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A solid CanSat taking on demand photos with simultaneously position determination - an approach to two-way communications and an interactive online presentation of data for teaching purposes

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Abstract: Our CanSat primary mission was to measure temperature and pressure, and, by knowing the pressure, to calculate the altitude of our CanSat. Our secondary mission was to create a two-way communication between the ground station and our CanSat with an on board camera in order to be able to take a picture on demand and, by using acceleration, gyroscope and GPS, determine the exact position and orientation of the CanSat at the moment each picture was taken. Also we wanted to store all of our data on a micro-SD card. The GPS also improved the possibility to regain the CanSat after descent. We used 3D printed mechanical components in order to create solid CanSat mechanics. Upon arrival in Santa Cruz, Portugal telemetry and all our other sensors were working and we were able to take pictures and store them on an on-board Micro SD-card, however only pre-programmed and not yet on demand from the ground station. The solid 3D printed shell managed both a drop from a plane and a rocket launch with only insignificant damaged. Furthermore all the sensors, the telemetry and the live transmission of selected data worked perfectly well during launch and we were, after the launch, able to calculate the position and orientation of the CanSat during its entire descent. However during the ejection from the rocket, the camera broke and we were not able to take pictures during the descending. Also our on board datalogger storing on a micro-SD card was unintended reset and therefore failed to save the data correctly during the entire launch. Thus we could not entirely fulfil our secondary mission, since we didn’t have both picture and data at the same time. We did, nevertheless, get some pictures from before and whilst the CanSat was inside the rocket. If we had had a picture, we would have been able to find the time of which it was taken and thereafter find the position of our CanSat at this exact moment. Despite the small failures, we think of our mission as a success since we did receive very good data from all of our sensors and the 3D printed mechanical components proved it able to withstand the forces applied to it.

I. INTRODUCTION

For our **primary mission** our CanSat measures the air pressure and temperature as a function of elapsed time. This allows us to calculate the altitude (height) as a function of time elapsed and the descent speed as demanded in the requirements.

The goal for our **secondary mission** consists of the following parts:

- We want our CanSat to take a picture on demand during descent and therefore we want to be able to make a two-way communication with the CanSat during flight
- At the same moment as the picture is taken, we want to be sure of the exact position and direction of the camera. In order to determine the exact position and direction of the camera and the CanSat, our secondary mission includes measurements of the magnetic field strength, 3-axis acceleration, a 3-axis gyroscope and a live tracking of the CanSat position by an installed GPS sensor.
- We include some 3D-print in our CanSat, because we have experienced that a 3D-printer now is available in the ISS, so we want to explore, how we can use this innovatively in our CanSat. We have designed and printed a CanSat-box consisting of two parts that is more easily attached to or detached from the CanSat electronics and main mechanics than an ordinary soda can.
- With respect to the ground station, we want to make it possible to transmit live data from the CanSat using a Linux based webserver that can be addressed from several computers simultaneously
- All data will for "safety" reasons be stores on a microSD card in the CanSat during flight and data will be transmitted to the ground station as required.

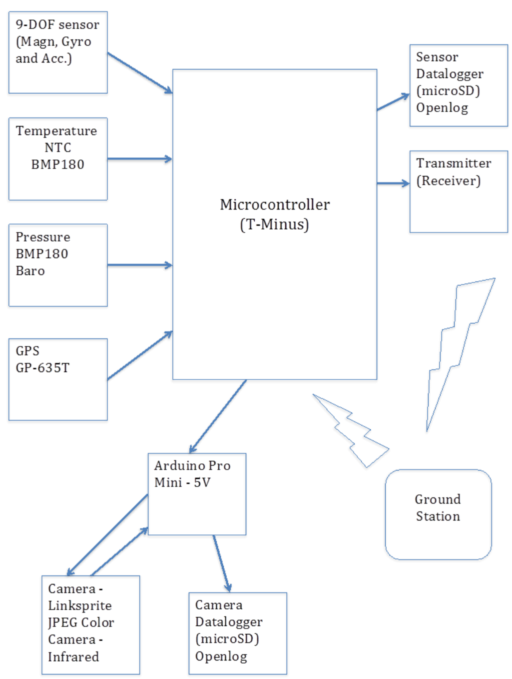
The reason for including GPS, direction measurements and camera in our CanSat is that in the future it will be desirable to perform remote measurements like satellite photos of areas of vegetation or wildlife. These Earth observations, are not possible using ground equipment, but require that you observe / photograph from the air.

