GUIDANCE, NAVIGATION AND CONTROL FOR THE AUTONOMOUS RETURN-TO-LAUNCH-SITE FUNCTIONALITY OF EXPERIMENTAL FREE-FALLING-UNITS EJECTED AT HIGH ALTITUDE FROM A SOUNDING ROCKET

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ABSTRACT

This paper presents the work of the BOOMERANG project from the REXUS/BEXUS programme, with a focus on its aspects of guidance, navigation and control. The project is developing a return-to-launch-site solution for free-falling units that are ejected from sounding rockets for research purposes. This functionality makes use of an autonomously controlled paraglider that uses onboard sensors to steer to the desired location. First, an introduction to the project and the programme is given, followed by an overview of the mechanical and electrical design of the experiment. The work then describes the navigation system, that makes use of a multiplicative extended Kalman filter, as well as the approach for the control system. Finally, testing procedures and results are presented.

1 INTRODUCTION

1.1 Background

Sounding rockets hold an important role in scientific research related to the near-Earth environment. Reaching altitudes of 50 to 150 kilometres, they represent an important means to study different aspects related to the atmosphere and the magnetosphere. In order to conduct measurements and collect data, free-falling units (FFUs) are often ejected from such rockets. Such experiments have been conducted several times by KTH Royal Institute of Technology in Stockholm, Sweden, which conducts active research in the field of plasma physics. After ejection from the vehicle, the units involved in these experiments deploy wired booms that are used to collect data in the ionosphere. After the measurements, the units reenter the atmosphere with the use of a parachute and they are retrieved via helicopter from their landing area. Recovery operations though are very costly and time-consuming, as numerous people and resources need to be mobilized and the airspace near the launch site is kept busy for several hours. Furthermore, it is often the case that the landed units are impossible to locate and retrieve, resulting in the loss of the experimental data.

For this reason, the work presented here is developing a return-to-launch-site functionality that allows the free-falling units to fly autonomously to a desired location, in order to facilitate retrieval operations. The work is carried out by the student team called BOOMERANG (nonBOOM-deploying Experiment with a Return-to-launch-site Autonomous Non-propelled Glider) [2].

1.2 Vehicle and flight

The demonstration flight for this experiment will occur onboard the REXUS vehicle [4]. The REXUS vehicle is a single-stage rocket, propelled by an improved Orion motor. The rocket has a diameter of 355 millimetres and a height typically varying between 5.5 and 6.2 meters, depending on the payload. The BOOMERANG experiment consists of two identical disc-shaped free-falling units that are ejected at T+61 seconds into the flight, once the vehicle reaches an altitude of about 60 kilometres. After reaching an apogee of 82 kilometres, the units begin the free-fall phase of the mission. During reentry, the units deploy the detumbling mechanism. The detumbling mechanism makes use of four aerodynamic surfaces that provide passive stabilisation of the fall of the unit, reducing angular velocity on all three axes. Once stable, at an altitude of about 10 kilometres, the unit deploys a paraglider, which is what drives the return-to-launch-site functionality. The paraglider is autonomously controlled through a motor making use of the onboard sensors. An overview of the BOOMERANG mission is shown in Figure 1.

