BeeSat Attitude Determination and Control System

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Abstract Berlin Experimental and Educational Satellite (BeeSat [1]) is a highly innovative pico satellite project of the Department of Astronautics at Berlin Technical University. Main objective of BeeSat is the on-orbit verification of miniaturized reaction wheels suitable for pico satellites which have been developed with our main industrial partner Astro- und Feinwerktechnik Adlershof GmbH [2]. Work is done to provide a number of additional pico satellite technologies. This paper outlines motivations for equipping a pico satellite with an attitude determination and control system (ADCS) based on reaction wheels. BeeSat's ADCS is exposed briefly alongside some of the solutions the research team at TU Berlin developed. A sun sensor system based on Position Sensitive Detectors is introduced, a new design principle for magnetic coils is explained and the Microwheel system is displayed.

1 Introducing Pico Satellites

At TU Berlin good experiences with micro satellites have been made. The series of TUBSAT [3] micro satellites has shown remarkable results and provided students with hands-on experience ever since the micro satellite TUBSAT-A was

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launched in 1991. Regarding the overall increase in capability, performance and efficiency of electronics pico satellites become a more and more serious subject to research.

CubeSats [4] are pico satellites, which means, that their total mass may not exceed 1kg. They have a cubic shape and standardized outer dimensions of $10 \times 10 \times 11.3\text{cm}^3$. Furthermore they have to meet special requirements to ensure the safety of launch vehicle and primary payload. Those limitations make it hard to realize features already taken for granted on larger satellites but on the other hand offer universities cheap and easy access to space.

Technologies for pico satellites can be used on larger satellites as well, one example being the reaction wheel developed for BeeSat which can easily be equipped with a larger flywheel mass and then meet the needs of nano satellites.

2 Beesat's Goals

The goals of the BeeSat project can be divided into three different groups:

2.1 Technology Demonstration

First and foremost BeeSat is a technology demonstration and evaluation satellite platform. The main goal is the on-orbit verification of newly developed reaction wheels for pico satellites. On the side of the ADCS also a new design principle for magnetic coils is evaluated as well as a sun sensor system based on Position Sensitive Detectors (PSD). Technologies tested on BeeSat also include: An in-house developed on-board computer, modified transceivers, a power control and distribution unit. The dependable operating system and middleware TinyBoss [5] developed for BeeSat eases programming and adds to overall security.

2.2 Widening the Field of Possible Pico Satellite Applications

Due to limited technological resources only few applications are suitable for the current generation of pico satellites. Acquiring technologies for pico satellites also means enabling them to fulfill the more demanding missions already envisaged at TU Berlin [6]. Possible applications and capabilities include:

- Occultation measurement
- Remote sensing and target pointing with one or more satellites
- High bandwidth communications
- Constellations
- Formation flight

2.3 Student Education

During numerous seminar papers and diploma theses students already have gained valuable experiences regarding mission analysis and satellite design. Once launched BeeSat will also serve as a means of teaching satellite operation.

3 Design Principals

Building a CubeSat means that a number of limitations will be encountered during satellite development. Outer dimensions of $10 \times 10 \times 11.3\text{cm}^3$ limit the room available within the spacecraft and put harsh limits on the overall energy consumption of the satellite. The mass limit of 1kg has also shown to cause many difficulties. In order to fulfill BeeSat's goals under the limitations of the CubeSat standard a couple of design principals have shown to be useful.

3.1 Use of Commercial of the Shelf Parts

Latest commercial of the shelf (COTS) parts often have better electrical, mechanical and monetary properties than their already space-proven counterparts. Due to their usually short life cycles (BeeSat is designed for one year of operation) and limited resources in space and energy, pico satellites can and have to take use of COTS components. Often they have to be adapted and always be qualified before being flown within the satellite. Another advantage of this strategy is that this valuable possibility for on-orbit verification of small parts can also help funding the satellite mission. BeeSat's sun sensor system (see Section 4.3) is a good example of a COTS part adapted to fulfill important tasks during a pico satellite mission.

3.2 Functional Integration Rather than Subsystem Separation

Enabling one assembly unit to fulfill a number of tasks means saving manpower during development as well as valuable mass and volume on the satellite. Due to its thin (1 mm) outer structure with many cut-outs BeeSat needs a structural fortification altering the natural frequency and adding to overall rigidity. This fortification also holds and isolates batteries so that they do not suffer from space conditions. Furthermore it serves as shielding for radiation sensitive parts of the on-board computer and provides various mounting points.

The printed circuit boards (PCB) (see Fig. 4) on each side of the satellite also fulfill a number of tasks within different subsystems. The magnetic coils for attitude control are printed within those boards; they also hold sun sensors and their aperture plates and electronics. Furthermore each PCB also holds solar cells for energy generation.

