C-HEMH-2: An Actively-Stabilised Model Rocket
Technical Milestone Report

David Wyatt, 18 January 2007

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Summary

The aim of this project is to design and build an actively-stabilised low-altitude rocket. The selected concept uses small carbon dioxide thrusters to control the vehicle's orientation in addition to the main rocket motor. Work to date has focused on overall system design, modelling, component selection and procurement. Incremental development of the control system should lead to an initial test flight near the beginning of March 2007, with scope for further development of the project thereafter.

Background

This project involves the design and construction of an actively-stabilised model rocket – one that uses an electronic control system to compensate for the inherent instability of its flight dynamics. In particular, this project will use non-aerodynamic means to effect stabilisation. The rocket will be built primarily from commercially-available components and materials.

This contrasts with conventional hobby rockets which are passively stable and rely on aerodynamic forces on their fins for straight flight. The increased complexity and expense of stabilisation, coupled with the small size of hobby rockets, means that actively-stabilised hobby rockets have been built only rarely in the past ([1], [2]), although the vast majority of commercial rocket-powered vehicles use such systems (since stabilising fins would be impractical on a vehicle of such a size).

Maximising height is not a goal of this project (although it is one of the motivations for it – see below); instead, the aim will be to maintain a relatively long flight at a low altitude through use of a long-burning motor. The baseline motor specified at the outset this project is the Estes E9-P, with a burn time of 3.09s with an average thrust of 9N ([3], [4]).

The main motivations for undertaking this project are as follows:

- As stated above, it is difficult – and hence an interesting challenge – to engineer an active stabilisation system for the small size and mass of a model rocket.
- A common aim in hobby rocketry is breaking apogee altitude records. Here passive stability can be a hindrance on a windy day as it causes rockets to turn into the wind and fly at an oblique angle ("weathercocking"), reducing their apogee height and increasing the drift distance from the launch point. An active stabilisation system fitted to a high-power hobby rocket would ensure vertical flight even in windy conditions.
- Non-aerodynamic attitude control systems are obligatory for vehicles that operate outside the atmosphere – for example, landing on the lunar surface. NASA's recent Vision for Space Exploration [5] involves the development of hovering rocket-powered lunar landers, to which end the agency made development of a such a vehicle one of its Centennial Challenges with a $2 million prize [6]. On a model rocket scale, Cambridge University Spaceflight's Martlet project [7] aims to launch a small rocket from a weather balloon at an altitude of 30km; since the density of air at this altitude is

1.5% of that at sea level [8], and thus the aerodynamic restoring torque is significantly reduced, non-aerodynamic stabilisation is of key importance.

Progress to date

Concept selection

Numerous methods of non-aerodynamic attitude stabilisation and control have been implemented over the history of spaceflight; Table 1 describes the main methods. Although previous non-aerodynamically-stabilised hobby rockets have employed a gimballed engine to give the required control ([1], [2]), the concept evaluation in Table 2 suggests that attitude thrusters would offer a better alternative; thus this was the concept chosen.

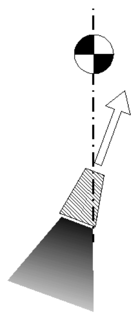
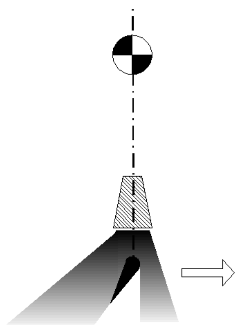
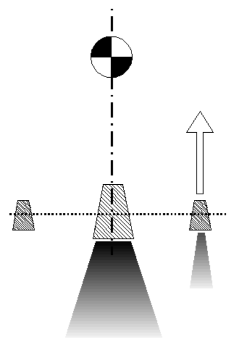
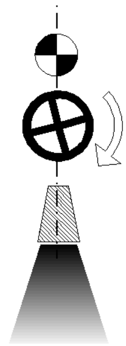
Method	**Gimballed main engine**	**Jet vanes**	**Attitude thrusters**	**Reaction wheels**
Diagram				
Description	Main engine(s) is/are offset from the centre of mass with two actuated rotary degrees of freedom, producing control moments by tilting the thrust vector.	Aerodynamic vanes of a refractory material are placed in the exhaust plume of the rocket to redirect it and (by reaction) exert torques on the vehicle.	Small throttlable thrusters are offset from the centre of mass and activated to provide control moments.	Heavy flywheels are accelerated or decelerated to provide (by reaction) control moments about their axes.
Examples	Saturn IB/V, Space Shuttle (main engines), Apollo Lunar Module (descent stage), Gyroc [1], Casimiro [2]	Robert Goddard's early rockets, World War II V2 missile	Satellites, Apollo Lunar Module (ascent stage), Space Shuttle (reaction control system), Harrier aircraft	Satellites

