VTVL technology demonstrator for planetary landers

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VTVL TECHNOLOGY DEMONSTRATOR VEHICLE FOR PLANETARY LANDERS

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ABSTRACT:

There is increasing interest within Europe in carrying out a robotic Lunar or Martian planetary landing mission. This kind of mission requires the development of technologies such as autonomous landing and hazard avoidance. These technologies require testing in a representative environment, such as on a VTVL (vertical take-off, vertical landing) vehicle. VTVL platforms have been developed in the USA, such as the NASA Morpheus project. However, there is a need for access to such a vehicle in Europe for evaluating technologies such as LIDAR instruments and for validating hazard detection and avoidance algorithms.

To address this need, a project is underway at Airborne Engineering to develop a VTVL technology demonstrator. A sub-scale vehicle, based on a 300N throttleable bipropellant thruster, has been constructed and static tested. The paper will present details of the design and testing of the sub-scale vehicle as well as outline details of the full-sized platform which will be able to flight-test lander instrumentation, payloads and propulsion sub-systems.

1. INTRODUCTION

Robotic exploration of celestial bodies requires a technique of safely landing on the surface. Where there is no appreciable atmosphere, such as in the case of lunar missions, this is achieved with retro-rockets to control the descent. Where there is an appreciable atmosphere, such as in the case of Mars, this is achieved with aeroshells followed by parachutes for initial deceleration, before an additional method of final deceleration for landing. In both the Mars Exploration Rover and the Pathfinder missions, this was achieved with retro-rockets followed by airbags.

In almost all cases to date, the trajectories have been modified before atmospheric entry to choose a rough landing site, but there has been no method of controlling the exact final landing position. A step change in technology was demonstrated by NASA's MSL mission in 2012 with the landing of the Curiosity rover, however, with the introduction of the Sky Crane concept. Here the entry vehicle consisted of two parts: the Sky Crane and the rover. The final deceleration was achieved with eight retro-rockets on the Sky Crane, which retarded the vehicle to near zero velocity; then four of these retro-rockets steered and hovered the vehicle whilst the rover was lowered to the surface with a bridle and umbilical cord. Once safe touchdown was detected, the bridle was cut and the Sky Crane used the remaining fuel to evacuate the area to protect the rover from damage and the landing area from contamination.

This technique presents several advantages: first, it allows a much higher landing mass than is possible with airbags; second, the touchdown velocity can be arbitrarily slow and the touchdown orientation is known; and third, it allows for the possibility to control the exact landing position to avoid small scale hazards such as boulders, craters or slopes. Although the MSL mission had descent imaging and steerable retro-rockets, this imaging was not used by the craft for real-time hazard avoidance.

Real-time hazard avoidance is now technologically feasible due to advances in imaging, computer vision algorithms and computer hardware. Commonly, the hazard avoidance methods feature sensor fusion between an Inertial Measurement Unit (IMU) and a LIDAR to provide real-time relative terrain mapping. The mapped terrain is then scanned by hazard avoidance algorithms to provide the optimum landing position and flight path. Real-time hazard avoidance is now being actively studied by guidance, navigation and control (GNC) teams across the world, most notably by NASA's Autonomous Landing Hazard Avoidance Technology (ALHAT) programme.

The ALHAT programme has successfully demonstrated avoidance of slopes and boulders whilst flying on the Armadillo Pixel and later NASA Morpheus vehicles [1, 2], and also the Masten Space Systems' (MSS) Xombie vehicle [3]. NASA's Morpheus vehicle has a single gimballed 24kN engine and a roll reaction control system (RCS) that uses LOX/LCH_4 to provide realistic rocket dynamics with a flight time of several minutes. Masten's Xombie vehicle uses a single gimballed LOX/IPA engine with 4kN thrust. Such vehicles have been designed to be simple and wherever possible use commercially available components in order to reduce programme cost [2].