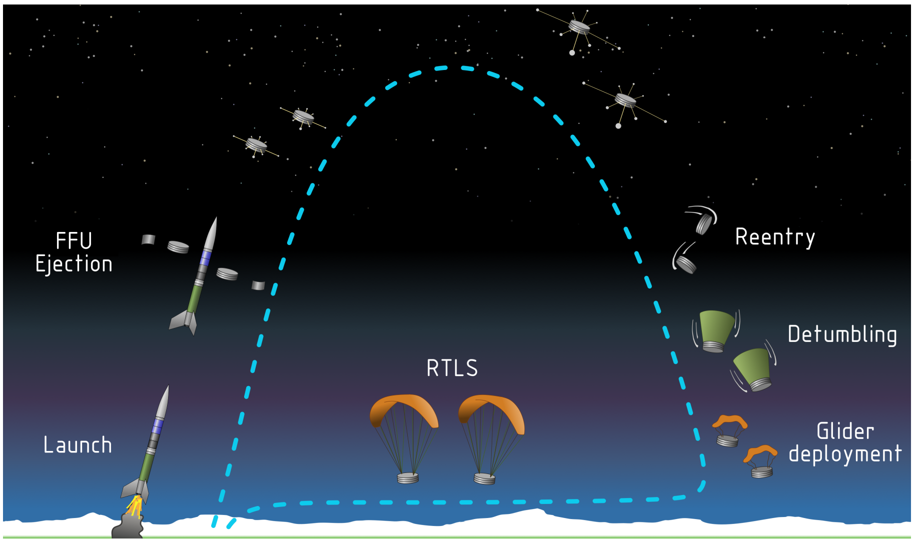

Figure 1: Mission overview

2 CONTEXT

2.1 The REXUS/BEXUS programme

The BOOMERANG project is part of cycle 14 of the REXUS/BEXUS programme (Rocket and Balloon Experiments for University Students) [3]. REXUS/BEXUS is an educational programme that allows university student teams from across Europe to design and launch their own rocket or balloon experiment with the support of experts from the space industry. The programme was born with the bilateral agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). Through the collaboration with the European Space Agency (ESA), the Swedish part of the programme is extended to all ESA member states teams. The launch vehicles and the campaign operations are handled by the Swedish Space Corporation (SSC) and the Mobile Rocket Base (MORABA), a department of DLR. Their cooperation in the field of sounding rockets and balloons was established in 2003 under the name of EuroLaunch.
Two rockets and two balloons are launched with every cycle of the programme, for a total of around 20 experiments. The students can count on the technical support of many experts from ESA, DLR, SSC and ZARM, that provide support in all aspects of the experiments throughout the different stages

of the development. Reviews and tests are conducted in the facilities of DLR, ZARM and ESA. The vehicles are launched from ESRANGE Space Center, Kiruna, in northern Sweden.

2.2 The BOOMERANG project

BOOMERANG is an experiment from KTH Royal Institute of Technology in Stockholm, Sweden. The experiment is mostly funded by the department of Space and Plasma Physics, under the School of Electrical Engineering and Computer Science; some external funds come from Airbus and the Swedish National Space Agency. The experiment was selected to fly onboard REXUS 32 in December 2021 and is scheduled to launch in March 2024.

3 MECHANICAL DESIGN

3.1 The free-falling unit

A rocket-mounted unit (RMU) is part of the payload stack of the REXUS vehicle. It envelopes the retention and ejection mechanism that will eject the two free-falling units from the rocket (Figure 2). An FFU has a mass of 2.1 kilograms, a diameter of 240 millimetres and a height of 75 millimetres.

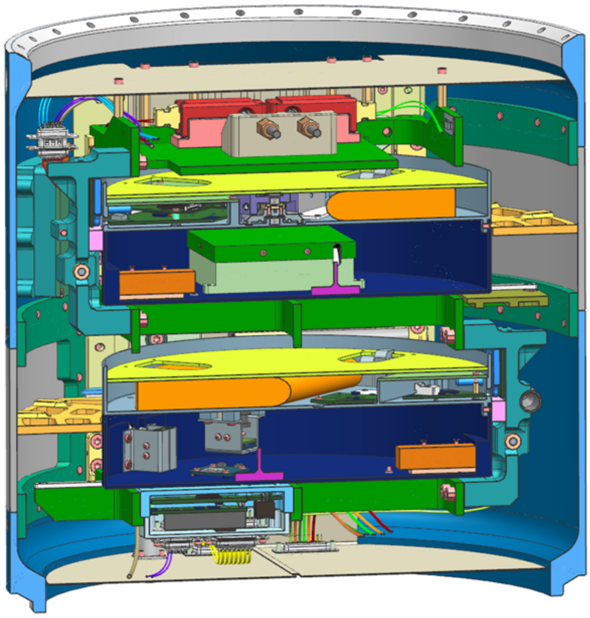

Figure 2: Section of the rocket-mounted unit: ejection mechanism

During free fall, the unit will deploy the detumbling mechanism, which makes use of four passive aerodynamic surfaces. Detumbling the free fall of the units is necessary in order to ensure that the paraglider can deploy from a stable configuration, avoiding undesired entanglement of the lines.