4 Attitude Determination

BeeSat will be equipped with a unique ADCS. Most of its parts were newly designed in order to provide future missions with the necessary hardware to fulfill more demanding tasks. During the TUPEX [7] experiment BeeSat's attitude sensors have all been successfully tested on a suborbital flight of the Rexus sounding rocket. Figure 1 shows TUPEX' main board and outboard plate containing sun sensor system and solar cell.

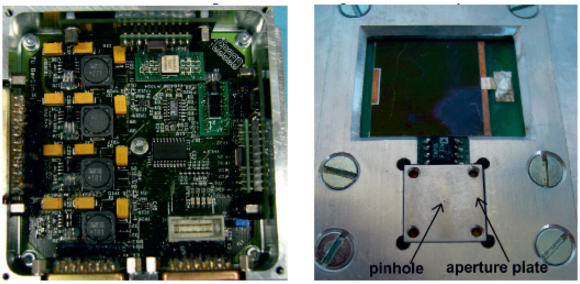

Fig. 1 TUPEX Experiment main board and outboard plate after recovery

4.1 Magnetic Field Sensor System

Two magneto-resistive magnetic field sensors, each measuring in three axes, will be used on BeeSat. An applied magnetic field changes resistivity within the sensor so that output voltage is proportional to the magnetic field. Once measured the magnetic field vector can be compared with the output of a reference model (IGRF10-13) calculated on-board the satellite in order to derive the satellites attitude.

4.2 Gyros

Gyros of appropriate size, weight and power consumption for pico satellites with a measurement range suitable for satellite operations are not available yet. Gyros used for BeeSat have a range of $\pm$ 150°/s while the predicted angular rates do not exceed 5°/s. They will be used as additional reference and for tests at high rotation rates necessary for verification of the Microwheel system.

4.3 Sun Sensor System

The sun sensor system developed for BeeSat consists of six Position Sensitive Detectors (PSD) each covered with an aperture plate. One is placed on each side of the satellite in order to calculate the sun vector in body-fixed frame.

Incident sunlight passes through the aperture plate and shows up as a spot on the surface of the PSD. A photo current is generated and split up to each side of the sensor, the magnitude depending on the distance between spot of incident sunlight and each side contact. The currents are transformed to voltages, amplified and measured. Through combination of all sun sensor measurements the direction of incident sunlight with respect to the satellite is derived. The on-board navigation system (ONS) delivers a sun vector in inertial reference frame. Both vectors can be compared in order to obtain attitude information. Figure 2 shows a sectional view of the aperture plate with subjacent sensor and sunspot.

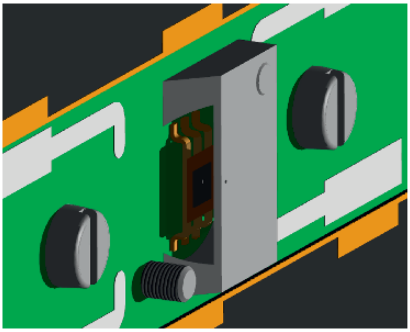

Fig. 2 Sun sensor and aperture plate

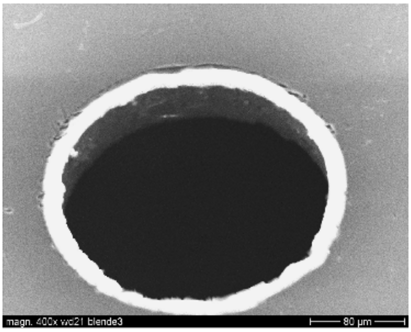

Fig. 3 Pinhole in aperture plate

During tests an accuracy of 1.5° has been reached after calibration. In order to reach better results a new aperture plate has been built. Other than the first version which had only a drilled hole here the aperture is angled at 120° and fabricated much more precisely. The outside of the aperture plate is polished while the inside is anodized in order to prevent scattered light. A scanning electron microscope image of the pinhole can bee seen in Fig. 3.

Table 1 Technical properties of attitude sensors

	Magnetic field sensor	Gyro	Sun sensor
Manufacturer	Honeywell	Analog Devices	Hamamatsu
Outer dimensions [mm^3]	$7.4 \times 7.4 \times 2.8$	$7.0 \times 7.0 \times 3.0$	$7.0 \times 4.8 \times 1.8$
Power consumption [mW]	30	30	1.5
Range	$\pm$ 6 Gauss	$\pm$ 150°/s	$2 \times$ 2mm

5 Magnetic Coil System

The magnetic coil system which induces an external torque on the satellite bus due to the Lorentz force, consists of totally six coils. A pair of two coils is mounted in each axis to allow redundant operation. The main tasks of the coil system are coarse three-axis stabilization of the satellite body and the desaturation of accumulated angular momentum within the reaction wheels.

