FLIGHT TESTING OF THE GYROC VTVL PLATFORM

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ABSTRACT:

Interest in Vertical Take-Off, Vertical Landing (VTVL) rocket-powered vehicles is now well established, both for re-usability for terrestrial launch vehicles, and for autonomous landing and flight-based ('hopper') exploration of other planets and moons. Low cost flight-test platforms are required for developing this next generation of VTVL missions, to prove new propulsion systems, guidance packages, and in the case of hoppers, test control strategies to minimise propellant consumption to safely and autonomously execute a hop. The utility of such techniques has been well proven, for example with NASA's Mars 2020 Lander Vision System, used to accurately land the Perseverence Rover in February 2021. This subsystem underwent extensive flight testing on Masten Space System's Xombie VTVL vehicle at Mojave Air and Space Port in California. Airborne Engineering (AEL) has created a VTVL platform (Gyroc) to develop experience in the design and testing for VTVL vehicles, with the goal of providing a european capability to test technologies for the new class of VTVL missions being considered.

The Gyroc vehicle has just begun a flight test programme, the bulk of which is to be carried out in the summer of 2022. We present the approach we are taking to the flight test programme and the results of some preliminary hovering and translation flights.

1. INTRODUCTION

Having demonstrated a first hovering flight with the Gyroc vehicle (see \cite Gyroc20), a programme of flight testing and vehicle modifications has now begun in order to learn more about the control and dynamics of VTVL vehicles. A collaboration has been started with the Technology for Aerospace Control Ltd. (TASC) who will assist in the analysis of the vehicle and make recommendations for more advanced control architectures. This project is being supported by the European Space Agency as a GSTP programme.

2. OVERVIEW OF GYROC VEHICLE

Gyroc is an experimental VTVL vehicle designed and built by AEL in Westcott, UK. It uses a liquid bipropellant engine (SNARK), which features an ablative phenolic liner and graphite nozzle. The oxidiser is Nitrous Oxide and the fuel in Isopropyl Alcohol. The SNARK engine has a nominal thrust of approximately 300N and can be deeply throttled (of order 5:1). More information about the engine can be found in [2].

The propellants are stored in composite-reinforced pressure vessels. The Nitrous Oxide is pressurised by its own vapour (~ 50Bar at 20℃) and the Isopropyl Alcohol is pressurised by Nitrogen Gas in the ullage volume at the top of its tank, at 80Bar. The propellants are metered through servo-actuated valves under the control of the avionics system, to select a specific thrust and mixture ratio. The engine is mounted on a universal joint at the bottom of the vehicle and is pointed by a pair of linear actuators of AEL's own design, controlled by the vehicle avionics. This allows a thrust vector to be commanded and realised an so allows complete control of the vehicle except in roll. There is currently no means of controlling the roll axis of Gyroc. More details about the vehicle can be found in [1].

Gyroc has a dry mass of ~16Kg and a wet mass of ~25Kg. This allows for flight times of approximately 30s (with comfortable margin) which for the basis of

Figure 1: Gyroc configured for its 2022 flight test programme

the design of this initial flight test programme. The vehicle as configured for a test flight can be seen in Figure 1.

Figure 2 gives an overview of the system architecture of Gyroc. Measurements from inertial sensors (Accelerometers, Gyroscopes), GPS and LIDAR are fused to provide an estimate of the vehicle's state. Control inputs are then calculated and sent to the engine control system to provide a commanded thrust and thrust angle from the propellant metering valves and engine actuators.

Gyroc has undergone some configuration changes for this flight campaign to address some issues identified in the first shake-down hovering test (see [3]). These are described below.

2.1. Vehicle Modifications to Support the Flight Test campaign

The initial shake-down hovering flight identified some issues that AEL elected to resolve in advance of the flight test programme. A number of ergonomic issues to improve and speed-up ground handling have been implemented (an important consideration when the test programme is to be conducted in the UK where only short good-weather windows may be available, and at short notice!). Additionally, two more serious vehicle modifications have been undertaken to improve the quality of the test flights - both the control and the quality of the data recorded.

