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DESIGN AND IMPLEMENTATION OF AN ATTITUDE DETERMINATION SYSTEM FOR THE CUBESAT UWE-2

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Abstract

An *Attitude Determination System (ADS)* is a mandatory component of many satellites. The challenge of its implementation into small satellite structures is especially obvious in PicoSatellites, like the CubeSat UWE-2, which was developed at the University of Wuerzburg, Germany. The restrictions of the structure as pre-defined by the CubeSat standard for cube shaped satellites with a side length of 10 cm (maximum mass: 1 kg) pose big challenges for the design and implementation of a good performing sensor system composed of multiple sensors to be used as a base for attitude determination on board the satellite.
The selection of the sensors was based on the restrictions implied by the existing satellite model and the defined size and mass limit. Special attention was paid to create a very energy efficient and highly modular system. The attitude determination system consists mainly of a three dimensional magnetometer, sun sensors, a perpendicular set of three gyrometers and an accelerometer. For higher modularity and lower noise sensibility, all sensors are connected to a central microprocessor over a digital communication bus.
Tests have been conducted to provide sensor calibration, performance evaluation and a derivation of power requirements and statistical sensor properties.
The following article will present the system design and the sensors. The methods for attitude determination and test results are discussed which show that the designed work fulfills the requirements and obeys the restrictions set by the existing satellite model. The hardware implementation as conducted during the thesis project is described. The system is integrated in the UWE-2 structure and will show its real life performance in the upcoming mission for which the launch is planned to happen in 2008.

1 INTRODUCTION

The Department of Computer Science at the University of Wuerzburg had great success developing and manufacturing a Pico-Satellite during the UWE-1 project where the main goal was to test common network technologies, like the TCP/IP protocol, in the space environment where complications like major delays and low bandwidth in communication arise. For this mission to accomplish, a passive attitude control system on the satellite without an active attitude determination was sufficient.

During the ongoing UWE program, it was then defined to be necessary to determine the attitude and orbital position of the satellites in forthcoming missions. To achieve this on board an ADS had to be developed. This article will give insight about the design, development and implementation of this crucial satellite component.

The system should be useable as a base for further developments in the series of the UWE satellite missions. The attitude determination will remain a crucial part of the overall system when additional mission objectives will be introduced in upcoming projects. The accuracy that is provided shall be sufficient for providing an *Attitude and Orbit Control System (AOCS)*, which could also be extended for the operation of formation flight maneuvers. The tasks which are necessary for such a system can be listed as:

- Investigation of attitude determination methods with respect to hardware requirements and feasibility
- Integration of additional needed sensors in the UWE architecture
- Implementing drivers for new sensors
- Hardware tests of the implemented ADS
- Verification and performance determination

1.1 Background

The main context of this projects work is related to the *CubeSat* project which was introduced by the Cal Poly State University and Stanford University ([2, 1]). The CubeSat is a standardized satellite platform of defined mass ($\leq 1\,\mathrm{kg}$) and dimensions (a cube of $10\,\mathrm{cm}$ side length). Besides of the mechanical properties, the satellite is not further defined or restricted. Additionally, a launcher structure is proposed which can be used without further effort by the satellite developer.

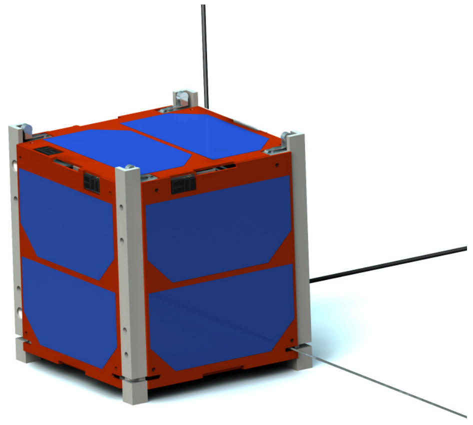


Figure 1: View of the UWE-2 satellite including the newly developed ADS. The sun sensor windows can be seen in the panel cutouts.

Many CubeSat projects have been started at multiple universities over the world. As every satellite model is based on a common hardware structure with already existing launcher structures, the launch cost itself as well as the development cost for the system base is minimized to a level so that the universities are able to provide even students the possibility to collaborate within satellite projects. One of this projects is conducted at the University of Wuerzburg.