In order to get the idea for our secondary mission, we have studied the homepage of ESA where all their missions are presented (ref. 1) and also looked at previous students work on Cansat projects at Silkeborg Gymnasium*.

II PROJECT DESCRIPTION

As seen in the block diagram below our system consists of the following parts:

- Sensors needed to determine the position and direction of our CanSat: 9-DOF (3 axis magnetic field, acceleration and gyroscope), NTC-temperature and a digital pressure sensor DMP180. The pressure sensor also has a temperature sensor included.
- two on board data loggers to store data on two Micro SD cards



* explained by our teacher: Bente Jensen, bj@sg.dk

Fig. I: Mission Overview

- A very small GPS that can be placed on the top of the CanSat
- A LinkSprite color camera to take pictures on demand
- A T-Minus microcontroller board based on the Arduino Mega processor
- The T-Minus transceiver as receiver and transmitter to and from ground station
- A Pro Mini microcontroller based on a ATmega328 16MHz processor
- The ground station

II.I Materials and structural design

For our internal design a T-minus kit (ref.2) was used, because we then would be able to solder all of the components by our self. This gave us knowledge of how every component was attached. In case of a mistake we would know where and how the different sensors where attached to the board and it would be easier to correct the errors. A second reason why we decided to use a T-minus kit was due to its structural design. It was easier to make a symmetric design by using the T-minus kit, which we were highly aware of, because we wanted a stabilised CanSat. We also made sure to centre the mass and place the heaviest components in the bottom as to get the CanSat stable during descent.

Fig. II: Structural design of our CanSat.

Fig. III: 3D printed shell

As for our recovery system we decided to make and use a semi-spherical parachute (ref.3 and ref.4) and we made sure to use calculations where the air resistance at terminal speed was equal to gravity force as to find the correct area of which the parachute needed to have to achieve the wanted terminal speed. The parachute was tested several times and proved to be sufficiently strong and able to withstand a force of 1000 N.

For our external design we decided to 3D print some mechanical components using an online program (ref.5), which is a free of charge 3D design program. It did take a long time for us to create the perfect shell to surround the mechanics due to the fact that this program is very primitive and it is hard to get the measurements right. Nevertheless we were able to successfully print a solid shell and also we created a top and bottom for the CanSat. In order to print the designs we used the MakerBot replicator 2x printer.

II.II Electrical components and sensors

We will in this section in more details describe the different sensors and electrical components used in our CanSat during the launch campaign in Portugal. Our main on-board computer was the T-minus controller, which has a fixed output voltage of either 3.3V or 5V. Since we had sensors requiring different supply voltages, we had to make both 3.3V and 5V voltages available.

II.II.I 3.3V-Voltage Regulator

As a consequence of our choice of using the T-Minus controller instead of for example a Seeeduino Mega and corresponding prefabricated shields, we had to make our own on board voltage regulator to be able to convert the voltage from 5V to 3.3V. We needed 5V to power the majority of our electrical components, but we needed 3.3V to power our pressure sensor and our 9-DOF sensor (more details explained in the next section). This was achieved by constructing a simple circuit including a LD1117V33 voltage regulator with a fixed output voltage, and two capacitors.

II.II.II Pressure, temperature and 9-DOF sensor

In April 2015 we participated in the Nordic CanSat competition in Norway. During the launches we experienced a lot of unstableness in the data collected from the pressure sensor - an analogous MPX4115 sensor. We decided to change the sensor to the more sensitive BMP180 digital pressure sensor that requires 3.3V voltage.

Furthermore the BMP180 sensor also housed a temperature sensor. Due to the BMP180 sensor being located in the middle of the CanSat surrounded by different sensors, the temperature measurements were defective because of the artificial higher temperature in the CanSat. We therefore decided also to use an analogue NTC temperature sensor, located right behind the shell, for the temperature measurements. The NTC was connected to a 5V voltage and a resistor.

For our acceleration, magnetic field and gyroscope measurements we decided to use the Sparkfun LSM9DS0 9-DOF, a versatile chip that houses a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer. The 9-DOF requires a 3.3V voltage and we used a Bi-directional converter to convert 3.3V signals to 5V signals and to step down 5V signals to 3.3V signals.

