even downstream the rotor, the divergent does not invoke flow separation. However, in forward flight (Fig. 8.b), the airflow changes direction dramatically, whereby the air is encouraged to separate much more easily. Still, at 7m/s, the lip radius seems to be adequately dimensioned, minimising losses.

Figure 8: Rotor flow visualisation in a wind tunnel in vertical (a) and horizontal flight (b)

4.0   RUAV CONSTRUCTION

The different components of the RUAV have been build. Some pictures for the manufacturing of the main rotor blades are shown on Figure 9. Those blades have been statically balanced only, not dynamically. The mould is in Ureol.

Figure 9: Main rotor composite blades and their mould

After the manufacturing, these components have been assembled into the RUAV. A first prototype was build mainly in order to have a mock-up and after a second prototype using a structure in carbon composites was assembled. This second prototype has been and is still used for test flights and the fine tuning of the control laws (Figure 10).

Figure 10: First mock-up prototype and the flight test prototype

5.0   RUAV FLIGHT CONTROL

The platform stabilisation is realised thanks to four gyros with accelerometers. The RUAV is also equipped with a Globalsat BR305 GPS, working with the NMEA 0183 V2.2 protocol. The refresh rate amounts to 10 Hz. For the data transmission, two 2,4 GHz channels are foreseen. One channel transmits the video data, the other sends position and flight data and receives flight commands. The channels are coded to avoid interference.

Before implementing the definitive control laws in the stabilisation system of the RUAV, it had to be decided which control strategy needed to be used and developed. With this objective in mind, different control strategies have been defined and simulated in Simulink for the case of hovering flight. Four control variables are available in our application : the collective pitch (u1), the lateral and the longitudinal inclination of the cyclic pitch (u2 and u3) and the anti-torque through the position of the blades of the anti-torque system (u4). Those 4 variables will be used to define and manage two controllers : one for the

altitude and the yaw (with u1 and u4) and another one for the attitude and the horizontal position (with u2 and u3).

Four control laws will be studied and simulated :

- Thanks to a PID controller, the altitude and the yaw position of the RUAV are controlled whereas the attitude and the horizontal position are controlled through a LQR method (Linear-Quadratic Regulation) on the linearised system around a hovering position – this method is therefore a "local" method;

- A PID controller is still used for the altitude and the yaw moment but a cascade of saturated controls is used for the two others (this is a MIMO method);

- The third method is based on backstepping, i.e a non-linear law which is not using the SISO structure and thus does not require to split up the controller into two separate units;

- A backstepping method including also an integration action.

Through the simulations that we realised on the RUAV described here above, the PID/LQR method has proven to be very efficient for the trajectory quality as well as the lower sensibility to a perturbation like a gust. The reason is inherently that the weak coupling existing between the vertical and yaw dynamics and the other state and the control variables allows to reduce the whole system to a SISO with a linearisation of the input and that the controller describing such a system in the best way is the PID controller. The only real concern existing for the implementation of this method is that the controls have to send signals to the actuators which are the final element of the control chain and will decide of the final movement of the RUAV. The problem is that those actuators can be easily saturated leading a highly non-linear system (the system will work in open loop until the end of the saturation). This phenomenon is known as the windup of the control system. Anti-windup schemes have then been implemented and tried with some success.

The second method has proven to be too slow and not very robust against the perturbations of the loads, like a wind gust. This is due to the typically low gains that are used in this method. An advantage of this method is its robustness against low signal-to-noise ratio's.

The third and fourth methods are purely non-linear and relies on Lyapunov's theory. Here we stabilise the whole system directly through a cascade from the signal the most separated from the controller back to this controller. The lack of an integral requires high gains to react to a perturbation adequately, what can be dangerous for the controller stability in an environment with a low signal-to-noise ratio. That is why we add in the fourth solution a time integration of the error that must converge to zero for all possible initial conditions. The fourth method offers a very large advantage : it reacts very quickly and with a low amplitude to any perturbation (gust, noise in the signals, ...). This solution offers also a very acceptable solution for the trajectory but not as good as the PID/LQR.

