VERIFICATION OF 3-AXIS CONTROL FOR A PICO SATELLITE VIA FLUID DYNAMIC ACTUATORS

Daniel A. Sullivan [1], Johannes F. Fürstenau [2], Carl-Ludwig Wonneberger[3], Cassandra Posada Garcia[4], Sebastian Grau[5], Klaus Brieß[5]

[1] Technische Universität Berlin, Department of Aeronautics and Astronautics, Marchstraße 12, 10587 Berlin, Germany, +49 (0) 176 23724194, d.a.sullivan44@gmail.com
[2] Technische Universität Berlin, Department of Aeronautics and Astronautics, Marchstraße 12, 10587 Berlin, Germany, +49 (0) 179 9344913, ferdinand.fuerstenau@outlook.de
[3] Technische Universität Berlin, Department of Aeronautics and Astronautics, Marchstraße 12, 10587 Berlin, Germany, +49 (0) 176 43482535, carl-ludwig.wonneberger@campus.tu-berlin.de
[4] Technische Universität Berlin, Department of Aeronautics and Astronautics, Marchstraße 12, 10587 Berlin, Germany, +49 (0) 152 29728261, cassandraposada@gmail.com
[5] Technische Universität Berlin, Department of Aeronautics and Astronautics, Marchstraße 12, 10587 Berlin, Germany

Attitude control systems developed for small satellites are limited by a combination of volume consumption, cost, or pointing capabilities. Technische Universität Berlin is currently researching a new means of attitude control via fluid dynamic actuation. Technische Universität Berlin Pico Satellite Experiment - 6 will test this technology when scaled down to fit the CubeSat form factor. A free falling unit and deployer are under development to launch on a sounding rocket in March 2019. The free falling unit, which closely resembles a CubeSat, will eject from the rocket, conduct attitude control maneuvers, and test redundancy of the system in a milligravity environment. The mission is conducted by a large student team via the Rocket Experiment for University Students program. Data collected by the onboard attitude determination and control system during the experiment phase of the mission will be used to verify the utility of pico fluid dynamic actuators.

1 INTRODUCTION

Contemporary attitude control systems used for CubeSat missions typically utilize a system of reaction wheels and magnetorquers. Technische Universität Berlin (TU Berlin) is researching a new attitude control technology, called fluid dynamic actuation. The goal of the new actuators are to combine low-cost and precise attitude control, while increasing integration density. Furthermore the technology is being scaled to fit the CubeSat form factor via pico fluid dynamic actuators (pFDAs) [1]. The pFDAs stand to provide expanded capabilities for future CubeSat missions.

Technische Universität Berlin Pico satellite Experiment - 6 (TUPEX-6) is a student project to demonstrate the capabilities of the new actuator design via the Rocket and Balloon Experiments for University Students (REXUS/BEXUS). The REXUS program offers a great opportunity to test the pFDAs while advancing their technology readiness level. The experiment has been selected to launch via the REXUS 26 rocket in March of 2018. The team is developing a deployer and necessary electrical interfaces, which will remain onboard the rocket's experiment module. Additionally, a free falling unit (FFU) that closely resembles a CubeSat, is under development to be ejected from REXUS. Following ejection, the FFU's payload will conduct a series of attitude control maneuvers to test performance and redundancy in the milligravity environment. Data collected during this experiment phase will be analyzed to confirm the operational capabilities of the pFDAs for future space missions. Upon reaching a predetermined altitude, the FFU's recovery unit will deploy a parachute and transmit geolocation information. Recovery of the FFU is pivotal to mission success, as telemetry data is stored onboard.

The REXUS/BEXUS program is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA).

Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. EuroLaunch, the cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles.

2 PAYLOAD

Pico fluid dynamic actuators are the subject of the attitude control experiment and therefore the main payload of the TUPEX-6 mission. By changing the flow rate of the medium inside the actuators channel, the attitude can be controlled. The flowing medium of pFDAs is a liquid metal driven by an electromagnetic pump within a closed loop channel [2]. The functional principle of fluid dynamic actuation in orbit is currently being demonstrated with a circular fluid dynamic actuator operating onboard the TU Berlin satellite TechnoSat [3]. In order to scale the actuator to a single unit CubeSat form factor and provide 3-axis redundancy, a novel L-shaped pFDA has been developed. Arranging four L-shape pFDAs into tetrahedral configuration allows for 3-axis redundant attitude control. Hosted inside the FFU, the pFDA system influences the pseudo-CubeSat's rotation. The utilized configuration has the added benefit of acting as secondary structure for the FFU. As shown in Figure 1, another distinct feature of channel structure is the ability to insert printed circuit boards (PCBs) hosting different subsystems. A configuration of four L-shape pFDAs containing all subsystem PCBs acts as the FFU bus, which occupies approximately 70% of the inner volume of the pseudo-CubeSat. The remainder of this volume could be allocated to payloads on future orbital missions.