All the data collected from the 3 sensors was stored on an Openlog datalogger together with the primary mission data.

II.II.III GPS module

We used the GP635-T GPS module to determine the exact geographical position of our CanSat. We wanted to place the GPS on the top of the CanSat, for better communication capabilities. A major struggle was to find a good GPS, small enough so it wouldn’t block the screw for our parachute, which is positioned in the centre of the CanSat top. With this in mind, we chose the GP635-T module, which is a very slim module with the dimensions of 35x8x5.2 mm. To get the module in use, we connected the GPS to the ground, 5V voltage, RX, and TX on the T-minus board. The data collected from the GPS was transmitted to the ground station and in addition stored by an Openlog datalogger on an on board microSD card.

II.II.IV Sensor datalogger

We wanted to make sure, we had eligible data, and because a lot of difficulties with the telemetry can arise, we wanted to log the sensor data on an on board datalogger, in case the connection between the transmitter and the transceiver did break off. We decided to use the Sparkfun Openlog datalogger for this purpose. The only connections the datalogger requires is a ground connection, a 5V supply voltage, and an RX connection.

II.II.V Mini Pro, camera and datalogger

As a part of our secondary mission we wanted to establish a two-way communication to be able to take pictures on demand. Because taking and transmitting or storing a picture is very time consuming compared to the measurement and transmission frequency, we wanted to achieve for our primary mission, a second controller circuit was included in the CanSat design. The Circuit was included a main computer (Pro Mini), a camera (Linksprite JPEG Color Camera), a datalogger (Sparkfun Openlog), and a digital connection to the T-Minus controller board. We established a communication path between the T-Minus board and the Pro Mini controller, so we were able to send a signal to the camera circuit in case the T-Minus circuit received a “take a photo”-request from the ground station. Instead of sending the huge amount of data collected in one picture from the camera back to the T-Minus board and further to the ground station, we decided to save the picture on the second on board Openlog datalogger. We could also have used an additional radio with a separate transmission frequency to transmit the photo to the ground station.

III HARDWARE AND SOFTWARE SETUP AND CONFIGURATION

An advanced and highly functional technical setup is a prerequisite for the success of the mission. The setup and configuration encompasses everything from a stable telemetry setup to the processing and filtering of received data in real-time.

III.I Hardware setup

The nature of our secondary mission requires data to be received, filtered and processed in real-time, which in turn requires a low-noise radio-link between the CanSat and the Ground Station. For the launch in Portugal, a telemetry setup with a frequency of 434.43 MHz was used. The transceiver module of the CanSat featured a wire-based 1/4 λ-antenna. This type of antenna is well suited for the mission, as it does not take up much space and is not easily damaged during the ejection of the CanSat.

As explained before a true two-way communications link between the CanSat and the ground station was not set up. At the ground a Yagi-antenna was used to achieve a long-ranged telemetry setup and to achieve a true two way communications link at the relevant distances the antenna situated on the CanSat and corresponding amplifier had to be more sensitive than the 1/4 λ-antenna used. Unfortunately we did not have time to work sufficiently on this issue.

III.II Ground Station

The Ground Station is in charge of receiving data via the connected Yagi-antenna as well as filtering, processing, and displaying it. In actuality, it is a complicated process pipeline. As it is essential that the data is processed in real-time, the entire process has been solved programmatically by using the Python programming language and employing a modular design and a "set it and forget it"-principle.

One program, the Listener, is in charge of reading the data from the antenna and storing the data in a temporary communication file as well as a permanent log file. Another program, the Feeder, reads the communication file and filters, parses, and processes the read data. The processed data is then sent to any connected users, the Clients.

Simultaneously the Ground Station is running a web server, the Presenter, which serves any connected Client the requested web page. The Presenter is capable of establishing a connection between a Client and the Feeder and instructing the Client's browser on how to render the graphs found at the "/live/graph" and "/graph/" endpoints.

The Presenter also hosts a custom-made blog at the "/blog/" endpoint, a page explaining the project at the "/about" endpoint, and a live map rendered using Google Maps at the "/live/map" endpoint.

Naturally, data from previous missions can also be found at the Presenter website.

The Ground Station is also able to set up a wireless hotspot. This is particularly useful during launches in locations without internet access, as it allows bystanders to connect to the hotspot and see the data in real-time without any connection to the internet.