Table 1: Concepts for non-aerodynamic attitude control

Criterion	Weight	Concept			
		Gimballed main engine	Jet vanes	Attitude thrusters	Reaction wheels
Cost	2	DATUM	0	0	-1
Applicability to high-power hobby rockets	2		1	-1	-2
Simplicity of design	3		-2	1	-1
Simplicity of construction	3		-1	1	0
Robustness & reliability	3		-1	1	0
Mass	2		0	-1	-2
Independence of attitude control system from rocket motor, to simplify testing	3		0	1	1
Total score		0	-10	8	-10

Table 2: Attitude control system concept evaluation

Control system architecture

The proposed architecture for the vehicle's attitude-thruster-based control system is shown in Figure 1. The microcontroller reads the values of the inertial sensors (rate gyros and accelerometers) to estimate the current position and orientation of the vehicle. The control law is then applied to the estimated position to derive thruster commands. Through pulse-width modulation, the thruster commands govern the duty cycle of solenoid valves which allow the flow of compressed gas to the thruster nozzles. A log will be kept of all key variables to assist future development of the control system.

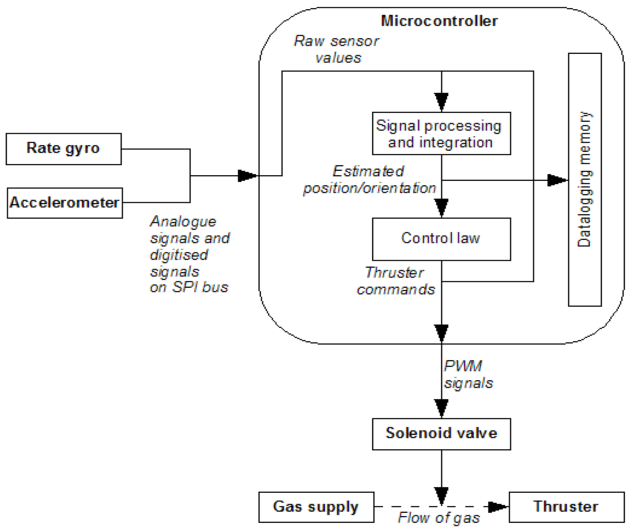


Figure 1: Control system architecture. In the complete system there are multiple rate gyros, accelerometers, solenoid valves and thrusters; for clarity, only one of each is shown.

Flight simulation (1D integrator) and mass selection

Since the thrust curve of the rocket motor is fixed (to within manufacturing tolerances), and since aerodynamic forces are relatively unimportant at the low flight speeds at which the vehicle will operate, the main variable giving control over the flight profile is the rocket's mass. A 1D numerical integration was constructed in Matlab to simulate flight profiles for a range of masses (disregarding aerodynamic forces and changes in mass of the rocket during the flight) using a sample E9-P thrust curve ([4]), the results of which are shown in Figure 2. For a vehicle mass of over 1.02kg the flight ends before motor burnout (hence the sharp "kink" in the landing velocity curve), which is potentially dangerous; conversely, it is desirable to minimise the landing velocity to avoid damage to the vehicle's components. A nominal mass of 1.00kg was thus chosen, giving a theoretical apogee height of 1.54m and landing velocity of 4.18m/s. The flight profile for this mass is shown in Figure 3.

