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DELFI-C3 CONTROL SYSTEM DEVELOPMENT AND VERIFICATION

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Abstract

Delfi-C3 is a nano satellite, currently under development by primarily Msc. students from Delft University of Technology in the Netherlands. As the satellite is carried into space as a piggyback payload and deployed from a P-POD or T-POD canister, orbital parameters and initial and angular velocity can not be chosen, but are the consequence of the launcher's primary mission and uncontrolled deployment velocities respectively. Delfi-C3 is to fly two payloads: Thin Film Solar Cells (TFSC) and an Autonomous Wireless Sun Sensor (AWSS). Both the Thin Film Solar Cells and the Autonomous Wireless Sun Sensor are best tested under gradually changing light conditions. None of the payloads require a fixed or stable attitude. Therefore, the satellite is designed to gently tumble about all three axes in its orbit. Two concepts for a passive magnetic attitude control system are being designed: one with a permanent magnet and hystersis rods on both other axes and one using only hysteresis rods on all three axes. Although hysteresis based control mechanisms in combination with a permanent magnet have been used in many missions before, Delfi-C3 would be the first to fly with hysteresis rods on all three axes. At the faculty a Helmholtz cage is being build to verify the design.

Full text

1 INTRODUCTION

In October 2004, the University of Technology Delft decided to start its own satellite project. The CubeSat standard had just become known to the faculty of aerospace engineering and two Dutch industrials were looking for a flight opportunity for new technology.

This paper will introduce the Delfi-C3 satellite in chapter 2. It will address the requirements on attitude control as they follow from the payloads in the 3th chapter. Chapter 4 will explain the basics of the behavior of soft magnetic materials in external magnetic fields. Chapter 5 suggests possible solutions for the attitude control system. The next chapter (chapter 6) discusses the simulation of the attitude control system. The test setup for the system is treated in chapter 7. Finally, the future work on the Delfi-C3 is discussed in chapter 8 and conclusions are drawn.

Figure 1: The Thin Film Solar Cells

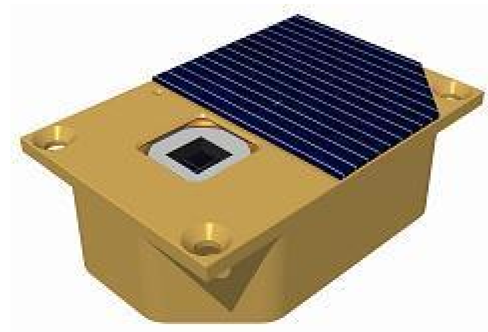

Figure 2: The Autonomous Wireless Sun Sensor as designed by TNO

2 THE DELFI-C3 PROJECT

The Delfi-C3 project started in October 2004. With the nano satellite Delfi-C3, the wishes of the Delft University of Technology and two Dutch industrials could be fulfilled: students working on a real satellite project and flight opportunities for newly developed technology.

DutchSpace was looking for a flight opportunity to conduct an in-orbit test of their newly developed TFSC. The TFSC are displayed in figure 1. Though the efficiency is lower than conventional solar cells, these new solar cells have a much higher power to mass ratio. Four sets of two TFSC's will be flown on the Delfi-C3.

TNO (Dutch institute for science) is developing a digital autonomous wireless sun sensor. As designing and manufacturing the digital sun sensor would take too long for this flight, a conventional sun sensor is equipped with the envisioned technology: autonomous power supply and wireless communication.
This combination results in a small sensor that can be attached to a satellite without the need for external power or information lines and cable harness: the AWSS is a plug and play device. It is depicted in figure 2.

At the International Aeronautical Congress 2004 in Vancouver, a faculty professor was introduced to the CubeSat concept. This concept sets a standard for nano satellites with a satellite structure and on board computer.

With the two industrials seeking flight opportunities, a standard satellite kit and the ambition of the university, a real satellite project came into being.

Figure 3: The antenna's of the Delft ground station

To retrieve the data, a ground station is already present at the university (figure 3). The SSETI express was tracked by the Delft ground station. Delfi-C3 will be launched into such an orbit that it will cross Delft. The Delfi-C3 will fly over the ground station six times a day, of which three will be during daylight, and thus while test data is sent down. As not all test data can be registered by the ground station in Delft, radio amateur all around the world have been asked to record the data and send it to Delft via the internet. In return for this support, the Delfi-C3 has a radio amateur platform on board. This enables radio amateurs around the world to communicate with each other.