III.III Data Exchange Protocol

During the development of the code for both the CanSat and the Ground Station two separate data exchange protocols were used. In the development and testing phase the data was encoded using the ASCII-encoding. ASCII's advantages lies in the fact that it is used as an encoding for text-representation, making it readable by humans without much effort. The cost of this is a much larger data footprint - representing numeric values is very inefficient, as each digit is represented with a whole byte, leaving a large amount of the possible bit combinations entirely unused. Another upside to using the ASCII encoding is easy filtering. Due to the large amount of unused bit combinations, a packet of data containing any irregular bytes must have been subject to unwanted disturbances and should therefore be discarded.

The second protocol was tailored for mission and thus offered a drastically reduced packet-size. This reduction stems from the utilization of all bit combinations in the sensor data part of each packet.

Each packet starts with a mandatory header, which in our case is the ASCII-representation of "SGCan". A protocol version identifier follows the packet header, enabling the Ground Station to process the packet in accordance to the sensors on board the CanSat. Next comes the length of the sensor data represented using a single byte, followed by the numeric values from the sensors in a binary representation. Last is the checksum of the sensor data, a static byte with the decimal representation of 255 and an ASCII line terminator.

As the primary way of checking for alteration from disturbances is gone in the tailored protocol, two new means of validation have been set in place. First is the checksum, which is two bytes calculated using a cyclic redundancy check, CRC, on sensor data. If the checksum calculated by the Ground Station matches the checksum calculated and sent by the CanSat, the data is valid. Secondly it is checked that the checksum is followed by the static byte and ASCII terminator. If this is not the case, the disturbance has likely effected several packets and the Ground Station will have to realign the data using the packet header.

Due to the difference in packet-sizes, a baud rate of 19200 was needed when using the ASCII-based protocol and a data-frequency of 10 Hz, while the tailored protocol allowed the baud rate to be reduced to 9600 without compromising data integrity or frequency.

III.IV CanSat Server and teaching materials

In order to make the collected data available to teachers, students and the public in general, a website was launched (ref. 6). The website is powered by the same software that powers the Ground Station, but has been configured to be permanent. The source code to the Ground Station, the CanSat, and the website is also available to the public (ref. 7).

IV SCIENTIFIC RESULTS

IV.I Primary mission

Our primary mission was accomplished with data from all the installed sensors. The data from the sensors were measured and transmitted 6-7 times per second and the following graphs show the most important results:

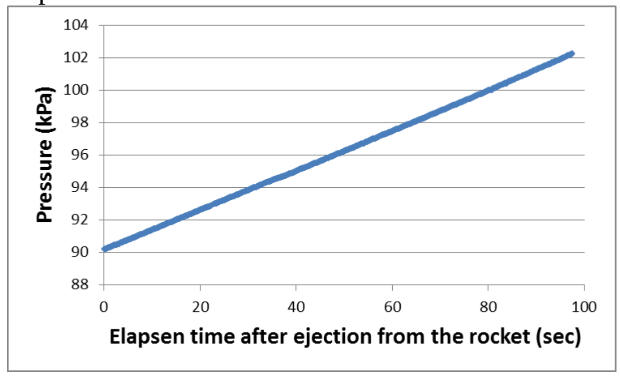


Fig. IV: Pressure as a function of elapsed time after ejection from the rocket

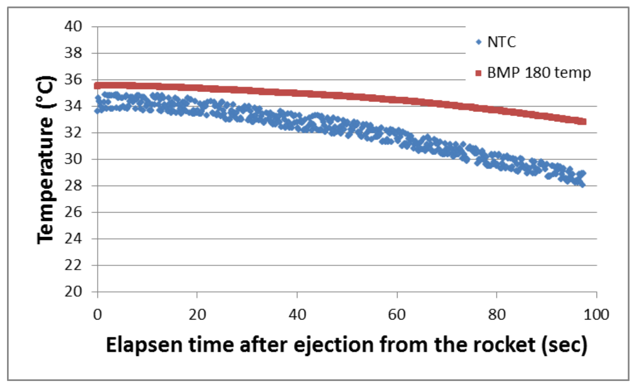


Fig. V: Temperature as a function of elapsed time after ejection from the rocket.