1.2 Previous work

During preparatory studies for the UWE CubeSat satellite program, passive as well as active attitude determination and control mechanisms were already discussed and elaborated in theory ([3, 6]). As the requirements for the UWE-1 mission were not too high for the needed accuracy in attitude, a fully passive attitude control mechanism was implemented, using stabilizing dummy antennas for energy dissipation together with permanent magnets implemented in the mechanical structure ([7, 4]). This allows a passive control of satellite attitude in 2 axes for rough pointing of the transceiver antenna for providing good contact opportunities during communication with the groundstation. [5] deals with results that have been obtained after in orbit tests in the UWE-1 mission. Examinations regarding the time dependent panel temperatures and solar cell output currents have given some insight about the rotation behavior of the satellite and the control stability that could be achieved.

Following the context of the previous subsection, the need for a more elaborated ADS was expressed to overcome the low accuracy results that can be obtained using the mentioned system parts for deriving the attitude. Also, for an active control system a higher accuracy as well as on board realtime operation is necessary for the attitude (and orbit) determination. In a previous study the requirements for an attitude determination system on board UWE-2 and following satellite missions were observed and discussed. Some sensors have been examined and possible combinations presented. Concerning the software development of the UWE on board data handling system, a scalable and modular software platform was newly designed after experiences have been collected during the UWE-1 mission.

2 SYSTEM DESIGN

In a thorough consideration and also based upon previous work conducted at the University of Wuerzburg the decision was made to include absolute measurements as well as relative ones.

For determination of the attitude in absolute numbers, the decision was made for a 3D magnetometer and sun sensors on each panel of the satellites cube. The magnetometer does provide measurement of the magnetic field vector with respect to the coordinate frame fixed to the satellites body. The sun sensor as a whole is composed of six individual sun sensor parts which include the actual sensor on each panel of the CubeSat to have the sun in the field of view all the time.

Additionally, for relative attitude information and direct measurement of turn rates, gyrometers are included. They are - by principle - not depending on the presence of external fields. Therefore, they offer the possibility to provide turn rate information at a much faster rate than the absolute sensors with no dependence on further prerequisites. Also, an accelerometer is used to form a complete *Inertial Navigation System (INS)* with the gyrometer.

The whole system is shown in figure 2 as a logical overview with all sensors shown as well as power and data lines. The sun sensor is consisting of 12 dual photodiodes, fixed in pairs of 2 connected to an individual *Analog-to-Digital Converter (ADC)* on each of the 6 CubeSat panels, which allows to keep the analog lines as short as possible.

3 HARDWARE IMPLEMENTATION

This section about hardware implementation describes considerations about the placements and mechanical fixing of the sensor boards as well as the design of the boards itself, especially the electronic layout.

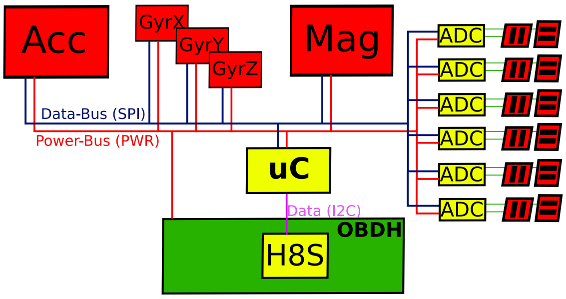


Figure 2: Schematic view of the interconnections of all sensors, the microcontroller and the OBDH: Power bus (red), data bus (blue) and analog lines (green).

3.1 Structural design

As mentioned earlier, it was planned to integrate the full ADS without interfering much with the already existent hardware. Following this, changes made to the previous design are described and shown in pictures, showing the existent models of UWE-1 which is used as a reference for including the additional modules of the ADS.

3.1.1 Placement of sensors

The complete ADS is composed of the main ADS board (microcontroller board), two combined gyro/sun-sensor boards and four identical sun-sensor boards.

The complete system as it was integrated into the existing structure of the UWE-1 satellite is illustrated in figure 3. For better visualization purposes, the outer panels of the satellite, including the solar cells, are removed and the new integrated elements are shown in light green where the existing electronic boards are shown in dark green.