The faculty of aerospace engineering has a clean

Figure 4: The Clean room at the faculty of Aerospace Engineering

room facility (figure 4). Here, the satellite will be assembled. Also, the tests on the passive magnetic attitude system in the Helmholtz cage will be performed here.
To be able to encompass all the payloads and provide enough power, a three-unit CubeSat kit has been chosen to serve as the basis for this satellite. It has conventional solar cells for power for normal operation. The TFSC will not be used as power supply: the TFSC are an experiment and the satellite has to function even when this new technology fails. Likewise, the AWSS are not used for attitude determination.
The satellite has been designed as displayed in figure 5.
In summary, the satellite is 34 by 10 by 10 cm. The maximum mass is 3 kilograms. It runs on little over 2 Watts, produced by the conventional solar cells. It will be launched on July the 30th from the Indian launch site Sriharikota on board the Polar Satellite Launch Vehicle. Delfi-C3 will be launched into a Sun synchronous orbit, with an altitude of 630 kilometers and an inclination of about 98 degrees.

3 DELFI-C3 MISSION

The payloads flown on the make the Delfi-C3 a test platform. The TFSC and the AWSS on the satellite both require sunlight for operation. In eclipse, no data is produced and therefore no power is needed. There is thus also no need for a battery. This makes the electrical power system much simpler and more reliable.
The Delfi-C3 has its payloads distributed all around

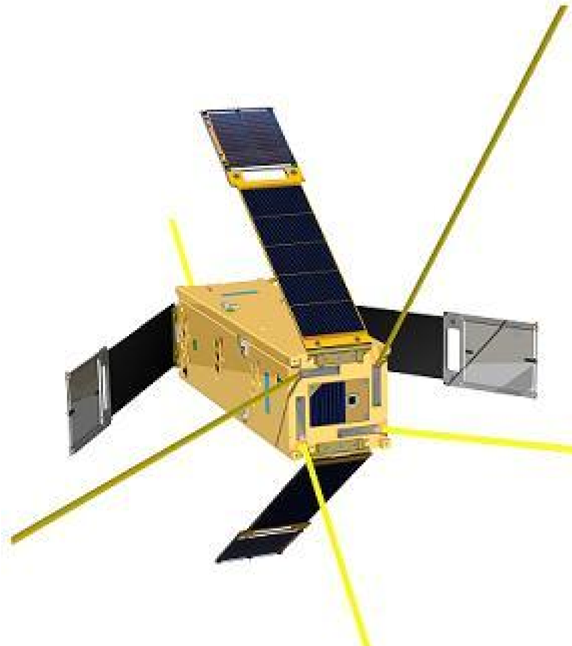

Figure 5: The Delfi-C3 satellite

the body. For proper testing of the payloads, one would like to have the payloads in gradually increasing light until full illumination and then in gradually decreasing light conditions again. This way the current-voltage (IV) curve can be established for the TFSC's. Also, gradual rotation allows for testing of the AWSS's. The payloads thus require rotation of the satellite.
The above wishes introduce a need for gentle rotation about all three axes of the spacecraft. Zero angular velocities are undesired; without rotation, only a limited number of the payloads would be in sunlight whereas the others are in the dark only. Also the thermal behavior would be very unfavorable with one side continuously in sunlight. On the other hand, high angular velocities are unfavorable as well, as this would not allow for representative testing. If, for example, the satellite would have a high angular velocity, the number of measurement points for the I-V curve of the TFSC would be very low.
The total rotation rate is therefore assumed to have to stay between 0.2 and 10 degrees per second. This is equivalent to rotation rates between 0.033 and 1,667 rpm. To realize this, the Delfi-C3 will be equipped with an Passive Magnetic Attitude Control System (PMAS).
A PMAS has been used before in other satellites. Generally it consists of a strong permanent magnet and hysteresis material on one or two other axes to

damp rotation. This system has for example been used in XI-IV, a CubeSat developed at the University at Tokyo. A satellite equipped with such a system has a single rotation left: the rotation about the axis parallel to the length of the magnet. Rotations about the x and y axis are dissipated. This way the satellite has a partially fixed attitude. None of the payloads on Delfi-C3 require any kind of fixed attitude or pointing direction. It only requires gentle rotation about all three axes. A permanent magnet is therefore a dispensable part of the system and hysteresis material on all axes becomes an option.
Two options are now available:

- A permanent magnet on one axis, hysteresis material on both other axes.
- Hysteresis material on three axes.