3.2 The paraglider

The lines of the paraglider are attached to the unit through two opposite attachment points. The design of the lines ensures the stability of the paraglider and that the shape of the canopy is maintained during flight. Control of the flight is achieved through the actuation of the two brake lines. These lines connect the trailing edge of the canopy to the wheel of a motor. When the motor rotates away from the neutral position, one of the two lines is shortened, while the other is loosened. This causes deflection of the trailing edge on one side of the canopy, thus producing a differential increase in the drag of the paraglider and ultimately steering the vehicle. The CAD model of the paraglider is shown in Figure 3.

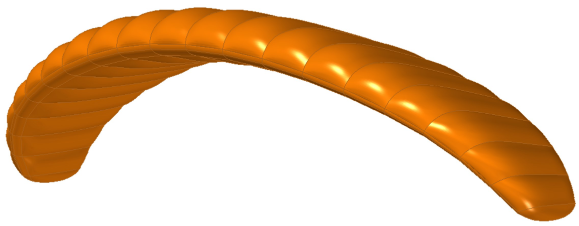

Figure 3: CAD model of the paraglider

4 ELECTRICAL DESIGN

The control of flight and recovery operations for the unit is performed in two *DataHubs* [1]. The DataHub consists of a compact PCB with the following components (Figures 4 and 5):

- ARM Cortex-M7 based microcontroller (STM32F767VIT6)
- ProASIC3 FPGA (A3P250-VQG100I)
- SD card slot
- Pressure sensor (MS5611-01BA03)
- MEMS angular rate gyroscope (L3GD20H)
- Accelerometer/magnetometer (LSM303AGR)
- Non-volatile memory, FRAM (FM24CL64B)
- 3 DF-9 stacking connectors for I/O and power
- PicoBlade connector for programming

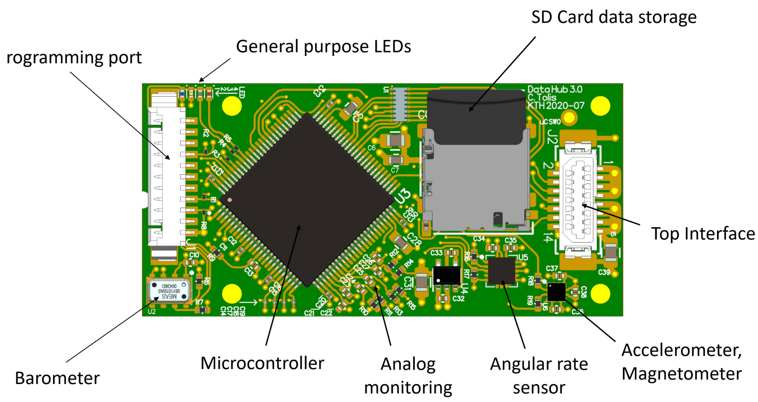

Figure 4: DataHub - Top side

For onboard navigation, data collection and recovery, each FFU is also equipped with a MAX-M8 GNSS module, stacked on top of the motherboard together with the DataHubs. This GNSS board is capable to either work as a commercial GNSS or only a GNSS front end that collects raw data. During flight, the position of the FFU can be transmitted to the ground station both through the Globalstar satellite system and through VHF.

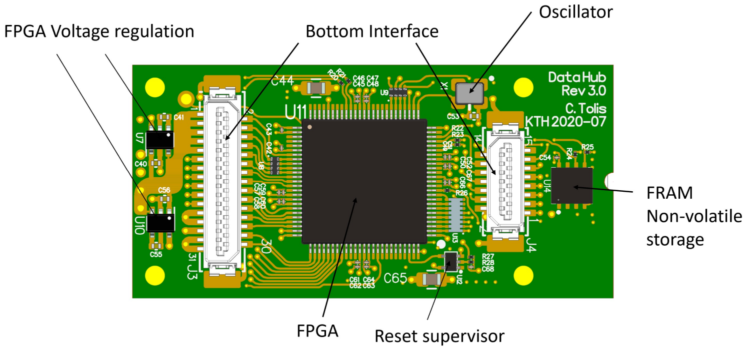

Figure 5: DataHub - Bottom side

5 NAVIGATION

The Navigation system makes use of the e-Compass (accelerometer and magnetometer), the angular rate sensor and the GNSS receiver to compute the estimation of the state of the FFU with the use of a multiplicative extended Kalman filter (MEKF). The overview of the filter is shown in Figure 6.