Sun sensors The dual-photodiodes which are measuring the sun incidence angle need to be placed on the outside of the satellite. As five out of six panels of the cubesat are covered with the solar cells, their placement and dimension are the main restriction for the final place of the sun sensor components. A more detailed look on the sun sensor attached to the panels along with the placement of the electronics board underneath the panel is shown in figure 4.

For easier integration it was first planned to directly attach all sensor panels to the internal structure which would mean no physical contact to the outside panels. But because of restrictions in constructing the structure bars of the satellite, the sun sensor panels need to be fixed to the outside panels instead as it is shown here. The placement on the top/bottom panel is not that much restricted by the solar cells. No screw holes are required here as the

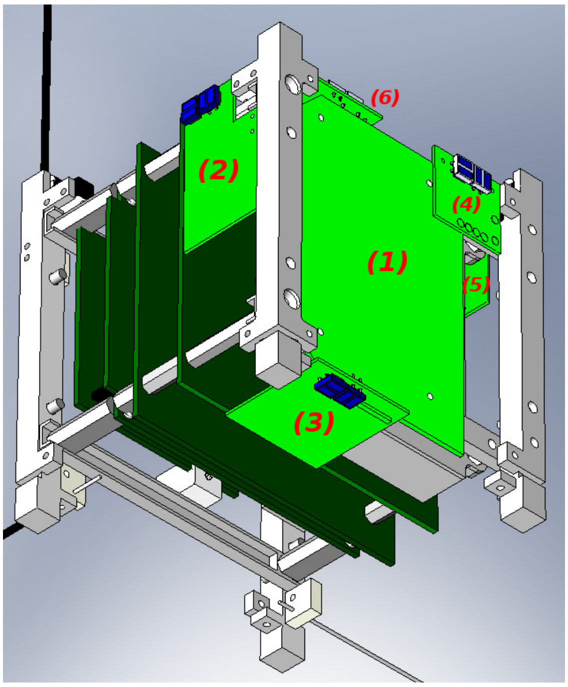
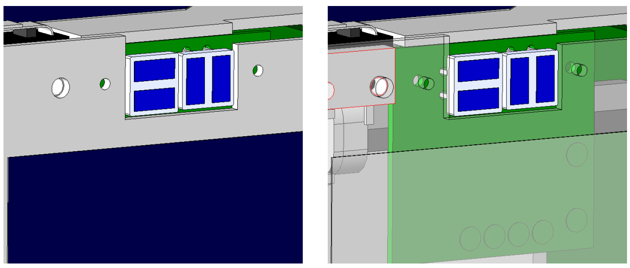


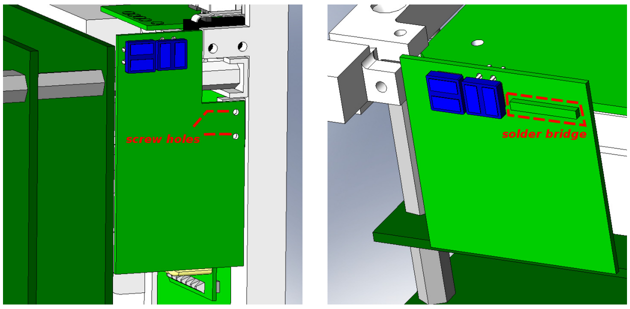
Figure 3: Overview of implemented structure and electronics elements in the UWE satellite structure. For visualization purposes, the outer panels of the satellite are removed. New integrated elements are shown in light green, existing electronic boards are shown in dark green. (1): The main ADS board, (2) and (3): The combined sun sensor and gyro boards in direction y and z of the satellite respectively. (4) to (6): three of four sun sensor boards.



(a) Outside placement. The window cutting pattern can be seen. The distance between the sun sensor components and the panel structure is about 0.5 mm on each side.

(b) Transparent view. The screw holes for screws fixing the sun sensor panel to the panel can be seen next to the dual-photodiodes (Screws not shown for illustration purposes).

Figure 4: Placement of the sun sensor, detailed view.



(a) Y direction. Fixing by screws as shown in red.

(b) Z direction. Fixing by solder bridge to main ADS board as shown in red.

Figure 5: Placement of the gyrometer/sun sensor board in Y and Z direction.

sensor panel is directly attached and fixed to the main ADS board (see figure 5b).

