BEESAT: A Pico Satellite for the On Orbit Verification of Micro Wheels

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I. INTRODUCTION

Today, more then 60 universities around the world are working on CUBESAT's, which is a standardized pico satellite based on the development of the California Polytechnic State University, and Stanford University [1]. The aim is the creation of affordable launch opportunities to universities, whereby the use of a deployment mechanism (P-POD) plays an important role.

The CUBESAT specification is very attractive, because it provides an relatively easy way to place a satellite in orbit. But most of the CUBESAT's have very limited capabilities compared with the larger micro satellites. This is due to the fact, that there are basically almost no space proven components available, which are suitable for pico satellite class regarding power, size and mass properties. For this reason most of the CUBESAT's have either no attitude control or only very basic attitude control capabilities which relay on the use of magnetic torquers. Satellite applications, such as earth observation or astronomy require precise attitude control capability, which is only possible if adequate sensors and actuators are available.

The Technical University of Berlin has the objective to develop such components, which are not available yet. The first device under development is the so called "micro wheel", which is designed to be used in pico satellites, allowing a precise 3-axs attitude stabilization. The verification of these wheels in space will be done by BEESAT, the first pico satellite of TU Berlin.

The main objective of BeeSat is the on orbit verification of newly developed micro wheels for pico satellite applications [2]. These wheels, with the size of a one Euro coin in diameter, supported by DLR (FKZ 50JR0552) and developed in cooperation with Astro- und Feinwerktechnik, will drastically improve the actuation capabilities of pico satellites.

II. MISSION OVERVIEW

The overall mission characteristics of Beesat are as follows:

Orbit:	450…850 km (LEO)
Life:	1 year
Payload:	camera
Communication:	UHF amateur radio
Key components:	reaction wheels

Beesat will be operated from the mission control center at TU Berlin (figure 1). The Satellite will be nominally in a standby mode in which it does nothing but wait for new commands. In this mode the attitude of the satellite is not controlled and tumbling. The attitude devices are switched off on order to save power. Once the satellite receives tele commands by the ground station it checks them for validity and executes them either immediately or by time tag. The nominal way of operation is by using time tagged commands which are executed, when necessary, e.g. to make a picture or to start downlink over a ground station.

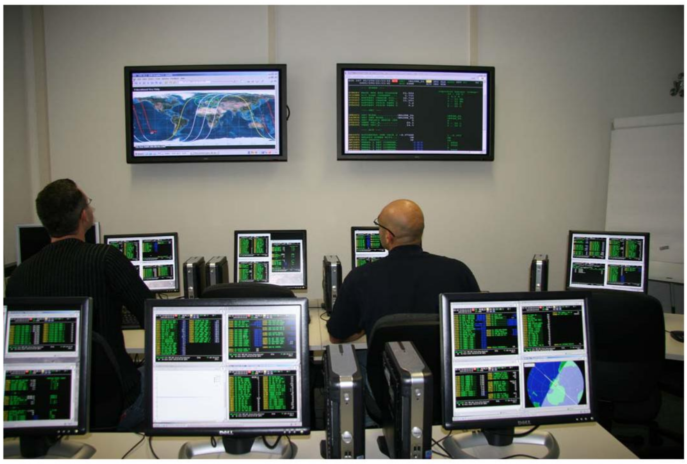

Fig. 1. Mission Control Center (MCC) of TU Berlin

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The verification of the reaction wheels will be done by a series of wheel performance tests in orbit. After this extensive testing phase, the wheels will be used to control the attitude of the satellite and also make some images from the earth. When a image is taken by the camera, it is stored and transmitted to the ground station offline when the satellite is within the ground station coverage.