Either system should be able to damp out any initial rotation rates due to ejection from the T-POD, and damp any disturbance during operation. The mass budget of the Delfi-C3 allows for an PMAS of 150 grams.
Before going into more detail about these PMAS themselves, it is desirable to first discuss the hysteresis effect.

4 THE HYSTERESIS EFFECT

The basis of all magnetic effects is the rotation of an electron about the atom's core. Depending on the composition of the atom, a material can be classified as diamagnetic, paramagnetic or ferromagnetic. Diamagnetic and paramagnetic materials have little or no susceptibility to magnetic fields. The ferromagnetic materials however are strongly attracted to magnetic field and can stay magnetized without presence of an external magnetic field. These materials have magnetic domains in which a large number of atoms have aligned magnetic moments. In some materials these domains have a fixed direction; this is a permanent magnet or hard magnetic material. In other materials, the domains are randomly distributed, resulting in a zero magnetic dipole. When subjected to an external field, the domains orient themselves. After the external field is removed, residual magnetization remains. This material is soft magnetic material. The material can be characterized by the maximum magnetization (saturation induction (B_s)), the remaining magnetization after removal of the external field (remanence (B_r)) and the magnetic field required to nullify the magnetization again (coercive force (H_c)). The way in which soft magnetic materials are magnetized depending on the external field can be displayed in a B-H curve. Figure 6 displays such a curve.

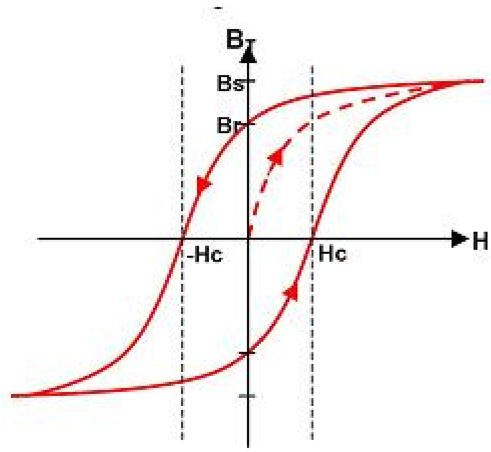

Figure 6: A typical hysteresis loop for a soft magnetic material.

Because of the lagging of the induction in the material with respect to the applied external field, this material is also called hysteresis material.
If the external field is changed, from zero to a maximum, to a minimum and back to zero, the path over the curve creates a surface. For a every unit volume of soft magnetic material, this surface represents a magnetic field strength (A/m) times an induction (Tesla = kg/(s^2A)), equals energy per unit volume (J/m^3). The energy dissipated during variation of the external magnetic field is the hysteresis loss. The energy for magnetization of the material drains the rotation energy. It is generally stated that the hysteresis effect only has effect in the length of a slender rod [2][3]. Thus, a rod rotating in the Earth magnetic field, can be modeled as a rod in a sinusoidal varying magnetic field. In simulations the B-H curve is usually approximated by a model. Multiple models are available. The easiest models are displayed in figure 7.
A more advanced model is the Preisach model. Though more complicated both in physical background and programmability, it produces more accurate results when the external field is much smaller than the field needed for saturation. The Preisach model is explained in [1].
The hysteresis material to be use in the Delfi-C3 is the nickel iron alloy PERMENORM 5000 H2. This is an 50 percent iron nickel alloy. Some properties of this material are stated in table 1.

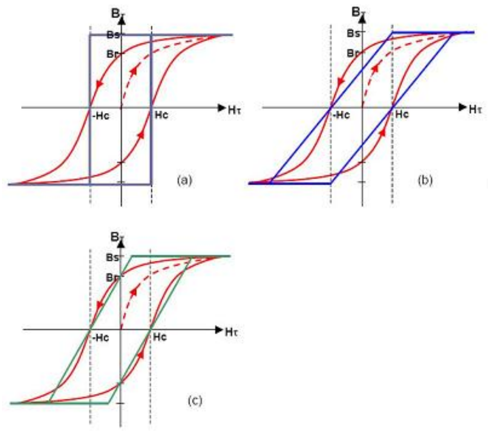

Figure 7: Different models to approximate the hysteresis loop based on characteristic values.

Table 1: Some properties of the hysteresis material to be used on the Delfi-C3 satellite.

Saturation induction Bs	1.55 T
Coercivity	5 A/m

5 PASSIVE MAGNETIC ATTITUDE CONTROL SYSTEM

As stated at the end of chapter 3, two options for the PMAS are being considered.