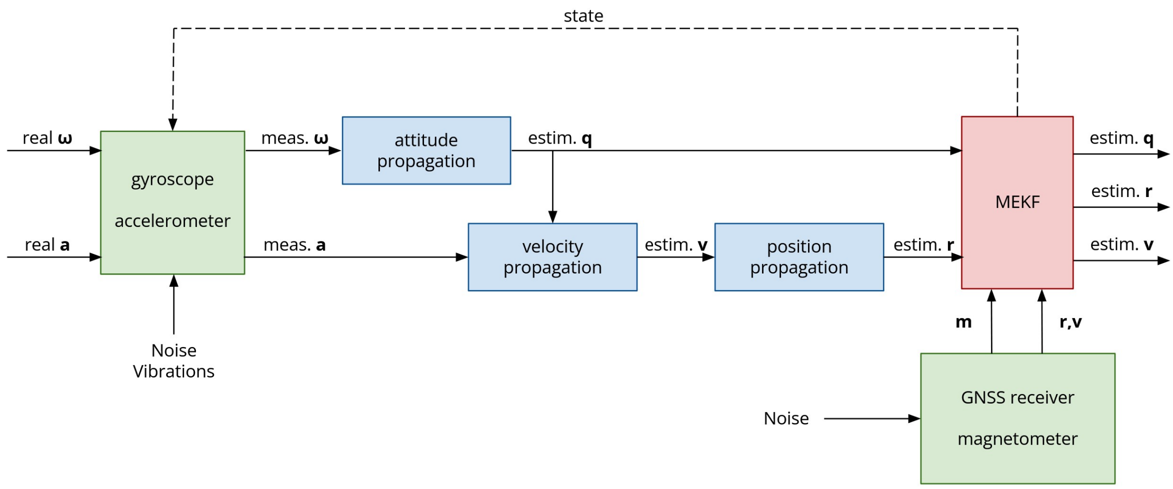

Figure 6: Overview of the navigation filter

5.1 States

The main frame of reference used for navigation, in which the states are propagated, is the Earth-Centered, Earth-Fixed (ECEF) frame. The quaternions represent the attitude of the body frame of reference with respect to ECEF frame of reference. The body frame has its origin in the geometric center of the FFU and it is defined as follows:

$\hat{x}_b$ = aligned with the nominal flight direction of the FFU
$\hat{y}_b$ = follows the right hand rule
$\hat{z}_b$ = aligned with the rotational axis of the FFU

The following states are used in the filter:

- Position (p_x, p_y, p_z)

- Velocity (v_x, v_y, v_z)
- Accelerometer bias $(\beta_{a,x}, \beta_{a,y}, \beta_{a,z})$
- Attitude error $(\delta q_1, \delta q_2, \delta q_3)$
- Angular rate sensor bias $(\beta_{g,x}, \beta_{g,y}, \beta_{g,z})$

Thus, the state vector results to be:

$$x = [\, p_x \;\; p_y \;\; p_z \;\; v_x \;\; v_y \;\; v_z \;\; \beta_{a,x} \;\; \beta_{a,y} \;\; \beta_{a,z} \;\; \delta q_1 \;\; \delta q_2 \;\; \delta q_3 \;\; \beta_{g,x} \;\; \beta_{g,y} \;\; \beta_{g,z} \,]$$

To improve computational speed, the state vector is never propagated as complete; rather operations are carried out with the individual states.

5.2 Initialisation

Position and velocity are initialised with the GNSS readings. Position coordinates are converted from geodetic to ECEF, while velocity coordinates are directly obtained in the ECEF frame from the GNSS board.

The initial attitude is computed with the Triad method, using data from the magnetometer and the accelerometer. The code makes use of the initial magnetometer and accelerometer readings (in their sensor frame components, converted to body components, together with the corresponding models for gravity and magnetic field).

5.3 Propagation

For position and velocity, the propagation is performed using the accelerometer data, after performing the necessary reference frame conversions. For attitude, the propagation makes use of the readings from the angular rate sensor.

5.4 Update

The update of position and velocity uses the data from the GNSS board, while attitude is updated using the magnetometer readings.