2.1.1. Oxidiser Valve

Figure 3 shows the Nitrous Oxide metering Valve in its new position directly on the injector of the SNARK engine. Previously it was mounted on the vehicle in the plumbing area beneath the Oxidiser tank, with a hose connecting its output to the injector. However, it was observed in the initial shake-down flight that altitude response authority was lower than expected, and this was identified as being because of the interaction of the multi-phase (and so compressible) Nitrous Oxide with the relatively large volume of the connecting hose causing a low-pass filtering effect on the mass flow of propellant into the combustion chamber from a change in the metering-valve position. Moving the

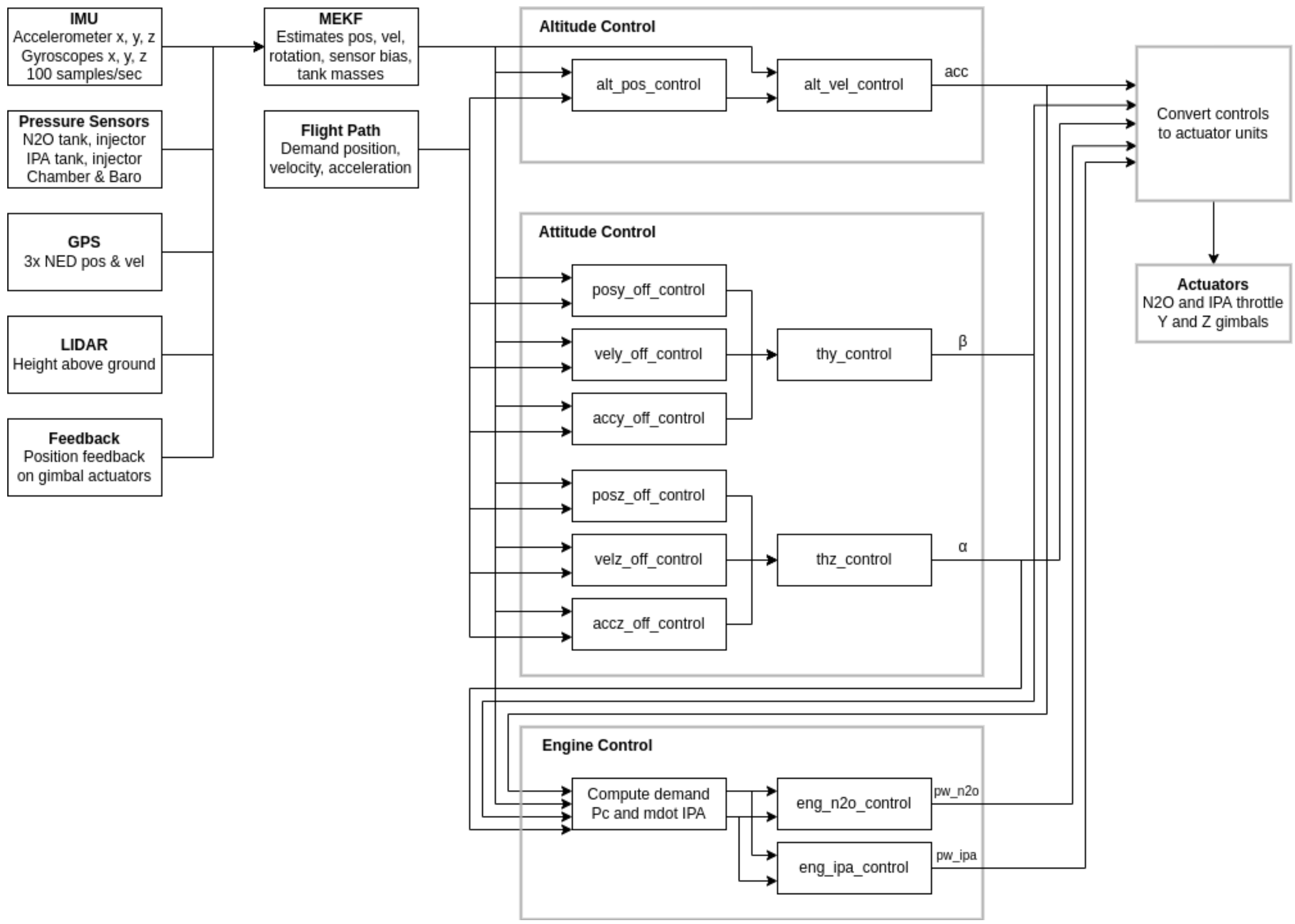

Figure 2: The system architecture of Gyroc's control system

metering valve directly to the injector head allows a more rapid response in mass flow into the chamber, and so an improved throttle response.

2.1.2. GPS Antennas

The second major change from the shake-down flight for this test programme is the replacement of the single GPS receiver with a Differential GPS (DGPS) system. In the shakedown flight the vehicle flew a single GPS receiver for position only, and relied upon the inertial sensors and a magnetometer to estimate its attitude. The magnetometer in particular proved an unreliable way to provide an accurate estimate for roll, given the magnetically 'busy' location of the test flights around AEL's J1 test bay.