5.1 PMAS with permanent magnet

The first option is the conventional permanent magnet on one axis with hysteresis material on the others. This system with permanent magnet aligns one axis with the Earth magnetic field. This system has been used before on satellites and is a proven concept. A schematic layout of this concept is shown in figure 8.
As stated before, zero angular velocities are also unwanted. A permanent magnet on an axis would induce two rotations per orbit already about an axis perpendicular to the magnet. The residual required angular velocity would have to be about the z-axis.

5.2 PMAS with hysteresis material only

The second option is hysteresis rods on all three axes. As alignment is not required for the Delfi-C3 mission, this gave rise to the idea to leave out the permanent magnet and use hysteresis material on this axis also. With this system, the rotation is damped about all three axis, but none of the axes is aligned. This is a system that has not flown before. This system is displayed in figure 9.
If hysteresis material would be applied on three axis, a never used before attitude control system would be used. With this concept however, in absence of any preferred attitude, the motion of the satellite is unknown.

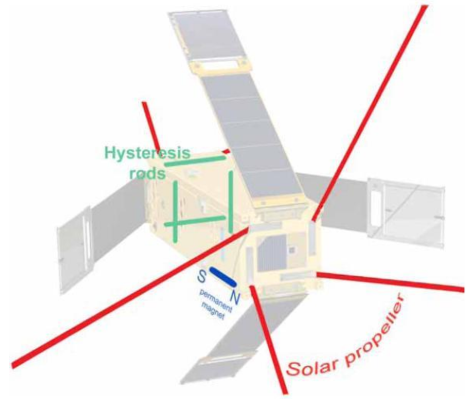

Figure 8: Schematic layout of the PMAS with permanent magnet and a solar propeller.

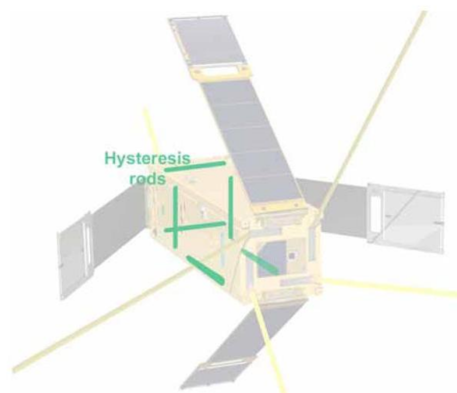

Figure 9: Schematic layout of the PMAS with only hysteresis material on all axes.

6 SIMULATION

Of both systems some initial and crude simulations have been done. Using the CubeSat simulator the some feasibility checks have been done on the system with hysteresis material only. To this extent the calculations for the permanent magnet were replaced by hysteresis calculations. Using the data then available, the qualitative conclusion was that the system would function properly: high angular velocities were reduced, while never bringing the entire satellite to a standstill. However, using new data (like the recently obtained orbit parameters) and more sophisticated models for the magnetic behavior, new simulations will have to be performed to obtain quantitative results. The Preisach model will be programmed to be used EuroSim and might also be added to CubeSim. CubeSim could then be rewritten to have a fourth hysteresis model. Using EuroSim some disturbance torques have been determined. These are collected in table 2.

Table 2: Some maximum disturbance torques on Delfi-C3.

Torque	Magnitude (Nm)
Aerodynamic torque	1.4E-7
Gravity gradient	3.5E-8
Solar torque	8E-9

To verify the simulations, especially concerning the magnetic system, a special test setup will be build.

7 THE HELMHOLTZ CAGE

A wish of the faculty is to be able to actually test the passive magnetic attitude control system and not rely on simulations alone. The tests can be used to both asses the behavior of the system empirically and to verify the simulations. To test a passive magnetic attitude system like the one to be used on Delfi-C3, a Helmholtz cage can be used. The purpose of a Helmholtz cage is to create any required homogeneous magnetic field. A complete cage consists of three pairs of Helmholtz coils. Helmholtz coils are relatively large round or square coils. If spaced about a radius apart (or a half side length, in case of a square coil), the magnetic field in between the coils is very homogeneous. An example setup of two Helmholtz coils is depicted in figure 10. When three coil pairs are combined on orthogonal axes, the magnetic field within the volume between all coils can be completely customized. This setup forms the complete Helmholtz cage. Possibilities with such a test facility are:

- nullification of any magnetic field

Figure 10: A possible setup of two circular Helmholtz coils. This setup displays two coils with a experiment table in between. A setup like this allows for control of the magnetic field in one direction only.