There is increasing interest within Europe in carrying out a robotic Lunar or Martian planetary landing mission with precision landing. This requires autonomous landing and hazard avoidance technologies to be developed. Hazard avoidance algorithms are being actively studied with computer simulations, but they require testing in a representative environment, such as on a VTVL (vertical take-off, vertical landing) vehicle. Current European work on autonomous hazard detection, such as the ESA StarTiger project, has demonstrated real-time hazard avoidance but only using a quadcopter test bed [4]. As yet, there is no European rocket powered vehicle suitable for testing these systems with representative dynamics.

1.1. Gyroc programme

Gyroc is a technology demonstrator for a VTVL planetary lander or hopper. It was developed at Airborne Engineering (AEL) as part of an internal R&D programme to develop experience in the design and control of VTVL vehicles. It is the fifth vehicle in the Gyroc series, but the first to use throttleable liquid propellants - previous vehicles used solid or hybrid motors. The current vehicle is designed as a technology demonstrator for an up-rated vehicle that will carry payloads for commercial use. Because the current Gyroc vehicle is not expected to carry payloads, several compromises in the design were made to keep project costs low and timescales short. This has allowed a lot of experience to be gained with a relatively 'quick and dirty' approach.

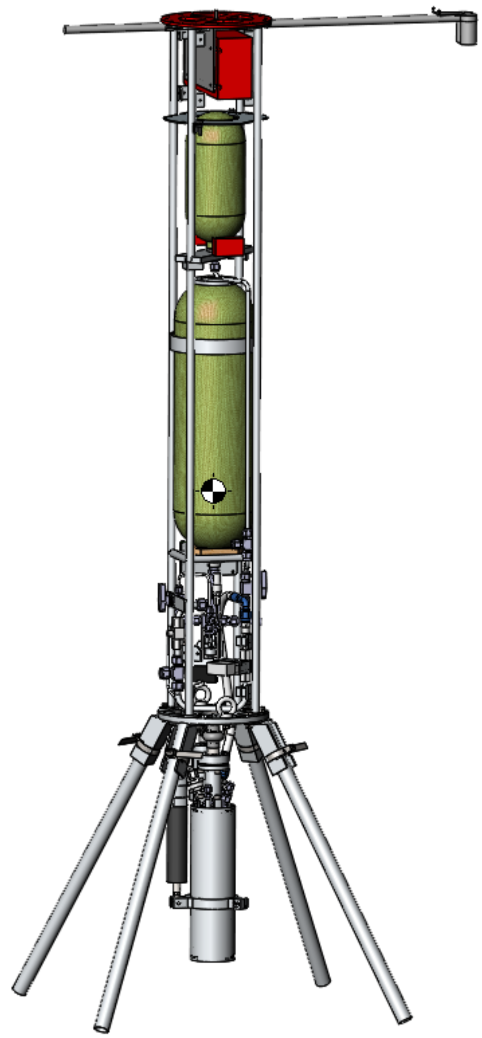

Figure 1: CAD rendering, configured for flight with lightweight landing legs

The Gyroc programme is somewhat unique within Europe, however, and with relatively little extra development the next generation vehicle could become a platform with a large variety of applications. In particular, for validation of advanced GNC hardware and software for planetary missions, in a manner similar to the MSS Xombie vehicle. This would yield high TRL demonstrations of new sensor hardware and new algorithms for landing site selection, optimal trajectory calculation and terrain avoidance.

It is intended that the current generation vehicle is used to gain VTVL experience and to qualify the GNC hardware and methodology before committing to a full vehicle redesign. It is anticipated that the next generation vehicle would use LOX/LCH_4 propellants with a 4kN regeneratively cooled engine to provide sufficient payload capacity and flight time.

This paper will cover the basic design of the current Gyroc vehicle, the status of testing to date and the roadmap for the future of the project.