The new DGPS system is comprised of three individual GPS receivers on the vehicle and a GPS receiver at a fixed point on the ground support equipment. A link between the ground GSE GPS receiver and the flight receivers allows each of the onboard GPS receivers to calculate their position relative to the GSE station to within a few mm in each of the three special dimensions. A lightweight spacing frame was constructed from carbon fibre and additively-manufactured plastic fixtures to mount these antennas to the vehicle but with a generous spacing from each other. In this way, measurements of the vehicle's attitude can be made in addition to vehicle's position, negating the need for a magnetometer and provided a stable reference for the inertial sensors to give an improved overall state estimation from the Kalman Filter. The DGPS 'hat' can be seen in Figure 4 and can be seen mounted to the top of the vehicle in Figure 1.

3. APPROACH TO FLIGHT TESTING

For safety reasons, Gyroc's intial flight test programme will be conducted with a safety tether. The

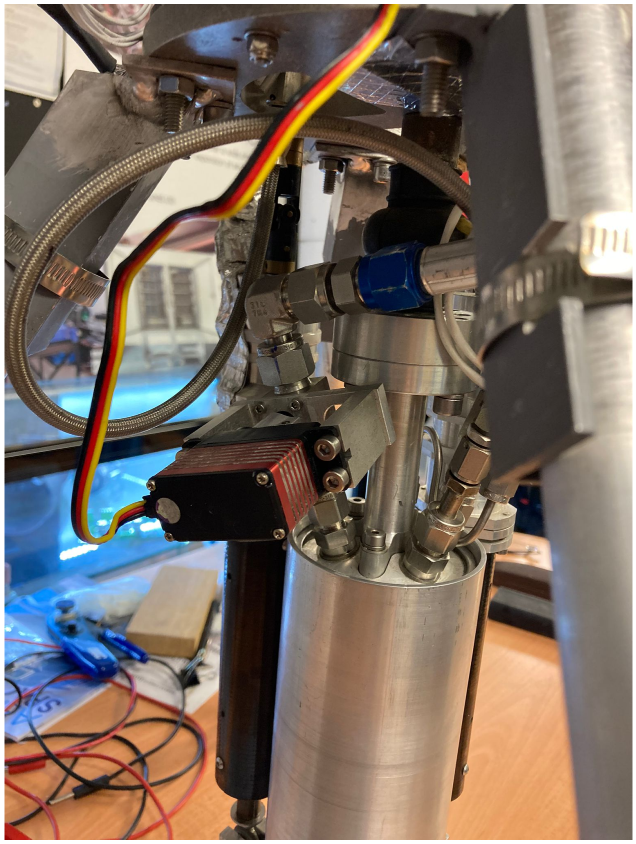

Figure 3: The Nitrous Oxide valve has been moved to the injector head from Gyroc's main fuselage to counter the response-filtering effects of the propellant feed line

tether is hung from a boom that has been extended from the roof of AEL's J1 engine test facility at Westcott.

Gyroc takes off from lightweight legs which lift it 0.5m from the ground. These legs are blown away after lift-off from the exhaust of Gyroc's SNARK engine. This means that in the event of a failure of the control system or engine, or an externally applied shut-down signal, Gyroc can be constrained by the tether without the risk of damage from re-contacting the ground (which would be the case if it took off directly from the ground without launch legs). As confidence in the vehicle's performance grows, it is likely the flights will be conducted with a longer tether and lift-off directly from the ground. This will allow precise landings to be studied.

All aspects of Gyroc have been developed internally at AEL - Mechanical, Avionics and Software. This fact, in combination with the tethered test facility being at AEL's J1 test stand - approximetely fifty meters from the design office and workshop, allows an extremely fast and iterative approach to flight testing, in which modifications can be rapidly made and then tested, without the logistics of external subcontractors or test facilities in the loop.

This ability has informed the approach that AEL is taking to the flight test programme, whereby the flight test envelope can be gradually and iteratively expanded based on the rsults of previous flights. Where necessary, hardware and software modifications based on the conclusions of preceding tests.

3.1. Flight Test Objectives

The purpose of Gyroc (or a derived vehicle) is to provide a simple and low-cost VTVL platform for testing hardware and ideas, for example scanning LIDARs or new control laws. This flight test programme aims to mature our understanding of the design, dynamics and operation of VTVL vehicles to reach this point. Some specific aims with this Gyroc vehicle are described below.