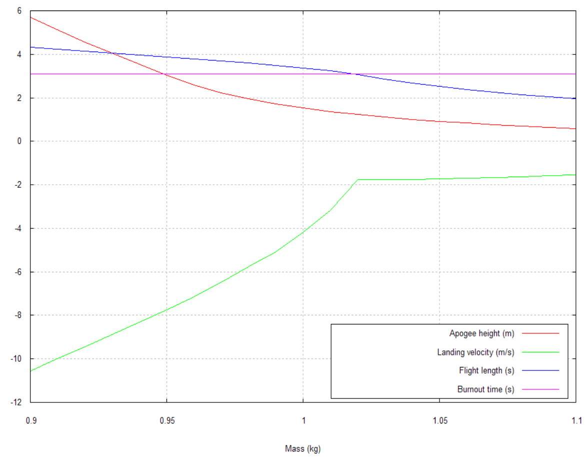


Figure 2: Modelled variation of flight parameters with mass.

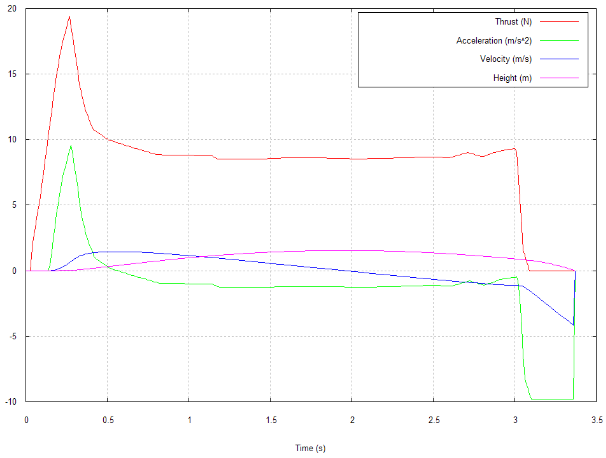


Figure 3: Modelled flight profile for a 1.00kg rocket.

Pneumatic system

The enabling technology for the attitude thrusters is the use of small cylinders of liquid carbon dioxide, commercially available for the inflation of bicycle tyres [9], as the gas supply. The vapour pressure of CO_2 at ambient temperatures is around 50bar [10], considerably higher than the pressure of industrial pneumatics systems; thus a pressure regulator is the first component in the test set-up that has been assembled. The pressure reduction corresponds to a decrease in specific impulse from 53s to 41s (exhausting to atmospheric pressure).

A converging-diverging de Laval nozzle was designed, following the method in [11], to give a thrust of 1N with an inlet gauge pressure of 5bar. Such a nozzle is predicted to consume 2.5g/s of CO_2. A prototype nozzle was fabricated by Mechanics Lab technicians and was measured to produce a thrust of 0.73N at 5bar using the workshop compressed air supply.

Key component selection

- **Microcontroller:** In order to avoid the need to change processors in future and to simplify construction and troubleshooting design effort, the union of the capabilities required for both this project and C-HEMH-1 (High power rocketry) were taken as a minimum specification for the processor. In particular, the number of analogue input channels and the speed requirement restricted the choice significantly. The processor selected was the LPC2138, produced by NXP [12], on a development board produced by Embedded Artists [13].

- **Rate gyro:** The selected component was the ADIS16250, produced by Analog Devices [14]. The built-in analogue-to-digital conversion and calibration features of this component will simplify the development of the control system significantly. Again, this component will also be used for the control system in the C-HEMH-1 project.
- **Solenoid valve:** The specifications on the valves controlling thruster duty cycle are low mass, high pressure rating and high flow rate. Prediction of the pressure loss across the pneumatic circuit produced a requirement on the valve of a minimum gauge pressure rating of 7bar and a minimum C_v value of 1.55; a suitable valve was found in the MHE3 produced by Festo [15].

Safety

Safety has been, and will continue to be, paramount throughout the project. The identification of safety issues in this project has involved submitting a comprehensive risk assessment to Cambridge University Engineering Department and adoption of the UK Rocketry Association (UKRA)'s published Safety Code [16], in particular the section relating to experimental rockets. Test flights will take place at East Anglia Rocketry Society (EARS [17]) launch days under the supervision of a designated Range Safety Officer.