5.1 Hardware Design

The coil is embedded within a printed circuit board of seven layers, instead of winding the wire into a coil. One coil is able to generate a magnetic dipole moment of 0.03Am^2, which corresponds to a maximum torque of approximately $1 \cdot 10^{-6}$Nm at a power consumption level of 0.2 W. This innovative design approach seen in Fig. 4 makes the mounting devices conventionally needed to patch the winded coil on the bus frame, unnecessary. Furthermore this design is cost reducing for the coil can be manufactured at once with the other circuits. Also this design method prevents the coil from shortcuts because the windings are not insulated by epoxy enamel but are fixed in the circuit board with a defined distance and is therefore more robust. One drawback may some loss of the inducible dipole moment due to the spiral form of the circuit path, which has to be compensated by an increased number of windings.

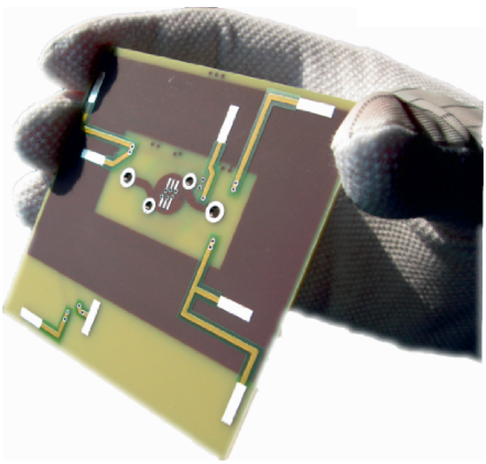

Fig. 4 Magnetic coil on PCB

5.2 Coil Control Algorithms

Bdot controller

The well known $\dot{B}$ algorithm (1) has been implemented for detumbling and attitude stabilization as well as for desaturation of reaction wheels. The $\dot{B}$ algorithm only requires knowledge of the current magnetic field and its derivative to dissipate the rotational energy stored in satellite bus or reaction wheels.

$$^{R}m_{Coil} = -K \cdot {}^{R}\dot{B} - m_c \tag{1}$$

With $^{R}m_{Coil}$ being the generated dipole moment in body frame, K the scalar gain factor, $^{R}\dot{B}$ the time derivate of magnetic dipole in body frame and m_C the constant dipole offset for steady state orientation.

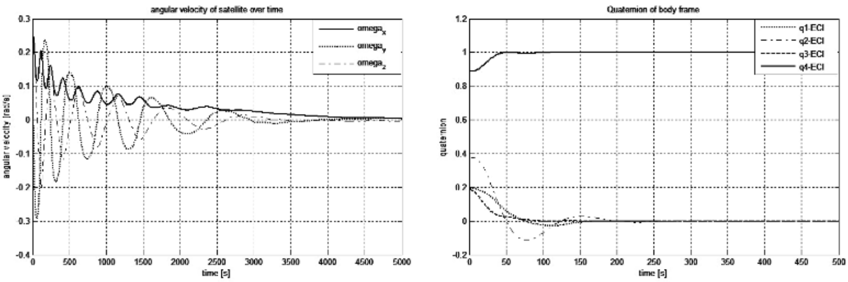

Fig. 5 Simulation results of Bdot controller (*left*) and PD controller (*right*)

PD Controller

Due to the fact that force cannot be generated alongside the earths magnetic field vector the coil system is not able to perform full three-axis attitude control. A PD controller [8] has been implemented to overcome this limitation. Using one reaction wheel and at least two coils in the remaining axes three-axis attitude control can performed even if one wheel looses functionality.

$$\begin{aligned} ^{R}m_{Coil,X} &= \tfrac{1}{^{R}B_y}(K_z \cdot \psi_{error} + K_{zd} \cdot \dot{\psi}_{error}) \\ ^{R}m_{Coil,Y} &= 0 \\ ^{R}m_{Coil,Z} &= -\tfrac{1}{^{R}B_y}(K_x \cdot \phi_{error} + K_{xd} \cdot \dot{\phi}_{error}) \end{aligned} \tag{2}$$

$$^{R}\tau_{Wheel,y} = -(^{R}m_{Coil,Z}{}^{R}B_x - {}^{R}m_{Coil,X}{}^{R}B_z) + (K_y \cdot \theta_{error} + K_{yd} \cdot \dot{\theta}_{error}) \tag{3}$$

Here K_x, K_{xd}, K_z, K_{zd} are scalar gain factors, ^{R}B stands for the earth's magnetic field in body frame, ψ_{error}, $\dot{\psi}_{error}$, ϕ_{error}, $\dot{\phi}_{error}$ represent the current error angels and $^{R}\tau_{Wheel}$ is the torque generated by a reaction wheel.