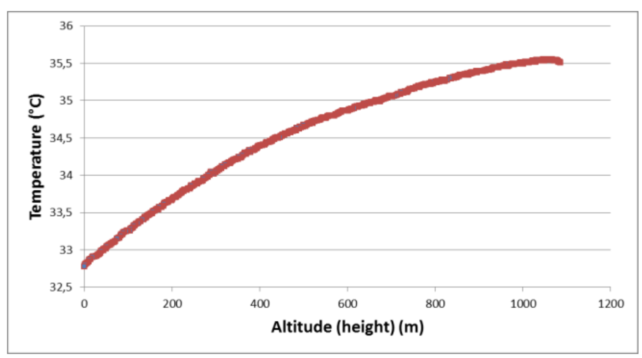


Fig. VI: Temperature (BMP180 sensor) as a function of height.

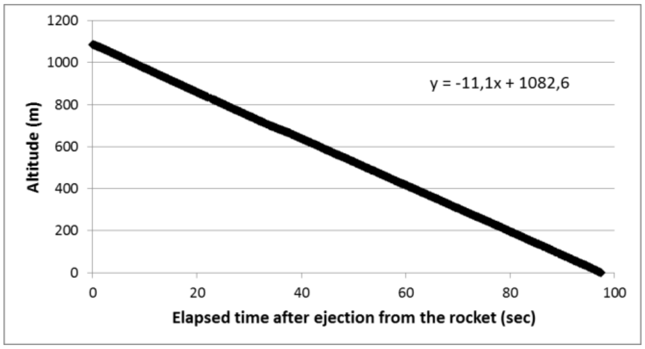


Fig. VII: Height (altitude) as a function of elapsed time after ejection from the rocket. The equation in the figure indicates the equation for the best straight line through the data points.

IV.II Secondary mission

For our secondary mission we measured and collected the CanSat rotational speed by the gyroscope, the magnetic field strength and the acceleration in 3 directions. We did track the CanSat with the GPS and took some pictures before the camera broke when ejected from the rocket.

The most important data obtained is presented in the following graphs:

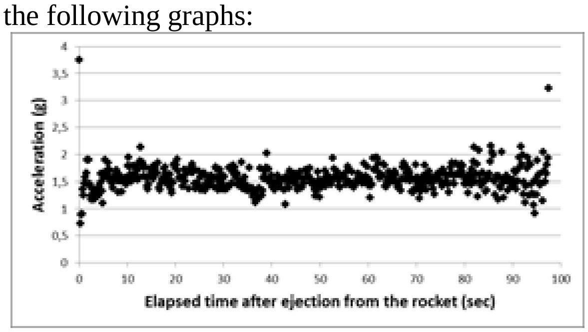


Fig. VIII: Total acceleration as a function of elapsed time after ejection from the rocket.

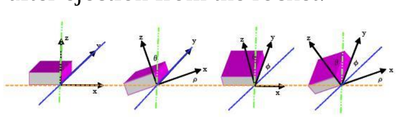


Figure 8. Three Axis for Measuring Tilt

$$\rho = \arctan\left(\frac{A_X}{\sqrt{A_Y^2 + A_Z^2}}\right)$$

$$\phi = \arctan\left(\frac{A_Y}{\sqrt{A_X^2 + A_Z^2}}\right)$$

$$\theta = \arctan\left(\frac{\sqrt{A_X^2 + A_Y^2}}{A_Z}\right)$$

Fig. IX: How to calculate pitch (ρ), role (Φ) and theta (θ) from 3-axis accelerometer (“A”) data (ref. 8)

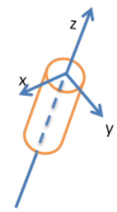


Fig. X: The direction of the three axis for our CanSat

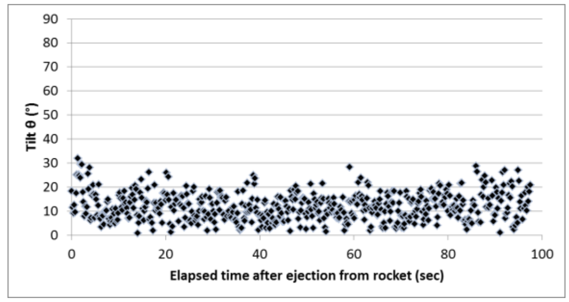


Fig. XI: The tilt angle θ calculated from the measured acceleration based on (ref. 8)

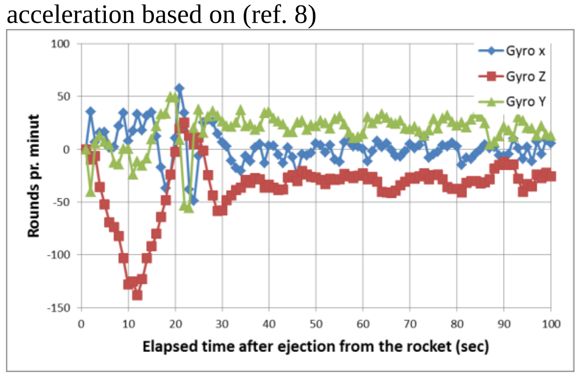


Fig. XII: Rounds pr. minute as a function of elapsed time after ejection from the rocket.