III. SATELLITE OVERVIEW

Beesat is compatible with the CUBESAT specification (single configuration). The basic requirements coming from this specification are:

- Dimensions: 10 cm x 10 cm x 11.35 cm
- Max. mass: max. 1 kg
- Center of mass within 2 cm of geom. center
- No pyrotechnics

The basic configuration of the satellite is a stack of electronic boards, which are placed inside of a aluminum structure with the typical CUBESAT dimensions. Figure 2 shows the internal 3-D view of the satellite model. Beesat uses 3 reaction wheels, which are placed on the bottom of the stack. The wheel control electronics board is placed on the opposite side to the wheel platform. The two transceivers are under it. The battery package is placed in the middle of the satellite just above the wheels. The next boards are in ascending order, the board computer, a power control unit and the payload data handling system including the CMOS camera and the EGSE interfaces on the top of the stack.

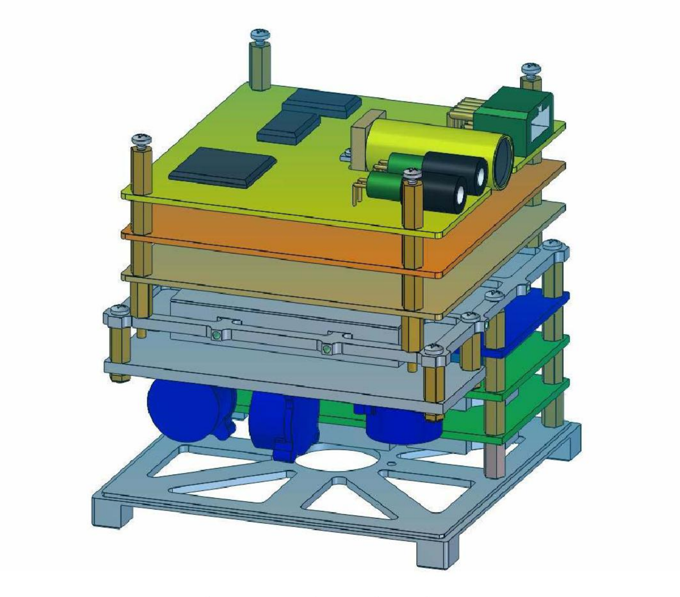

Fig. 2. Internal 3-D view of Beesat

Fig. 3. External 3-D view of Beesat

The external view of the Beesat model is shown in figure 3. This shows the two UHF antennas, and the solar arrays which are of different typ for one of the six sides of the satellites.

IV. MODEL PHILOSPHY

The model philosophy of Beesat will be according to the models listed below.

- SM Structure Model
- RTM Radio Link Test Model
- EQM Engineering Qualification Model
- FM Flight Model

SM is a structure model, which is build primarily for the mechanical tests and for the verification of the assembly process. RTM is a radio frequency test model, which is build to measure the radio frequency properties of the fully integrated satellite including antennas and the representative structure. This special model is necessary because of the short distances and complex structure. EQM is the engineering and qualification model. This model will be used to run all the qualification tests and then be used for simulations and diagnostic purposes after the launch of the flight model. FM is finally the flight model which will actually fly. Table 1 gives an overview of the planned tests for each model of Beesat.

TABLE I: BEESAT-VERIFICATION MATRIX

	SM	RTM	EQM	FM
Electrical function tests, Performance tests		x	x	x
Payload system tests			x	x
Physical properties	x		x	x
Vibration tests (search for resonances)	x		x	x
Random Vibration tests	x		x	x
Sinus vibration test (quasi-static)	x		x	x
Thermal cycles test			x	x
Thermal vacuum test			x	x
Thermal balance test			x	x
Antenna deployment test	x	x	x	x
Antenna field measurement		x		
Compatibility test		x	x	
Eject test (deployment)	x		x	x
Missionsbetriebstests	x	x	x	x
Software upload tests			x	x
End-to-End system tests			x	x

V. SATELLITE SUBSYSTEMS

Power Subsystem

Beesat is powered by high efficient solar arrays. There are Galliumarsenid solar cells on all 6 sides of the satellite. The number of cells is different on the interface panel. There are 2 cells on 5 panels and 8 smaller cells on the interface panel of Beesat (see figure 3). All panels are highly integrated, because they consist not only of the solar cells but also magnetic coils and a sun sensor (see figure 4). For energy storage, the system consists of 4 lithium polymer batteries from VARTA (PLF 503759 B) with a total capacity of 4400 mAh and a power control unit (PCU), which is responsible for charge control and power distribution. Like most of the subsystems, the PCU is also connected to the board computer via redundant CAN bus. The PCU monitors all power levels and is able to put the satellite into a safe mode if necessary.