2. MECHANICS

The current Gyroc vehicle is not expected to carry payloads, and only requires a typical flight time of 20s. It does not require a high propellant mass fraction, therefore, so it is designed to keep costs low and timescales short.

The Gyroc vehicle uses off-the-shelf parts where possible, or parts repurposed from internal stock. For instance, the fuel and oxidant tanks are metal-lined, composite-overwrapped pressure vessels that were re-purposed from breathing-apparatus sets, or paint-ball CO_2 cannisters. The propellant feed system is made using Swagelok components, preferring aluminium fittings wherever possible to reduce mass, or stainless steel for reduced cost or for particular items (e.g. valves).

Fig. 1 shows the current Gyroc vehicle. It consists of the following primary components: a gimballed Snark engine steered by two linear actuators, two pressurised propellant tanks, two low-mass throttle valves and the GNC avionics. Some of these primary components will be described further in the following sections.

2.1. Throttle valves

Throttling is achieved using modified Swagelok valves actuated with digital servo drives. Drive shafts were connected with either a rigid coupling (N_2O valve) or a bellows coupling (IPA valve) to allow valve shaft rise. The valves and servos were matched to give sufficient resolution over the required flow range and to provide a positive shut-off. The throttle valves are calibrated to characterise the relationship between pulse width and flow discharge coefficient.

One problem overcome during development was hysteresis in the flow rate; there was a substantial offset in measured flow rate dependent on the drive direction. This hysteresis was substantially reduced by upgrading the servo to a higher torque model, but it is uncertain whether the improvement was down to torque or the servo's internal control loops.

Table 1: Data for the Snark bipropellant rocket engine

Snark Engine Data (300N Version)	
Fuel	Isopropyl Alcohol
Oxidant	Nitrous Oxide
Throttle range	20%-117%
Nominal full thrust	300N
Measured performance at full thrust:	
Measured c*	1487m/s
c* Efficiency	95%
Specific Impulse (sea level)	215s
Oxidiser to Fuel Ratio	6:1
Equivalence ratio	1.1:1
Expansion ratio	1:4.7

2.2. Snark engine

The Snark engine is a variable thrust bipropellant engine developed by AEL. Snark uses low-hazard propellants (isopropyl alcohol and nitrous oxide), with the advantage that nitrous oxide is self pressurising and therefore does not require a separate pressurant. The isopropyl alcohol is fed from a tank that is pre-pressurised with Nitrogen. Because the tanks are rated to 300bar, the initial pressure can be high and the pressure drop over the short firing duration is acceptable. The throttle control system is calibrated to take account of this upstream pressure drop to maintain the required mass flow. Tab. 1 gives numerical details of the Snark engine.

Similarly to the rest of the Gyroc vehicle, the Snark engine is designed to be simple, easily modifiable and low cost, with the view that it will only be used for short duration firings. It has a modular construction which can be configured for a variety of thrust levels up to 4kN, to account for any changes in vehicle design. The injector block was designed for minimal parts count and ease of interchanging injector designs. The chamber is constructed from a simple aluminium tube around an ablative canvas phenolic liner of sufficient thickness for several firings; the nozzle is a simple conical design made from graphite. Both of these can be trivially replaced after they have become too degraded, or modified easily as required. It should be noted that the canvas reinforcement is wrapped circumferentially as this is a vastly more economical than conical wrapping.

The Snark engine has been static tested successfully at a range of throttle levels. Fig. 2 shows images