- simulation of in-orbit magnetic field magnitude
- simulation of the variation of the magnetic field during an orbit.

The required Helmholtz Cage will be build by the faculty itself. With all antenna's deployed, the Delfi-C3 fits into a volume with outer dimensions of roughly 1 cubic meter. This entire satellite should fit inside the Helmholtz cage. Thus, the coils should be 1 meter apart. As this distance is half the side length of the coil, the coils should have a radius or half length of about 1 meter. Both square and circular coils can be used. However, square coils produce a more homogeneous field, are easier in calculations and square coils are easier to build together than round coils. Square coils of 2 by 2 meters will be created. A design of one of the coils is depicted in figure 11.
Within the project it was agreed that the cage should be able to produce about three times the Earth magnetic field magnitude. The Earth Magnetic Field (EMF) varies between 30 and 60 micro Tesla. The cage will be able to create fields up to about 180 micro Tesla. As the cage has to serve more projects in the future than only the Delfi-C3 project, a multipurpose setup has been chosen: the coils can be positioned about 2 meters apart: this results in a large test volume of just under 2 by 2 by

Figure 11: A coil as designed for the Helmholtz cage that is going to be build at the faculty. The coils are squares with sides of about 2 meters. Six coils will be constructed in three pairs. Every next pair will be slightly smaller than the last so the coil pairs can be placed inside each other.

2 meters, but with less homogeneity. Also in a position with the coils spaced 1.25 meters aprt a test volume of 0.5 by 0.5 by 0.5 meters is available with very high homogeneity. The coils can be shifted inwards to a distance of 1 meter: this results in a maximum test volume of 1 by 1 meter with high homogeneity. For every volume a specific spacing between the coils, yields the most homogeneous field. The final cage design and the different layouts possible are depicted in figure 12. A field of little under 2 by 2 by 2 by 2 meter shows rapidly changing magnitudes near the boundaries of the volume. Differences might run over 100 percent, while direction might be off up to 25 degrees. The cage will be able to create magnetic fields of 1 by 1 by 1 meter with magnitudes on the boundaries not more than 20 percent stronger than the center and no more than 5 degrees misalignment. A small field of 0.5 by 0.5 by 0.5 meter can be best created by spacing the coils 1.25 meters apart: this results in a field with magnitudes not varying more than 3.5 percent and directions off by not more than 2 degrees.

Figure 12: Two possible layouts of the complete Helmholtz cage. The figure displays the design of the complete cage with the support construction surrounding the six coils; one coil pair per axis. On top a layout with inwards shifted coils is displayed. This allows for a test volume of custom size with matching homogeneous field. On the bottom, a layout in which the coils are all shifted to their most outwards position to create the largest possible test volume, but with less homogeneity than with inwards shifted coils.

8 FUTURE WORK ON THE DELFI-C3

Though the requirements, the concepts for design, simulation and testing are all there, the actual work is just getting started. All data and hardware available will be used to design and verify the 150 grams PMAS for the Delfi-C3. For reliable simulation, the Preisach hysteresis model will be written for EuroSim and perhaps also for implementation in CubeSim. Simulation inputs are constantly being updated with the latest values like the altitude and inclination (which only recently became known). With progressing design, more accurate mass moments of inertia become available. Multiple tests will be performed in the Helmholtz cage. The motion of a single rotating hysteresis rod in a magnetic field, the motion of a combination of a permanent magnet and hysteresis material and in the end the complete system in a Delfi-C3 mass dummy. The test results will be used to validate the computer simulations.

9 CONCLUSIONS

The payloads of the Delfi-C3 satellite are the drivers for the attitude control system: both high and zero angular velocities are unwanted. Zero angular velocities would not allow proper testing of all payloads distributed over the satellite body. Zero angular velocities would also give rise to unfavorable thermal behavior. High angular velocities would not allow for enough measurement time per time the payload faces the Sun. None of the payloads require pointing. As the satellite has a very limited mass and power budget, the most feasible attitude control system is a passive magnetic system. Two options, either with a permanent magnet, or without a permanent magnet, will be simulated and tested for their feasibility. To this extent a Helmholtz cage will be build. This allows for both empirical results and validation of simulations with CubeSim and EuroSim.

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AWSS Autonomous Wireless Sun Sensor

AE Aerospace Engineering

TFSC Thin Film Solar Cells

PMAS Passive Magnetic Attitude Control System

EMF Earth Magnetic Field