The average expected energy from the solar arrays is 1.36 W min. at end of life. The average consumption is 0.5 W. Within the nominal operations scenario only 3% of the nominal capacity of the batteries is used.

A number of analog housekeepings (38) are directly measured by the PCU and transmitted to the on board computer via CAN bus.

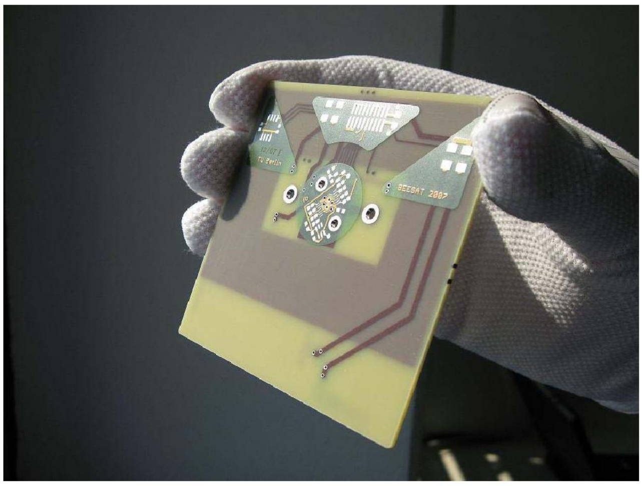

Fig. 4. Printed Circuit Board of solar panel (interface panel) without solar cells

Attitude Control

The main task of the attitude control subsystem is to control the attitude by different means. First of all, the attitude control subsystem is responsible for the control of the in orbit tests of the micro wheels as a minimum requirement. Furthermore a 3-axis attitude control system is implemented. The system uses the following sensors and actuators:

Sensors:

- 6 sun sensors, located on the solar panels
- 3-axis magnetometer,
- 3 gyros

Actuators:

- 6 magnetic coils, integrated into the solar panels
- 3 micro wheels

The main properties of the micro reaction wheels (see figure 5), which are designed to perform a 180° slew maneuver for a CUBESAT within 3 minutes, are as follows:

- Mass of the wheel system: max. 105 g
- Dimension's one wheel: 20 x 20 x 15 mm^3
- Min. angular momentum: 1.5 x 10-4 Nms
- Min. torque: 3 x 10-6 Nm

The micro wheels are controlled by the wheel electronic. This unit (see figure 6) is capable of controlling 3 wheels simultaneously using a FPGA and power electronics. The control unit is connected via redundant CAN bus to the board computer of Beesat. It accepts commands for the speed control and delivers the rotation speed as telemetry at 250 kBit/s.

Some of the components, which will be used for the attitude control subsystem, have already been tested on a sounding

Figure 5 Engineering model of a single micro wheel (Image: Astro- und Feinwerktechnik)

rocket, namely REXUS III within the TU Berlin Pico Satellite Experiment (TUPEX) in April 2006. The flight opportunity was provided by the German Aerospace Center (DLR) and Swedish space corporation. Figure 7 shows the main unit of TUPEX, which consists of the experiment control logic, magnetometer, 3 gyros, temperature sensors and the interfaces to the external sun sensors and solar cells, which were mounted on two sides of REXUS III. Results of the flight experiment, which reached an altitude of almost 100 km was recorded to an onboard flash memory and were transmitted to the ground station simultaneously during the flight using the s-band transmitter of REXUS III.

The results of TUPEX are used to improve the sensor design of Beesat, especially the new developed sun sensors. The sun sensors are utilizing a position sensitive device (PSD) as sensor and appropriate analog electronics for signal conditioning. The digitalization is done by the board computer.