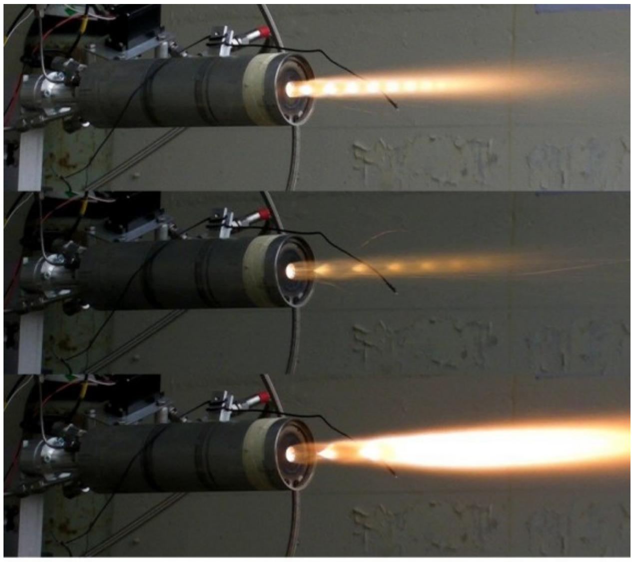

Figure 2: Throttle testing of the Snark bipropellant engine

from a horizontal static-test at three different throttle levels. The black wire visible in the image is a pyrotechnic igniter used at engine startup; the current generation of the vehicle cannot perform in-air restart.

2.3. Actuators

The Snark engine is gimballed by mounting it on a single universal ball joint, and is steered by two high-speed electric actuators. The universal joints of the actuators and engine are mounted in plane, such that the actuators can act independently in perpendicular directions. The actuators need to have high speed and low mass. High speed actuators available at the time of design were out of budget, while most other actuators were too slow with excessive torque.

Fig. 3 shows the design of the custom flight weight actuator used in the Gyroc vehicle. It uses a Maxon brushless motor with integrated tachometer, continuous torque of 21.8N and stall torque of 112N. When combined with a 1mm lead ball screw, the actuator has a maximum linear speed of 0.3m/s with high position repeatability and sufficient torque for high acceleration. An earlier design of the actuator used a linear potentiometer for absolute position reference and a standard brushed DC motor. This was susceptible to cogging, however, and therefore did not give the position repeatability required for maintaining stable control of the Gyroc vehicle.

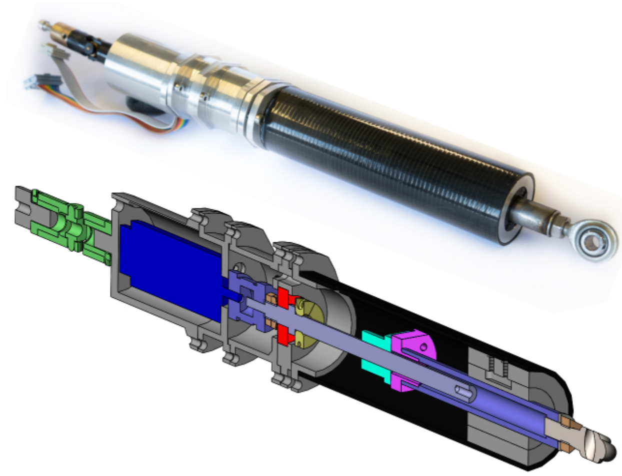

Figure 3: Custom flight weight actuator with aluminium and carbon fibre housing, showing the universal joint (green), motor (dark blue), coupler (light blue), retaining nuts (orange), thrust bearing (red), collar (yellow), ball nut (cyan), coupler (magenta) and linear ball spline (light blue).

3. AVIONICS

The GNC avionics are custom designed for the Gyroc vehicle. The avionics consist of an ARM Cortex M4 STM32F407 microprocessor with hardware floating point, an AEL data acquisition board for pressure sensors, an Analog devices ADIS16407 10-DOF inertial sensor, a Ublox MAX-8 GPS chip, a Lightware SF01/A single-point LIDAR and an AEL Touchbridge board for motor control. Both the data acquisition board and the Touchbridge motor control board are standard items from AEL's in house data processing and control system, designed originally for its static propulsion test facilities.