Figure 1. The FFU bus mounted to recovery unit [5].

3 FREE FALLING UNIT

A free falling unit is being developed to closely resemble the single unit CubeSat form factor. The FFU will be the primary vehicle for experiment operations after ejecting from the REXUS rocket. The initial design intended for the FFU bus to contain all subsystems typical of a spacecraft. However, the design has undergone simplifications to reduce the complexity of the FFU and therefore mission risk. As such the following subsystems will be onboard the FFU:

- Attitude control via payload
- Attitude determination system (ADS)
- Payload command and data handling (PCDH)
- Electrical power system (EPS)
- Recovery system
- Structure
- Thermal control system (TCS)

The FFU bus will not include a communications subsystem, nor redundancy in any of its subsystems except the pFDA attitude control and determination system. The EPS will power subsystems via primary batteries only. The ADS, PCDH, EPS, and TCS are designed to be configured on up to six PCBs encapsulated by the pFDA system. The recovery system will occupy the remaining volume outside of the FFU bus. Figure 1 shows the PCBs held by the channel structure of two pFDAs, sitting on top of the recovery unit. An example of what the FFU may look like is shown Figure 2.

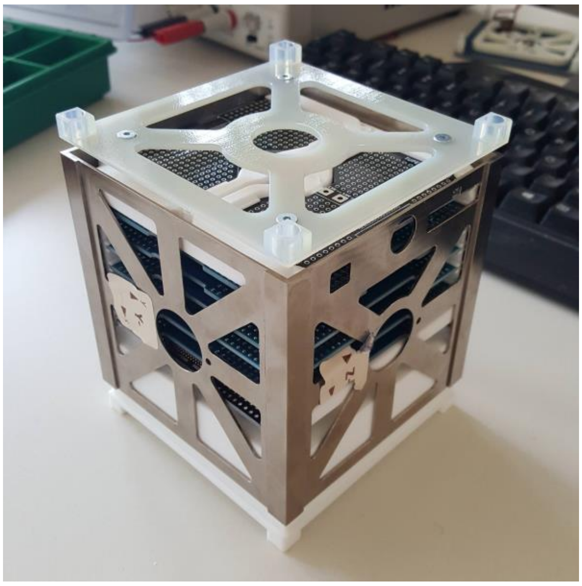

Figure 2. The fit check of the FFU [5].

Prior to launch, all subsystems will be powered on and begin collecting data throughout the launch phase. The PCDH is responsible for running the control loop between the payload and ADS. It will also collect data from the payload and ADS via CANBUS, format it, then forward it to redundant SD cards. Payload data will consist of electromagnetic pump speed and power consumption of the controllers and pump. ADS data will be compiled from magnetometers, rate sensors, accelerometers, and attitude quaternions.

Following ejection from the rocket, the PCDH will signal start of experiment to the other subsystems. The ADCS will immediately begin conducting attitude control maneuvers described in

Section 5. The experiment phase will begin with FFU ejection, continue through apogee and free fall, then end upon exiting from the milligravity environment.

As the FFU is primary means to retrieve the experimental data, a recovery system will be included onboard. The recovery system has the main objective of ensuring the de-acceleration and safe landing of the FFU, while providing geolocation data for the REXUS recovery team. This subsystem will be contained in a compartment integrated within the FFU structure, occupying a volume of 0.3 U. To achieve this, a parachute has been selected as a method for de-acceleration, and it will be ejected by a mechanism composed by permanent electromagnets and springs. The permanent electromagnets will keep the recovery compartment closed until the deployment is activated. At this point, an electric current will be applied to the electromagnets, inverting its polarity and releasing the lid, which itself will act as a drag surface, pulling out the parachute.