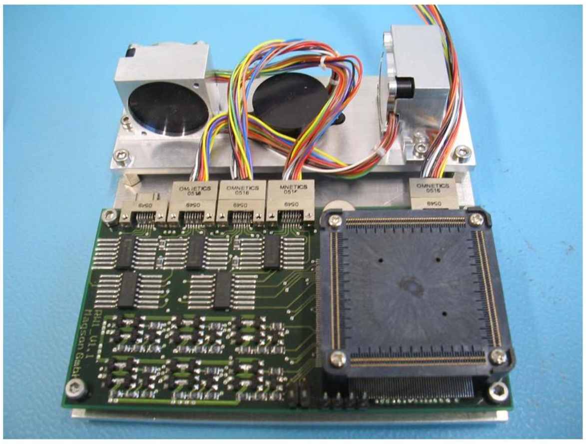

Figure 6 Engineering model of a micro wheel system

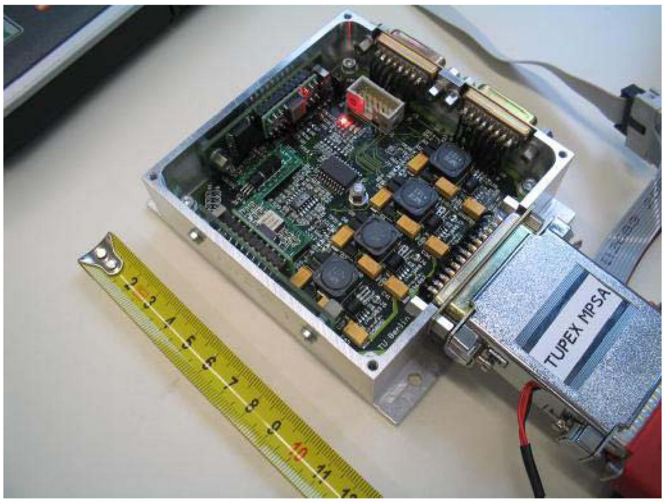

Figure 7 Main unit of TUPEX

On Board Computer

The basic task of the on board computer of Beesat is to control all subsystem functions and provide telemetry and telecommand capabilities. It consists of two redundant units which are based on a ARM7 core microcontroller from Philips, the LPC2292, as the main processor operated at 60 MHz. Each board computer uses a 16 MByte flash memory for program code, 1 Mbyte for telemetry data and 2 MByte SRAM. Each board computer is capable of measuring 48 analog channels with 12 bit resolution and a number of digital channels. The design of the board computer hardware is such that both computers are physically on the same board but functionally fully separated.

The software is based on the Tiny-BOSS operating system developed by Frauenhofer Institute FIRST. Tiny-BOSS is based on the BOSS, which is used as operating system for DLR's BIRD satellite board computer and was designed for maximum reliability. BIRD is a micro satellite of 94 kg. It was launched in October 2001 and is still operating.

Applications for the control of different parts of the satellite are organized in applications. Following applications are run on Beesat:

- Attitude Determination and Control
- Telemetry and Telecommand
- Acquisition of housekeepings (analog & digital)
- Surveillance of power conditions
- Redundancy Control
- Time Management
- Software Update

On top of the operating system Applications such as attitude control, telemetry and telecommand or time management are utilizing the operating system functions such as scheduling and hardware device drivers for the interfaces.

The software of Beesat can be updated in orbit and moreover at least two versions of the software are located in the program memory, so that if one fails, the other version is booted if necessary automatically.

Beesat software provides features to enable in orbit software upload, and time management. To increase the reliability of the system a special application is dedicated for the surveillance of the power conditions such as voltages and battery conditions. This application is responsible for the mode control of the satellite and can set the satellite into a safe mode if necessary. In safe mode, the satellite consumes only a minimum amount of power and only life critical systems are active. The limits for the different parameters can be updated by ground command.

Another feature of the on board computer, which is intended to increase the reliability of the system is the redundancy control, which manages the change of configuration, if one of the board computers should fail. In this case the board computer takes full control over the satellite systems. The detection of such an event is based on different watchdogs, which are implemented in both software and in hardware.