The avionics have 16 sensor readings relevant to inertial measurement: 3-axes of MEMS gyroscopes, accelerometers and magnetometers, GPS position and Doppler velocity, and a single-point LIDAR reading for altitude. Some care needs to be taken with the sensor data, however, because each reading has noise, accelerometers and magnetometers have bias offsets, and gyroscopes have drift - a much larger problem with cheap MEMS gyroscopes, rather than the more expensive fibre optic or laser ring gyroscopes.

The IMU in the current avionics system uses a sensor fusion algorithm to achieve the most accurate state estimate from the 16 sensor readings. The algorithm uses a Multiplicative Extended Kalman Filter (MEKF) with a 19-dimensional state vector to esti-

Figure 4: Main GNC avionics board, designed by AEL, featuring a 10-DOF IMU, GPS and interface to external LIDAR.

mate biases and offsets. The filter uses quaternions to quantify vehicle attitude in a local North-East-Down (NED) frame, fixed before flight begins. This requires conversion of Earth-Centred-Earth-Fixed GPS position and velocity measurements into the NED reference frame before they can be used in the Kalman filter.

3.1. Simulation and control

A full 6-DOF simulator has been written with the *Python* programming language to evaluate controllers for attitude and position control. Much of the vehicle dynamics can be expressed algebraically as transfer functions that incorporate the vehicle mass, moments of inertia and geometry, but these are constantly changing with time as the propellants are used. For the short flight times of the current Gyroc vehicle, transfer functions are generated based on the average masses and moments of inertia of the vehicle, rather than attempting to use more complicated adaptive techniques. Controllers are then designed for stability using standard root locus and frequency domain techniques. The controllers are then tested in the simulator to see how they perform when the transfer functions change during flight, and when there is sensor noise in the system.

The GNC software has been designed for ease of changing controllers whilst optimising performance during testing. Controllers are abstracted such that only the coefficients of the continuous domain transfer functions must be specified. On initiation, the software then automatically transforms the transfer functions from the continuous to the discrete domain, based on the control loop timescale, and then allocates buffers for the time delayed inputs and outputs of the controller. This means that it is extremely quick to apply a new controller to the flight vehicle.

Figure 5: Gyroc vehicle as built, configured for static-tests mounted on a heavy thrust measuring structure

4. ROADMAP

The Gyroc vehicle is fully built and currently entering final subsystem testing before proceeding to the first attempted hover test. The Snark engine throttling has been tested, as has the gimballing of the engine using the custom actuators. The GNC IMU has passed initial testing requirements and is currently undergoing final software modifications.

The immediate test roadmap for 2016 is as follows:

- Static-testing of the Snark engine to verify accuracy of throttling control loops.
- Static-testing of the ignition and abort procedures.
- Tethered hover tests.
- Free flight hover tests, followed by free flight with short traverse.

Subsequent to this, further free flight tests will be used to fully validate Gyroc's GNC system before up-rating the engine and tankage to allow longer flights and enable third-party payloads to be carried. It is anticipated that the next generation vehicle would use regulated pressure fed LOX/LCH_4 propellants with a 4kN regeneratively cooled engine to provide sufficient payload capacity and flight time.

5. CONCLUSIONS

There is increasing interest within Europe in carrying out a robotic Lunar or Martian mission with precision landing and autonomous hazard avoidance. These technologies require testing in a representative environment, such as on a VTVL vehicle with representative dynamics. Although such vehicles currently exist in the USA, no such European vehicles exist.

Gyroc is a technology demonstrator for a VTVL planetary lander or hopper. It was developed in-house at Airborne Engineering (AEL) as part of an internal R&D programme to develop experience in the design and control of VTVL vehicles. It is hoped that the experience gained with the current vehicle will guide the design of an up-rated vehicle suitable for carrying payloads to validate advanced GNC hardware and software. This would yield high TRL demonstrations of new sensor hardware and new algorithms for landing site selection, optimal trajectory calculation and terrain avoidance.

The Gyroc vehicle is fully built and currently entering final subsystem testing before proceeding to the first attempted hover test in 2016.

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