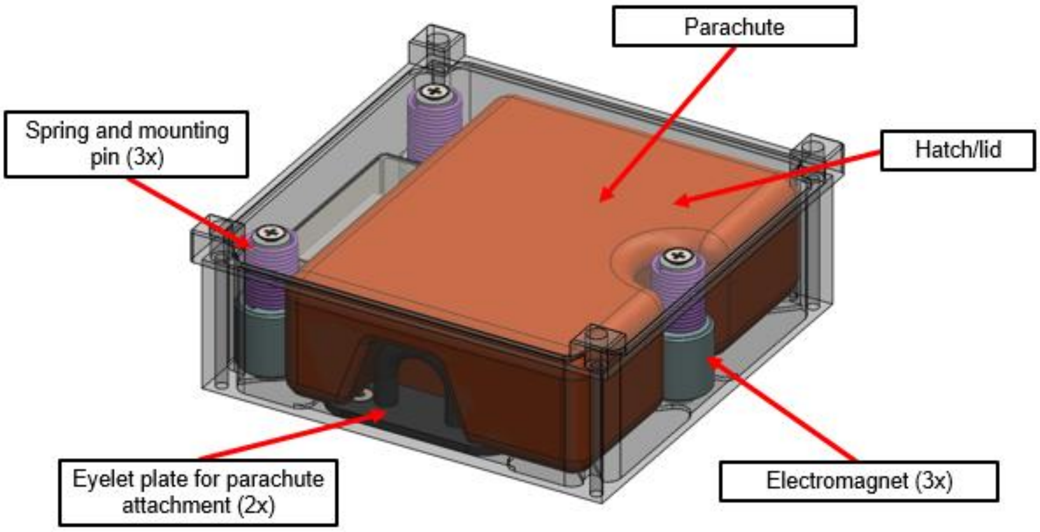

Figure 3. Preliminary mechanical model of the recovery compartment.

The main challenges for the recovery system are the small packaging volume and the high snatch loads generated by the sudden deployment of the parachute. According to the initial calculations, the FFU is expected to have a terminal velocity of 81.6 m/s at 5 km above sea level. The deployment of the parachute will reduce this velocity to 5 m/s in approximately 2 seconds, generating shock loads of 400 N. Once the parachute has been deployed, the geolocation coordinates will be transmitted to the ground station until its final landing position.

4 ROCKET BORNE EQUIPMENT

Until the start of the experiment, the FFU needs to be contained safely inside the REXUS rocket. The rocket borne equipment is designed to host the FFU and eject it at the right moment. It is mounted inside one of the experiment modules located in the upper half of the rocket. The experiment module itself is provided by ZARM and modified in order to allow the deployment of the pseudo-CubeSat. The RBE consists of the deployment container and the necessary electronics. Much like the FFU, the RBE complies with the CubeSat Design Specifications.

Inside the deployment container, the FFU will be positioned between guiding rails interfacing with the FFU's longitudinal edges. The rails not only confine the FFU's movement in two axes during launch, but also guide it towards the opening in the rocket's shell. This opening will be closed by the in-flight actuated hatch. The hatch's rounded outer side is flush with the shape of the launcher in order to minimize the influence on flight dynamics during ascent. The inner side of the hatch is a flat plate that will press the FFU against the push plate inside the container. This push plate is connected to the back side of the container by the main ejection spring. The main ejection spring has two purposes: fastening of the FFU during ascent and ejecting it.

Upon the moment of ejection, the metal wire that is holding the hatch in place is severed using pyro cutters. Afterwards, the hatch no longer holds back the force of the main ejection spring, thus enabling the ejection of the FFU. With the help of the push plate, the acceleration from the ejection spring is distributed equally over the four corners of the FFU, allowing for reduced tumbling motion of the FFU. The firing of the pyro cutters is controlled by ZARM/MORABA through the pyro activation box located inside the REXUS Service Module.

Aside from the container, there is a compartment housing the RBE electronics that serve as an interface between the REXUS rocket and the FFU. This allows for recharging of the FFU's batteries, as well as booting prior to ejection. To connect the RBE electronics and the FFU, the push plate features a cut-out for the electrical interface composed of pogo pins.

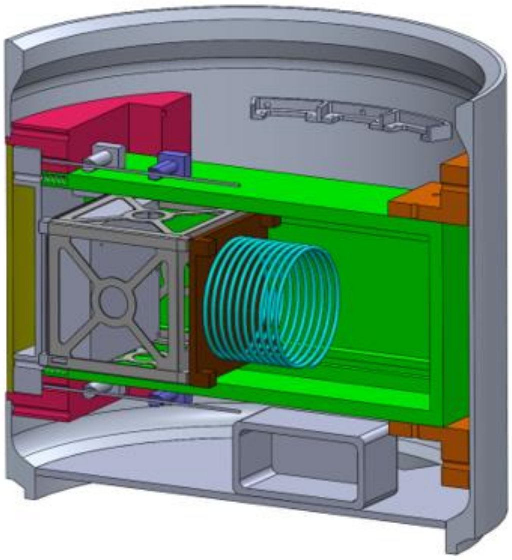

Figure 4. Cut away of the rocket borne equipment [4].

Figure 4 shows a cut away of the preliminary model of the RBE. Visible are the hatch (yellow), the container (green), and the spring (blue) with the push plate (brown). Furthermore, the REXUS experiment module, the FFU primary structure and the box containing any electronics (grey) are shown.

5 EXPERIMENT

An objective of the TUPEX-6 mission is to enable the conduction of the pFDA attitude control experiment. This experiment will demonstrate the capabilities of the newly developed L-shape pFDAs as well as the 3-axis redundancy of the attitude control system comprising four L-shape actuators. During free fall, changes in rotational rates are intentionally induced while the attitude is determined. Post-processing of gathered data will identify the success of the demonstration.