In the early phase of software development, where the board computer hardware is not complete, development boards for the target system are used. For the majority of software functions such as orbit calculations, where other hardware is not directly involved, this can be considered as a practical way to make progress in the work on the board computer.

Communications Subsystem

The communication subsystem of Beesat is responsible to receive telecommands from the ground station and send telemetry. The system has a digipeater mode feature, which can be used by amateur radio operators, when enabled. It consists of two independent UHF transmitters utilizing a modified BK-77 from STE Italy, two self developed Terminal Node Controllers (TNC) and two antennas. Figure 8 shows an engineering model of the communications subsystem of Beesat. The main characteristics of the system are as follows:

- Frequency band: UHF, 435 … 436 MHz
- Transmit power: 0.5 W
- Modulation: GMSK
- Bit rate: 4.8 (uplink) / 4.8 or 9.6 (downlink) kbit/s

The system is fully redundant and is connected to both on board computers via CAN-Bus.

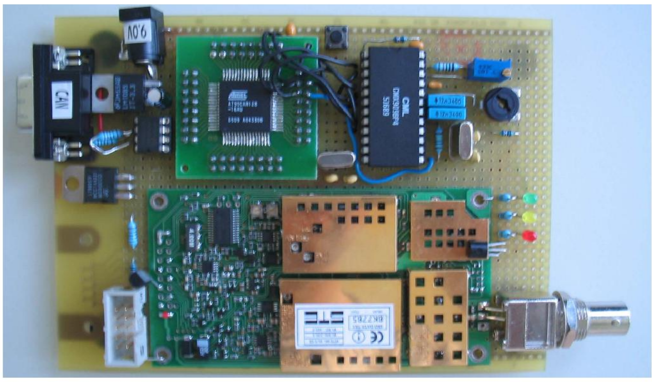

Figure 8 Engineering model of the Beesat Communication unit

Structure and Mechanisms

The primary structure of Beesat conforms to the CUBESAT specifications. The structure is made of aluminum. The total mass of the structure is less then 20% of the total mass. It is made of 3 main parts: top cover, main body and bottom cover. The battery compartment is placed in the middle of the main body in order to fulfill the requirement regarding the center of mass.

The structure provides mechanisms for the antenna deployment and for the “kill-switch”, which in fact switches on the power to the satellite, when it leaves the deployment mechanism.

Thermal Control

The thermal control of Beesat is done passively. Thermal simulations show, that very deep temperatures up to -20 °C can locally occur. For this reason, especially the batteries must be protected in a proper way. To prove the proper isolation of this critical part, it is planed to make qualification tests in a vacuum-thermal chamber.

Payload

The payload of Beesat consists of a CMOS camera. The camera will be used to make color images from the earth with a resolution of 640x480 pixels. It is connected to a dedicated payload data handling (PDH) unit, which controls the camera settings and stores the images. The PDH makes use of the same parts as the board computer in order to have a common design and make the system more reliable.

A maximum of 10 images can be stored on board. Selected images can then be transmitted over the ground station. The PDH is connected via CAN bus to the board computer. The image data is transmitted on request with low priority to the transmitter.

VI. GROUND SEGMENT

The ground segment of Beesat consists mainly of the Mission Control Center (see figure 1) and the ground station. Figure 9 shows an overview of the complete system. The primary ground station of Beesat is located at the top of the building of the Institute of Aeronautics and Astronautics at the TU Berlin. It consists of the UHF antenna, the steering motor and the computer, which controls the antenna and the transceiver (ICOM 910). The transceiver is connected to a TNC, which was developed for Beesat. It utilizes a GMSK modem chip and a micro controller to perform the time critical functions for the communications. The TNC is connected to a computer via RS-232 interface on which a telemetry and telecommand server (TTS) acts as the counterpart to the TNC and manages the half duplex communication. Other main tasks of the TTS are the management of the telecommand client and the telemetry clients as well as the archiving of all received data. The functions of the TTS can also be controlled remotely and status information is provided by TTS to a dedicated control application via network.