Future work

The work to come comprises three key phases, the completion of the last of which will involve a successful flight with 2DoF stabilisation at an EARS launch day, and thereafter a number of potential extensions (described below). Figure 4 shows a Gantt chart outlining the tasks to be completed for each of the phases and a projected timetable; if this schedule is maintained, the first test flight will occur on on Sunday 1st April.

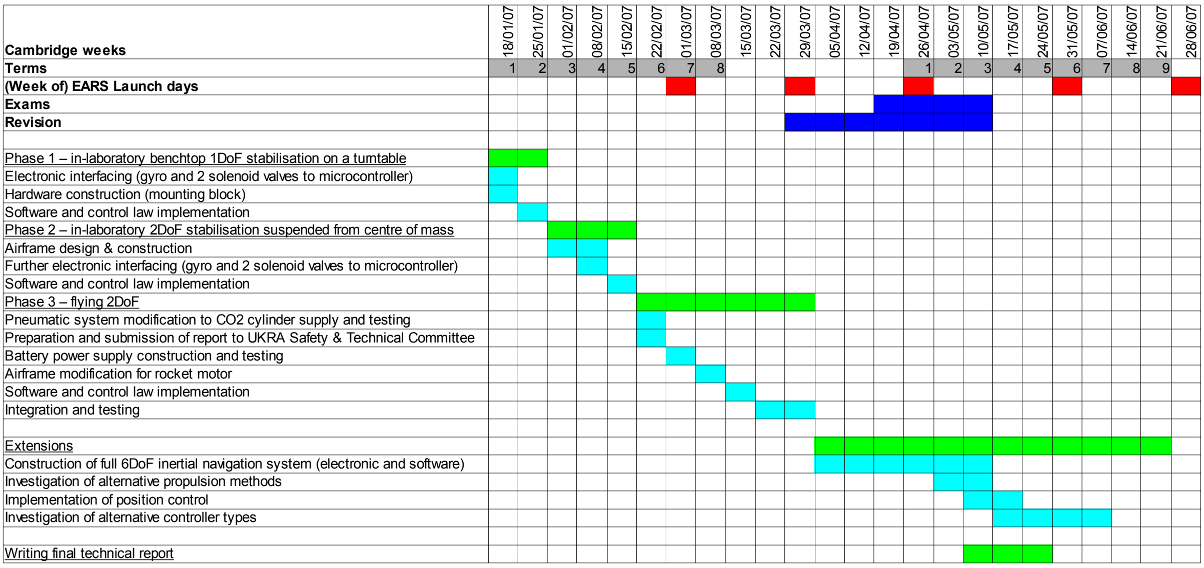


Figure 4: Gantt chart for the project, showing breakdown into Phases 1-3 and extensions.

Extensions

Alternative propulsion: In order to extend the vehicle's flight, longer-burning motors with the same thrust level as the Estes E9-P could be used; one option would be the Aerotech G12-RCT [18], with a thrust of about 9N maintained over 8 seconds. An alternative, which would also allow operation within an enclosed space, would be a non-explosive propulsion system such as an electric ducted fan mounted in place of the rocket engine.

Position control: By controlling the vehicle's attitude, the actuators give indirect control over position in a horizontal plane. In order to implement this, sensors would be required to measure the vehicle's attitude in all 6 DoF and additional thrusters would be necessary to control the roll axis.

Other control law types: Typical controllers assume that all the plant parameters are perfectly modelled and unchanging; however, adaptive controllers lift this restriction and allow the controller to adjust itself to the real system dynamics.

Additional sensors: The vehicle could be equipped with sensors (e.g. for light reflectance) to allow it to execute simple tasks while airborne (e.g. following a white line).

References

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Other work I could do before TMR deadline:

- predict nozzle thrust with air,
- interface gyro to MCU,
- test PWM frequency of valve vs thrust force,
- design controller (roughly)