Promptly after ejection, the FFU is exposed to the milligravity environment of the upper atmosphere and the experiment is initiated. Comprising two sequences of five events each, the experiment takes a total of 100 s. In increments of ten seconds, the ten steps are executed. During the first sequence, a single pFDA is used, while the second sequence utilizes solely the remaining three actuators.

The goal of the first phase is the demonstration of a pFDAs capabilities by changing the rotational speed the FFU about the actuators' axis of angular momentum. The second sequence aims to demonstrate the 3-axis redundancy of the developed system by simulating the malfunction of the previously used actuator. To demonstrate this, change in rotation rates about the same vector of angular momentum as in the first sequence will be demonstrated. The sequence events 1, 3, and 5 mark distinct pauses in attitude control, to allow for determination of the rotation rates without any changes. Meanwhile, step 2 and 4 are the attitude control events where torque is intentionally induced to change the FFUs' angular rates. Figure 6 depicts the two experiment phases with the induced changes on angular rates.

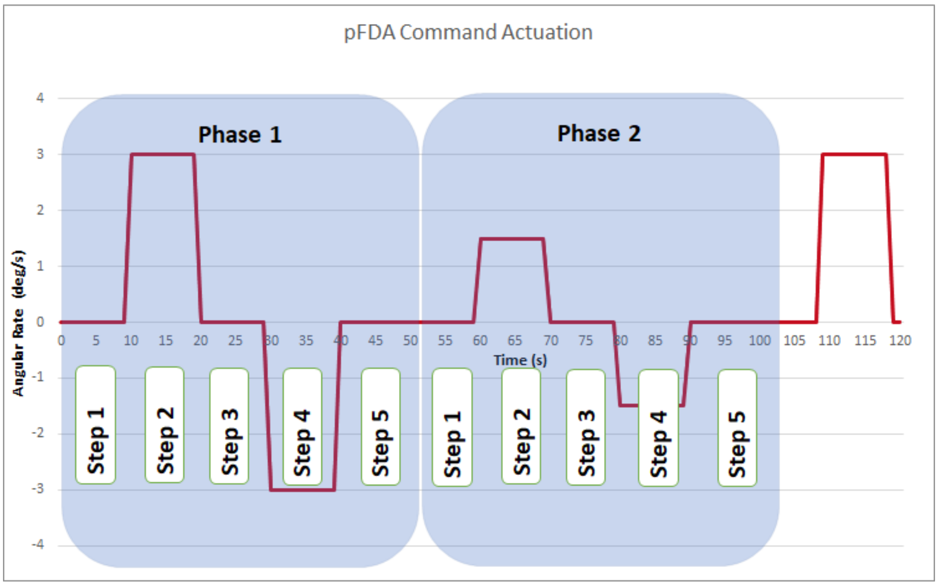

Figure 5. Two experiment phases and change of angular rate over time [7].

To demonstrate the redundancy of the system and the performance of the actuators, it is not necessary to actively control the satellite. In this special case, a preprogramed attitude control time line, in cooperation with attitude determination, will suffice. To determine whether the experiment was conducted successfully, post-flight data analysis will be performed. By post-processing attitude determination data in conjunction with pFDA housekeeping data, changes in rotational speeds can be identified and attributed to the pFDAs.

Although it is possible to perform attitude control tests using single L-shape pFDAs, it is not feasible for a system of actuators. This is due to disturbance forces and rapid saturation of the actuators in use. Therefore, the experiment must be performed in a milligravity environment [6]. Nevertheless, single actuators will be tested on an air-bearing to verify functionality and provide training for the post-flight analysis. Additionally, ground tests allow for performance estimations prior to launch.

6 TEAM

TUPEX-6 unites a group of over 30 students from TU Berlin to work together towards a common goal. The majority of the team consists of master's students with backgrounds ranging from aerospace to computer science, but also includes several bachelor students. With members from 10 different countries from across the globe, the TUPEX-6 team provides an international work environment typical for a space project. During the mission, the team is supported by several members of the Department of Aeronautics and Astronautics at TU Berlin.

7 CONCLUSION

With further advances in development, the TUPEX-6 mission moves closer to achieving the objective of demonstrating 3-axis redundant attitude control using the novel L-shape pFDAs and their capabilities. Though, several preceding conditions are necessary: firstly, the opportunity to launch into a milligravity environment, provided by the REXUS/BEXUS campaign; secondly, development of an experiment vehicle, namely the free falling unit, and its ejector; lastly, the successful conduction of an attitude control experiment while in the milligravity environment. The TUPEX-6 mission is in the process of achieving these conditions to advance the novel pFDA technology.

8 ACKNOWLEDGEMENTS

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