The software to control Beesat has a telecommand and a telemetry component. Figure 10 shows the graphical user interface of the telemetry interface. A alpha numeric display is shown in this example but the software is also capable to show plots of selectable parameters. It is a client based application, which can be run on any computer and receives its data via TCP/IP from the ground station server. Many instances of the software can be run on the same computer or on different computers in parallel. The telemetry is organized in so called pages. Each user can view different pages, which group the telemetry parameters in different ways (e.g. power subsystem, attitude control). The parameter definitions like telemetry id, calibration, engineering unit etc. is maintained on a telemetry database, so that the definitions can be changed easily for other satellites in the future.

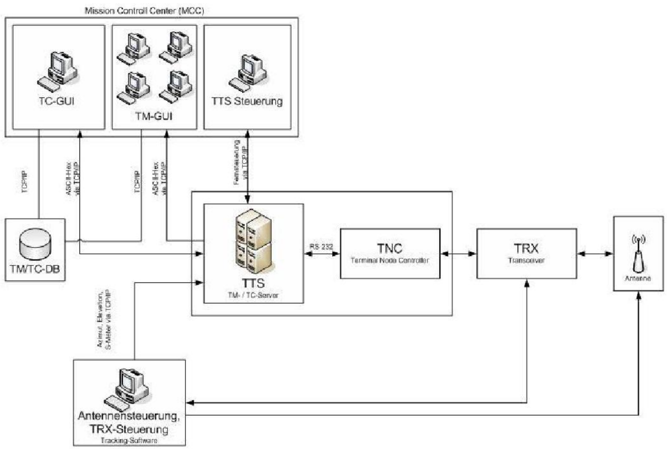

Figure 9 Overview of the Beesat ground segment

When the transmitter is switched on, Beesat transmitts its telemetry periodically ca. every 2-3 seconds automatically. Because the total amount of telemetry parameters, which is collected is too large, only a selected part is stored on board and transferred to the ground station periodically. The other part is transmitted only by request from the ground station. The telemetry format is widely based on the CCSDS standard , which provides packetizing of different telemetry sources.

Following the same philosophy, the telecommand software is also database driven and can be configured for different satellite missions. It is also network enabled and can be run on any windows computer over the network.

Beesat will provide a digipeater service to the amateur radio community. This feature will be enabled based on the operations plan, which will be announced on the Beesat web page. Beesat is also capable of sending a beacon signal, which is considered to be used in the Launch and Early Operations Phase (LEOP). It is also envisaged to cooperate with other, external ground stations for the critical LEOP operations.

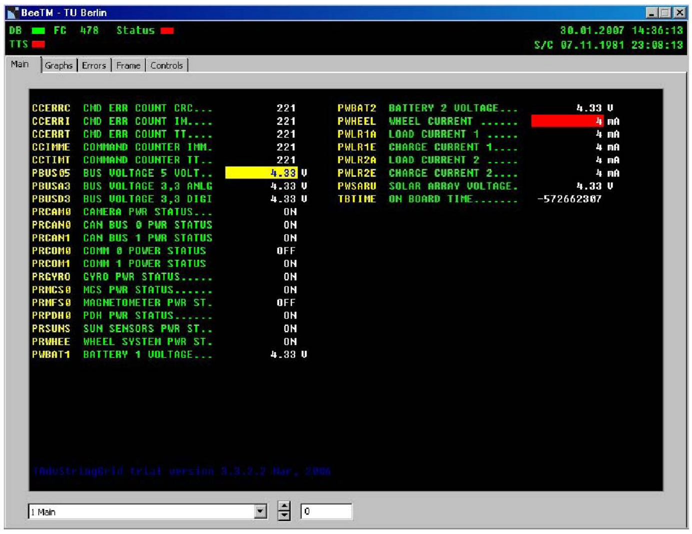

Figure 10 Beesat telemetry display example

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[2] Technical University Berlin, Institute of Aeronautics and Astronautics; Department of Astronautics; Beesat Phase B Report, Revision 1.1; June 2006