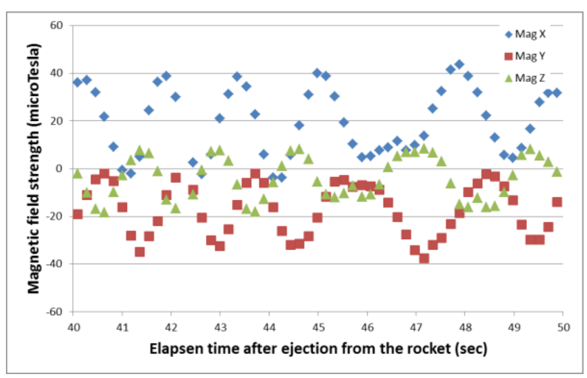


Fig. XIII: Magnetic field strength in three directions as a function of elapsed time after ejection from the rocket for a randomly selected time period during descent.

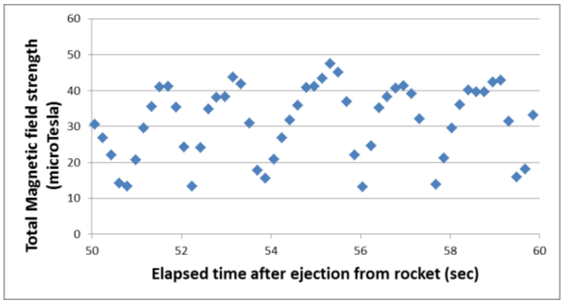


Fig. XIV: Total magnetic field strength as a function of elapsed time after ejection from the rocket for a randomly selected 10 sec time period during descent.

Fig. XV: One of the pictures taken before launch.

Fig. XVI: Tracking of CanSat by using GPS. Colour indicates the altitude of the CanSat.

With the obtained data it is possible to determine the position of the CanSat and in which direction a picture has been taken.

V DISCUSSION

Overall, both our primary and secondary mission went largely as planned and we received the data needed to construct trustworthy scientific results. We received all the data we were supposed to be gathering through our telemetry setup.

V.I PRIMARY MISSION

V.I.I Pressure

One of the most important, if not the most important task, is to collect pressure data. This data is used to calculate the height and apogee of the CanSat. During the descent, we received a direct feed containing the pressure and the height of the CanSat.

As presented in Fig. IV, the pressure went from 90 kPa to 102 kPa as the CanSat descended. Please notice that the time equals zero is the time when the CanSat was ejected from the rocket. The reason for this is that we only got telemetry at the ground station from the CanSat while it was outside the rocket after ejection. As expected, the pressure increases at a constant rate as the CanSat comes closer to the ground, as we can see in Fig. IV. The importance of successful pressure data cannot be underestimated. This is due to the importance of comparing height with all the other collected data. The graph shows a very steady increase in pressure, which is due to the precision of the BMP180.

V.I.II Height (Altitude)

From the pressure data, we were able to calculate the height of the CanSat using the barometric formula (ref.3 and ref. 4).

Displaying the height as a function of elapsed time (Fig. VII) allows us to get a good representation of the descent speed and the apogee of the CanSat.

From this data, we were able to conclude that the CanSat reached an apogee of 1085 meters. The rocket was supposed to reach a maximum height of just above 1000 meters, which is well represented in the data collected by our CanSat. We were also able to calculate the descent speed of 11.1 m/s as indicated in Fig. VII. This was approximately 10% faster than expected from previous flight tests, but we believe this was caused by the odd deployment of the parachute: A piece of isolation tape had detached the can and instead attached some of the parachute wires preventing a full deployment of the parachute. The CanSat had a safe landing, even though our parachute did not deploy quite as intended.