Microcontroller-Board The main board of the ADS including the microcontroller, which is used for interfacing all the sensors will be placed in parallel to the already existing electronic boards. It will feature all necessary connections to the existing microprocessor and the power board as well as connections to all other sensor boards and additional interfaces for debugging purposes. The board is fixed to the internal holding structure of the satellite. Directly attached is the gyro-z board with the help of a solder bridge.

Gyrometer-Board The gyrometer sensors for Y and Z direction need to be placed under the appropriate panel, i.e. panel 2 or 4 for the Y direction, panel 5 or 6 for the Z direction. Placing locations for the board, including one gyrometer sensor along with the sun sensor for the appropriate panel, are shown in figure 5.

3.2 Electronics design

For setting up the electronics circuitry of the main ADS board the guidelines that have been followed are presented, afterwards one sun sensor board is specified in its details and differences to the main board in the development process. All sun-sensor boards only differ in slight points regarding the placement of mainly the pins and drill holes. Therefore it is enough for understanding the logical structure to present only one prototype board. The combined gyro/sun-board will only be shown in short as its characteristics are mainly already known from the sun sensor and main board parts.

3.2.1 Main ADS board

The main ADS board is the main part of the attitude determination system.

The board layout as seen in figure 6describes the actual placement of components, connectors and signal/power lines in the electronics circuit. The boards show the main microcontroller Atmel ATMEGA16 in the low power version and all connectors interfacing the main board with the existing microprocessor and power board as well as all additional sensor boards plus connectors used for programming and debugging. For the gyrometer sensors there is the control circuit of power supply. Since these sensors do not feature an efficient power-saving mode, an high-side electronic switch is implemented here to effectively shut down this circuit part. Included in line in every outgoing and incoming connection line there are filter coils that are designed to filter out high-frequency noise disturbances on the signal and power lines. Especially the radio frequency is incorporated in the noise mitigation design. One gyro sensor, as a part of all three gyro sensors for the three spatial dimensions, is implemented on the main ADS board. As the gyro sensor uses a different supply voltage, a level shifter was implemented in the in/out lines. The same mechanism is also used for the other two gyrometer sensors.

For designing the actual layout, the points that have been considered are:

1. Placement restrictions for components
2. Noise disturbances caused by components
3. Noise sensibility of components
4. Placement restrictions for connectors
5. Noise disturbances emitted by signal and power lines
6. Noise absorption of signal lines
7. Noise absorption of power lines

Based on these principles, the board layout can be created. In which way this has been considered is described in the following paragraphs.

Placing of Components The components are more or less spread over the board so that mutual interference is minimized. All other, secondary components are placed near to each device where they are logically connected to.

Furthermore, a very heavy noise source, the radio transceiver of the satellite, is minimized in its impact on the complete ADS by placing the main ADS board as far away as possible, that means on the other side of the cube. Only one sun-sensor board is in closer vicinity to the radio device where the panel direction itself dictates the necessity for placement

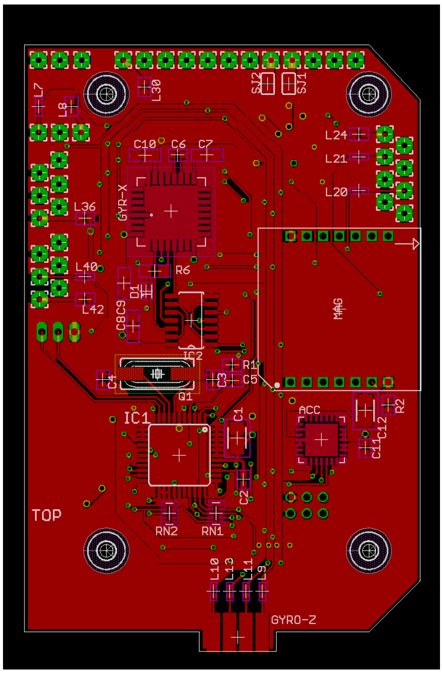


Figure 6: Layout of the ADS main board, TOP layer. All sensors and main components are placed on this side. The layer is filled with ground connected covering if not used by signal connections.

of this board.

Additionally, attention was paid not to place any components - except for low-height resistors or filter coils - in the line of the mounting holes so that there will be no obstruction or direct contact to the horizontal bars of the satellite structure when the board is mounted.