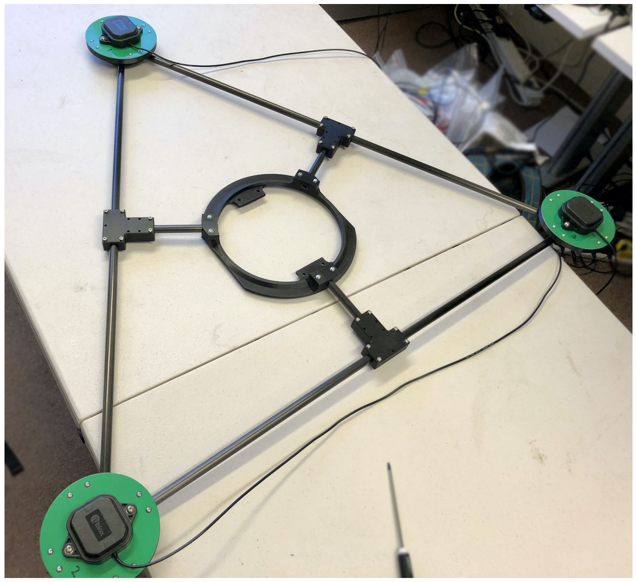

Figure 4: The three new GPS antennas fitted to a frame made of carbon fibre and additively-manufactured plastic. This upgraded system will provide three-dimensional position and attitude information.

3.1.1. Ignition

Gyroc is currently ignited pyrotechnically and the ignition timings are quite sensitive because of the requirement to get the Nitrous Oxide stably decomposing before offering the fuel. We aim to improve the robustness of the ignition sequence and explore how quickly the engine can be throttled up after ignition. This is especially important to allow the possibility of in-flight re-ignition in the future.

3.1.2. GSE Software Validation

A custom simulation environment has been created in-house by AEL to test the control system in advance of a real flight. Flight data gathered in this test programme with help validate our in-house codes, which can then be applied to the development of more advanced vehicles and more dynamic control systems.

3.1.3. Control Law Development

The initial shake-down flight was conducted with vary conservative control laws just to safely get the vehicle aloft and check-out all of its subsystems. There is a great deal of scope for improving the control law of the vehicle and assessing its robustness. We with to be able to analytically ascertain the performance envelope of the vehicle. AEL's collaboration with TASC will help greatly with this objective.

3.1.4. Free Flight

If, over the course of the test campaign, sufficient confidence has been developed with the vehicle and its control system, we would like to attempt a free-flight of the vehicle without the presence of the safety tether. The feasibility of this will also be determined by the availability of a suitable facility to perform a test flight - it is anticipated that going to an existing test range will be beyond the scope of this GSTP, however a 'drone cage' (a large netted enclosure) is scheduled to be constructed at Westcott 2022 and could be suitable. This opportunity will be explored as the flight test programme develops.

4. PRELIMINARY RESULTS

Gyroc has been flown on several occasions in 2022 so far, in advance of the test programme over the summer. Two particular representative flights are described here.

4.1. Hover Flight

This flight was the first flight to be performed after the hardware modifications were made as described above, and consisted of maintaining position and attitude a height of 1m above the liftoff position for approximately 10s before a powered descent onto the tether. A sequence of stills from the video of the flight

Figure 5: A sequence of stills from a hovering flight under the tether. The stills depect the lift-off and shut-down sequences, the central hovering still are ommited.

is shown in Figure 5. The vehicle was able to maintain its position over the ground to within approximately 0.2m throughout the flight.

4.2. Translation Flight

Having demonstrated a stable hover, a flight was attempted that included some lateral translation. The flight path consisted of lift-off, 4s of hover, 4s of translation 1m, 4s of hover, 4s of translation back to the original position, 4s of hover, then descent onto the tether. Figure 7 shows a sequence of stills from this flight. The 1m of translation commanded was in the direction away from AEL's J1 test bay, which appears to be a movement to the left from the point-of-view of the camera.

This was Gyroc's first attempt at translating from a stable hover to a new position and then returning. A graph of its position over the ground is shown in Figure 6. There is a slight over-shoot of approximately 0.4m on the return part of the manoeuvre. The cause of this is being investigated at the time of publication but may be something to do with the roll (which Gyroc cannot control) induced by the tether coming to rest on the top of the vehicle once it has lifted off.