6 Microwheel System

BeeSat's important task is the on-orbit verification of newly developed reaction wheels. In a partnership with Astro- und Feinwerktechnik Adlershof GmbH and funded by the DLR (FKZ 50JR0552), reaction wheels with brushless motors have been developed especially to the needs of pico satellite developers.

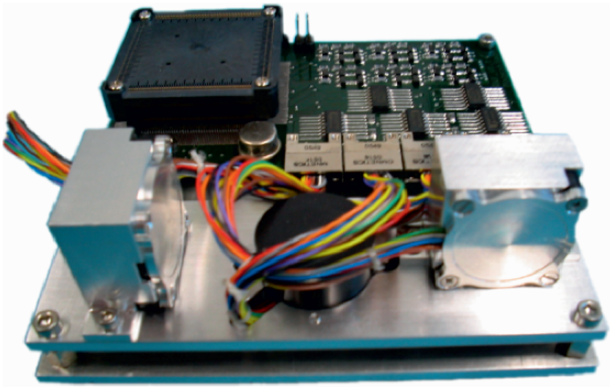

Fig. 6 Laboratory model of the Microwheel system

6.1 Technical Properties

Brushless motors and a special bearing system are used for the Microwheels.

With a total mass of 114.5 g, a torque of $4{\cdot}10^{-5}$Nm per wheel and a maximum power consumption of 1 W for the complete Microwheel system including the wheel drive electronics the qualification model of the reaction wheels exceeds the characteristics reached by the development model of Astro and TU Berlin. The small moment of inertia ($1.17{\cdot}10^{-5}$kg·m^2) is sufficient for pico satellites, it adds to overall accuracy while the high revolution speed of up to 16000 RPM still allows absorption of an angular momentum that equals BeeSat rotating at 7°/s. To allow easy adaptability for different missions or larger satellites the flywheel mass can be exchanged. A laboratory model of the Microwheel system including the wheel drive electronics can be seen in Fig. 6.

6.2 Microwheel Control Algorithms

The Microwheel system is controlled through a number of different linear single input/single output controllers for inertial pointing, earth pointing and large angle maneuvers. They consist of a state regulator and integrator as seen in equation (4). State variables are reconstructed through the state observer seen in Fig. 7.

$$\dot{\omega}_{MW} = -\underline{K} \cdot \underline{\hat{x}}(t) + K_i \int e(t)dt \tag{4}$$

Controller output is the desired wheel acceleration and its integral the target wheel speed. Matrix K is the state space control and $\underline{\hat{x}}(t)$ are reconstructed state variables. K_i is the integrator gain, $e(t)$ is the control error.

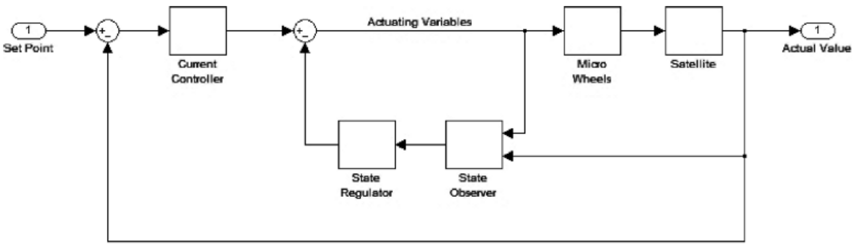

Fig. 7 Control loop

Figure 8 shows a simulated large angle maneuver over 60° in all three axes at the same time with a constant disturbance of $1.85{\cdot}10^{-7}$Nm. Oscillation during ascent and overshooting can be attributed mainly to coupling effects.

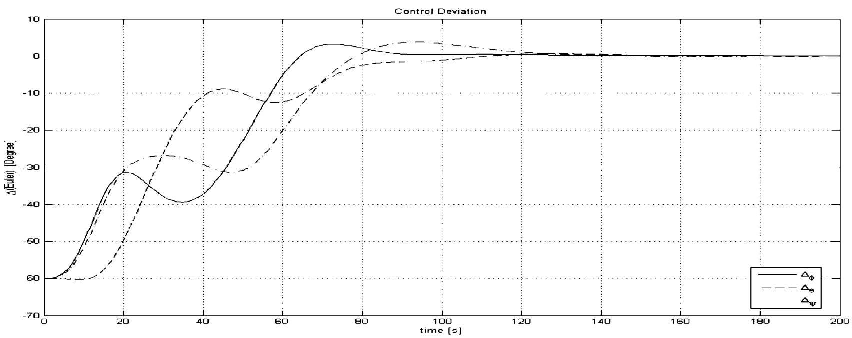

Fig. 8 Simulated large angle maneuver

7 Summary

Within the BeeSat project a number of components and strategies are evaluated in order to acquire pico satellite technologies. It's ADCS contains reaction wheels developed for pico satellites, a sun sensor system based on PSDs as well as a magnetic coil system on PCBs.

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