V.I.III Temperature

During the descent, we calculated temperature with two different sensors, an NTC and a BMP180. If we look at Fig. V we're able to conclude that the BMP180 is more reliable, as this sensor's data has little variation and has a steady decline.

At a quick glance, the temperature data may not seem reliable, as one would expect the temperature to rise, as the CanSat comes closer to the ground. This is clearly not the case with our data. This is caused by two main factors: The day of the launch, we had an inversion of the atmospheres temperature which resulted in the upper layers being hotter than the air at the ground. Another impacting factor is the heat dissipated from the other components in the CanSat, which heated the air inside it. This heat was then blown out, when the CanSat was ejected from the rocket. These two factors resulted in the readings being abnormal to what one would expect.

V.II SECONDARY MISSION

V.II.I Gyroscope

With the data collected from the 9DOF sensor, we were able to create a realistic representation of the rotational speed of the CanSat as it descended. From Fig. XII, were able to conclude that the main rotation of the CanSat was around the z-axis, which is to be expected. By looking at the y- and x-axis, we're also able to conclude that the CanSat was very stable during the descent. This is based on the small rotation on the y- and x-axis.

V.II.II Accelerometer

Fig. VIII shows the total acceleration of our CanSat during descent and as it is seen, the acceleration is highest as expected at the beginning at the ejection from the rocket and at the landing at ground level. A short periode after ejection, the acceleration shows a low value indicating that the CanSat is accelerating in a free fall towards the ground. A few moments later the CanSat with attached parachute has reached its terminal speed and the acceleration shows a value near 1g. The functionality of the accelerometer is such that it gives out the value 1g in the direction of the centre of the Earth if the accelerometer is not accelerating, so a value near 1g for our CanSat shows as written above that the CanSat has reached its terminal speed. With the data collected from the accelerometer, we were also able to calculate the tilt angle of the CanSat. The data shown in Fig.XI shows that the angle of the CanSat hovers around 10 degrees, which is close to 0 degrees which is directly down. This supports the claim that the CanSat had a very steady descent.

IV.II.III Magnetometer

We successfully collected data from the magnetometer, but even if this data is disturbed by magnetic fields generated by the other electrical components in the CanSat, we can use this data to give an estimate of how the CanSat is situated compared to the direction of the Earth's magnetic field. As shown in Fig. XIII and Fig. XIV the measured magnetic field oscillates which is caused by the rotation of our CanSat during descent. When for example the z-direction of our CanSat is pointing in the same direction than the Earth magnetic field the Earth magnetic field and the magnetic field from the other CanSat electrical components sum up to a high value and when the z-direction of our CanSat is in the opposite direction the two magnetic fields result in a low total magnetic field strength. These oscillations are fully comparable to the data from the gyroscope. Due to time constrains we were not able to compare these magnetic field measurements to the geographical compass directions.

IV.II.IV GPS

The GPS worked as intended and we got at lock approximately 20 seconds after the ejection from the rocket. The GPS was reset at the ejection due to ejection acceleration higher than the GPS's limit of 4g. The lock ensured that we could get live GPS data as the CanSat descended. Therefore we were able to display the position of the CanSat live. We were also able to use this data to show most of the the path of the CanSat as it descended. When the CanSat had landed, we were able to pinpoint the exact location of the CanSat, which later resulted in the CanSat being recovered successfully.

V.II.V Camera

The camera was one of the major letdowns. Even though the camera worked as it should before launch, it sadly got damaged during the extreme G-forces caused explosion which ejected the CanSat from the rocket. We were, though, able to display pictures, taken by the camera as the CanSat is on its journey to the rocket. One example is shown in Fig. XVI. Unfortunately, we did not get the corresponding data for position determination because of a failure in both the datalogger capture and in the telemetry to the ground station.

VI CONCLUSIONS

As a final statement we would declare the project a success, of course because of the launch and collected data, but also because of the entire project leading up to the final launch in Santa Cruz, Portugal. The project has been highly successful, because, despite all the technical lessons we definitely have learned during this project, we have also learned other things, which would help us, not only in the space industry, but for anything we might come across in life. Among these things is the realisation that building a CanSat, and making everything ready and fully working, takes time and most things are not going to be working perfectly after only a few seconds of work. Things fall apart or stop working due to unpredictable reasons, and small tiny mistakes can make you very frustrated. Thus we have learned to have more patience and to check everything to make sure that no mistakes happen.

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