A few examples of simulations showing the advantages and disadvantages of the different methods are shown hereunder.

In Figure 11, one shows the influence of the gain on the answer of the system after a lateral gust. One sees that increasing gains are dynamising the closed loop system. But too high gains are not needed. This is due to the equations fixing the movements of the RUAV for which the dynamics is characterised by a give time constant.
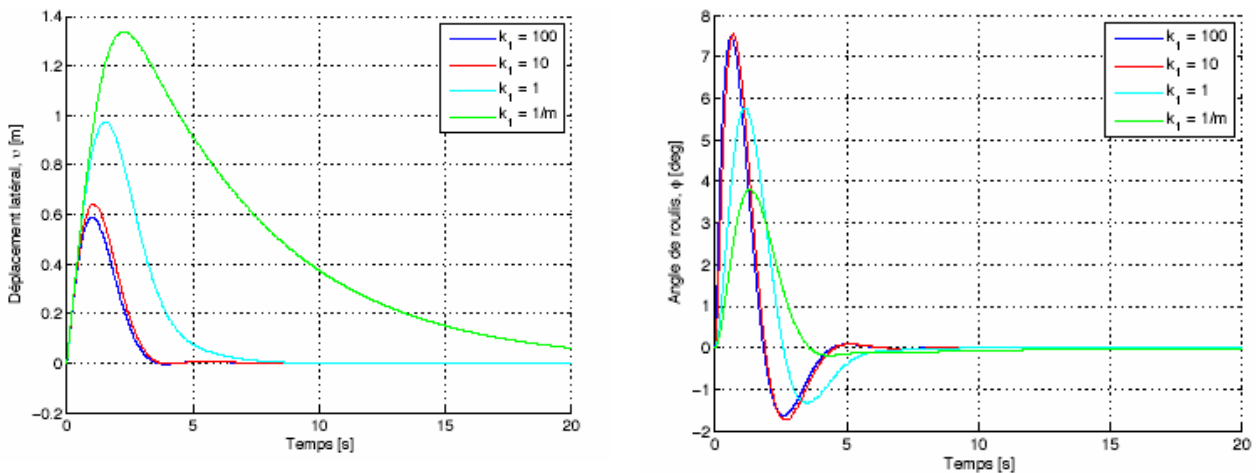
Figure 11: Backstepping method results (method 3) after a lateral gust

On Figure 12, one analyses the quality of method 1 and method 3 (with various gains) in the case of an error on the control variable u4 of the anti-torque system.
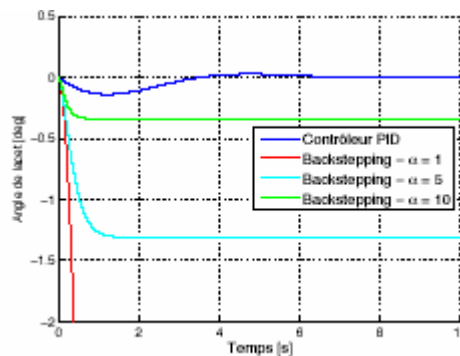

Figure 12

It is clear that method 1 reacts very efficiently on the perturbation, as this method contains an important integral action whereas method 3 needs high gains to obtain good results.

6.0   CONCLUSIONS

The design methodology followed for the definition and the manufacturing of a RUAV has been exposed and explained. Some elements of this RUAV manufacturing and assembly have also been presented.

For the control of this RUAV, a case study for hover has been realised, developing, simulating and comparing four control methodologies based on linear or non-linear theories. The robustness of these methods against realistic perturbations have also been simulated.

The most promising methods are the linearised PID/LQR method and, considering the uncertainty on the possible actuator saturation, backstepping method with an integration action on the steady error signal, allowing the use of not too large gains.

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