6 GUIDANCE AND CONTROL

Guidance and control can be developed and tested separately from the navigation. This allows isolating variables and sources of error. The independent implementation of the control system is presented here, making exclusive use of position and velocity as obtained directly from the GNSS receiver. The implementation of the hybrid navigation system allows for enhancing the control with the improved estimation of position and velocity and it can also provide an estimation of the trajectory of the flying unit in case of loss of GNSS fix for a few seconds. Its integration with the control system only requires a conversion of coordinates.

6.1 Error calculation

Simplicity and reliability are the drivers for the design of the control system. The system needs to run on limited computational power, it needs to be fast to test and has to work without failure for the expected 1.5 hours of flight.
The control algorithm is driven by the heading error e defined as the angle between the velocity of the flying unit in local coordinates and the direction that connects its position with the determined landing location (Figure 7).

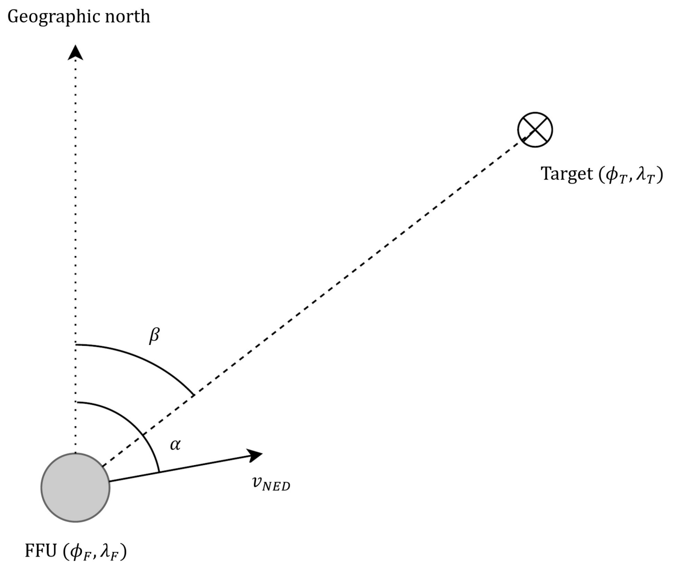

Figure 7: Heading error calculation

Multiple possible landing locations will be made available by the Swedish Space Corporation, and the targeted one will be chosen based on wind conditions prior to the launch.

Let (ϕ_T, λ_T) be the geodetic coordinates of the targeted landing location (latitude and longitude). This information is set before the flight and does not change. Let (ϕ_F, λ_F) be the position of the unit. These are used to calculate the bearing angle β, defined as the angle between the geographic north (used as the reference direction) and the direction that connects the two locations. It is calculated as

$$\beta = \text{arctan2}\left[\frac{\cos(\phi_T)\sin(\lambda_T - \lambda_F)}{\cos(\phi_F)\sin(\phi_T) - \sin(\phi_F)\cos(\phi_B)\cos(\lambda_T - \lambda_F)}\right] \tag{1}$$

Let

$$v_{NED} = \begin{pmatrix} v_N \\ v_E \\ v_D \end{pmatrix} \tag{2}$$

be the velocity of the unit in local north-east-down coordinates. The velocity angle α is defined as the angle between the geographic north and the velocity and it is calculated as

$$\alpha = \text{arctan2}\left(\frac{v_E}{v_N}\right) \tag{3}$$

The heading error e thus results to be

$$e = \alpha - \beta \tag{4}$$

and

- if $-2\pi < e < -\pi \longrightarrow e = e + 2\pi$
- if $\pi < e < 2\pi \longrightarrow e = e - 2\pi$

The value of the error then determines the state of the servo, and thus which brake line is to be pulled, if any:

- $e > \frac{\pi}{18} \longrightarrow$ pull left break line
- $e < -\frac{\pi}{18} \longrightarrow$ pull right break line
- $-\frac{\pi}{18} < e < \frac{\pi}{18} \longrightarrow$ stay in neutral condition

This bang-off-bang control law is implemented in order to evaluate the dynamic response of the flying unit through testing. The integral of the error is later to be introduced in the control law to ensure robustness against the wind during flight.