5. FUTURE WORK

This paper describes the progress of the Gyroc flight testing GSTP programme to date, but the bulk of the test programme will be conducted this summer. As described above, we will iteratively expand the envelope of dynamic performance under the tether and use the flight data to improve our control laws and simulation models. If the results suggest the vehicle is capable of performing such a flight, we will attempt to perform a free-flight off the tether. We will also work with TASC to test-fly an advanced control law of their design, as an experimental payload on Gyroc, to demonstrate its ability as a tool for testing control methodologies. This testing work will the inform the design of a more advanced and capable follow-on vehicle.

6. CONCLUSION

VTVL is an important and enabling technology in the future of both launchers and planetary and lunar exploration missions. It is vital to have a test-bed to explore and test the technologies and principles around VTVL. AEL has performed what it believes are the first flight demonstrations of a liquid-rocket VTVL vehicle in Europe. Specifically, it has shown that Gyroc can safely lift off and move around under its safety tether at its test facility in Westcott, UK. AEL is about to embark upon a flight test programme to better understand VTVL technology, with an emphasis on better understanding VTVL control with TASC Ltd, and expand the flight envelope of its Gyroc test vehicle.

The results of this flight test program should inform the design of a more sophisticated and capable, but still comparatively low cost VTVL test bed that will be available for end users to test fly any sort of technology relating to VTVL, both in hardware and algorithmically.

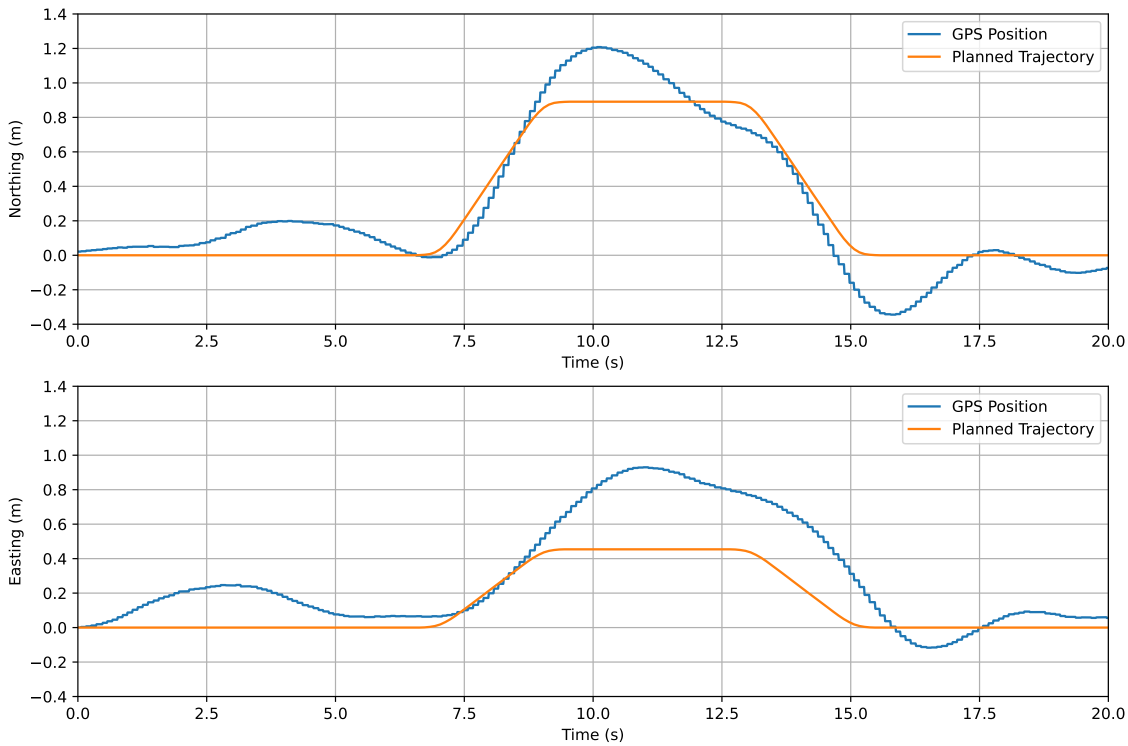

Figure 6: The Commanded translation manouvre of 1 metre (orange) and the measured result from the DGPS system (blue), in the Northing and Easting Co-ordinate system, vs time.

Figure 7: Sequence of stills from a test flight, Top-Left to Bottom-Right: Ignition and self-check, lift off to hovering altitude, begin translation left, hover in new position, begin translation right, hover in original position.

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