6.2 Actuator

The unit makes use of the Faulhaber 1024 006 SR motor, chosen for its torque output and efficiency. The controllers for the motor have been designed using the DRV8850 chip from Texas Instruments. These chips are mounted together with angular feedback sensors on a small PCB. The CAD model of the drive-chain is shown in Figure 8.

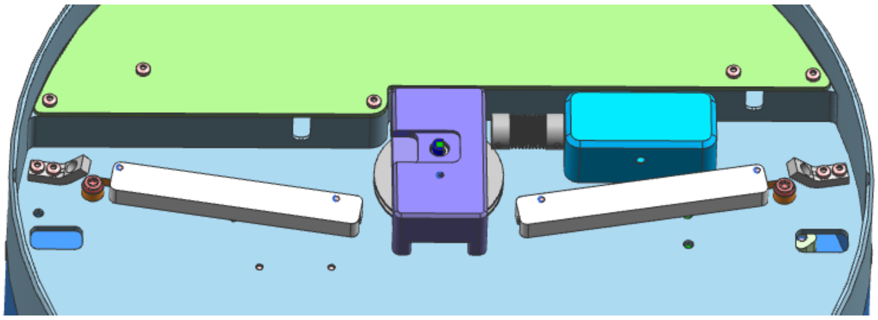

Figure 8: Drive-chain

7 TESTING

To analyse the flight of the paraglider and the behaviour of the control system, a testing procedure was developed, allowing for high repeatability at relatively low costs. The procedure involves a series of drop tests that make use of a tethered helium balloon. The balloon holds 2.36 m^3 of helium and can lift a payload of up to 2.17 kg. During flight, it is attached to a line that is connected to a winch on the ground, which allows to bring up and down the balloon for repeated testing. A remote-controlled release mechanism is used to initiate the flight of the paraglider from the ground. This testing procedure allows to test several critical aspects of the mission, including the deployment of the paraglider from the d-bag, inflation of the parafoil, flight mechanics properties and ultimately the response to control.

7.1 Trajectory

Although the in-flight response of the paraglider to control actuation is still to be verified, flight data was recorded during several drop tests, which can aid system identification. Figure 9 shows the trajectory of the paraglider during a drop test from an altitude of 120 meters, represented in a local north-east-down (NED) frame of reference. It is to be noted that given the relative wind speed during flight, the glide ratio of the paraglider results to be higher than what the trajectory represents. The represented passive flight has an overall duration of 45 seconds, of which the initial 5 seconds relate to the deployment and inflation of the paraglider.

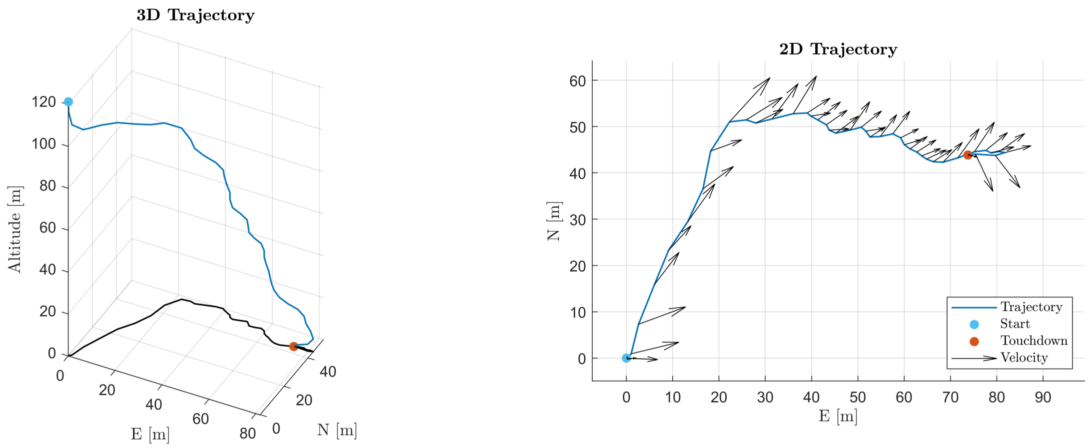

Figure 9: Flight trajectory - GNSS position and velocity in local NED coordinates, 1 Hz

7.2 Sensor readings

Figures 10 and 11 show the sensor readings from the same test. The rapid increase in acceleration and angular rate in the initial phase of the test corresponds to the deployment of the parafoil from its d-bag and the subsequent inflation.

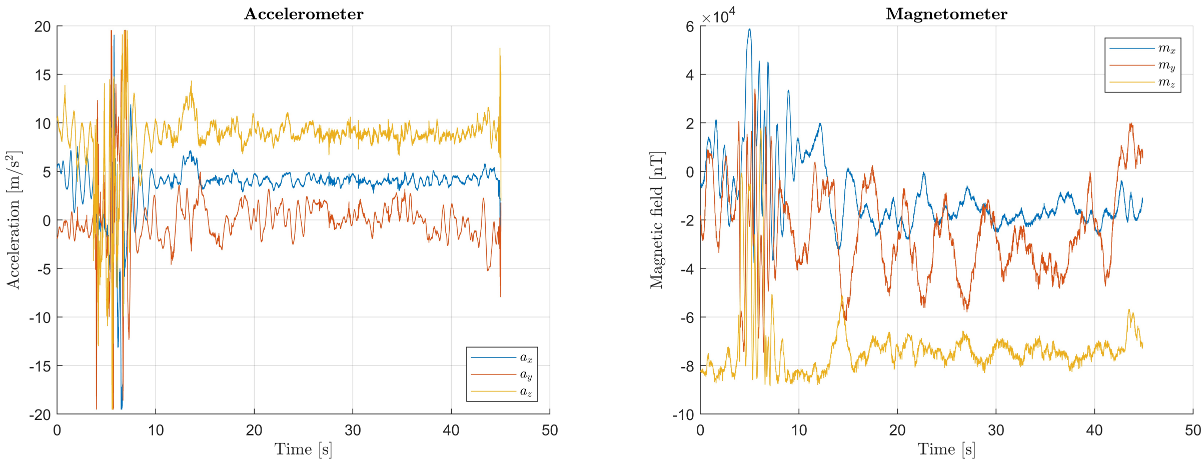

Figure 10: E-Compass flight data

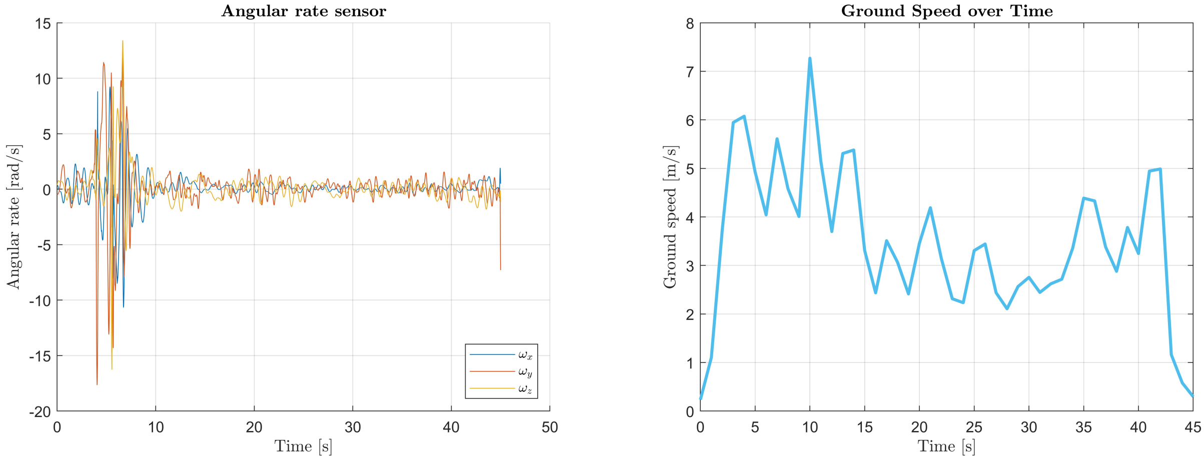

Figure 11: Angular rate and GNSS ground speed

8 CONCLUSION

Different approaches can and have been considered for the implementation of the return-to-launch-site functionality described in this paper, and the implementation of an autonomously controlled paraglider was deemed the most effective in satisfying the mission requirements and the constraints presented by hardware and mission objectives. Further testing is required to validate the design, culminating in its demonstration onboard the REXUS 32 launch.

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