Signal lines To protect every signal line from outside interferences as well as shielding for omitting noise radiation coming from signal lines, it was taken care that each line is separated by another one by a band of ground connected circuit part or in some cases a band of circuit that is connect to the positive supply voltage, in both cases a low-resistance circuit part with quite constant potential.

The critical communication lines of the *Serial Peripheral Interface (SPI)* and *Two Wire Interface (TWI)* bus with relatively high frequency are especially protected by a bigger distance to each other, each component of the bus lines itself and to other signal lines. Additionally, these lines have been designed so that they are interrupted by the least amount of vias. As it is visible in the layout illustrations (6), the SPI bus has a prominent placement following the vertical centerline of the board so that the connection length to each of the connected sensors is as short as possible. Also it was respected that each of the three main bus lines have the same length. The TWI bus lines run mainly on the bottom layer so that they are interfered by as few other lines as necessary and also no other connection points are needed besides of the microcontroller connection and the connector contact. The separation between the two lines is filled with a ground connected line for better shielding purpose.

Power lines The fifth and the last point of the enumeration, the noise impact of external disturbances on power lines and noise emitted from power lines, is regarded by three methods. First, the power connections to all external boards, i.e. the one going to the existing microprocessor or power board and all external sensor boards (sun-sensors and gyro-boards), are secured by T-type EMI suppression filters composed of a LC combined circuit (L = coil equivalent, C = capacitor equivalent). Second, the top layer of each board, as far as not used for signal lines, is filled by conductor material forming the ground connection, whereas the bottom layer is used for the positive supply voltage. At last, every critical component, i.e. every sensor chip, is additionally provided with power filtering capacitors.

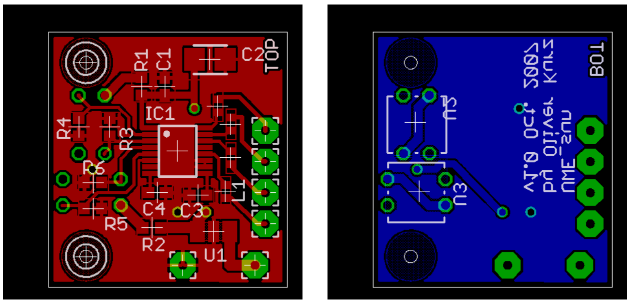
3.2.2 Sun sensor board

The sun sensor board is created with the same guidelines in main as for the main ADS board. The main difference here is that it also includes an analogue circuit part along with the digital connections.

This board includes two dual-photodiodes which measure the angle-dependent illumination (from the sun) in two perpendicular directions on each panel, where one sun sensor board will be mounted. The analogue current output is measured as voltage drop across the resistors with the help of the ADC. The measurement values are then provided by the converter to the digital bus. Basically the layout rules that have been respected for the layout of the main ADS board do also apply for the sun sensor boards. But additionally close attention was paid for designing the board as the sun sensor is partially composed of non-digital components for which analog current output needs to be transmitted and measured accurately. Therefore an ADC was integrated on every sun sensor board to have the analog lines as short as possible. The layout of the sun sensor boards can be seen in figure 7 with the top and bottom layer.

3.2.3 Gyro board

The same notes that are valid for the main and sun sensor boards also apply for the two gyro boards, *gyro-y* and *gyro-z*. These two boards differ from each other only in their dimensions and the the placement of components. What is common to



(a) TOP layer. Copper filling connected to GND.

(b) BOTTOM layer. Copper filling connected to power supply.

Figure 7: Electronics layout of the sun sensor board.

them is the combination of the sun sensor circuit together with the gyrometer sensor circuit combined on one board. To decrease the mutual influence and disturbance effects, the sun sensor part was separated locally from the gyrometer part.

3.3 Device specific notes

There are some specific notes about the sensors. The hardware related notes are given in this section.

3.3.1 Sun sensor

The sun sensor was designed by hand using the dual-photodiodes, which have already been explained, together with an ADC using an additional resistor for measuring the current output of the photodiodes as a voltage drop across this resistor.

3.3.2 Magnetometer

The magnetometer is supplied as an integrated board which is directly connected to the data and the power bus of the main ADS board. Additional components are only needed in form of a pull-down resistor for the magnetometer reset line (*MAG_RST*) and a pull-up resistor for the slave-select line for correct interfacing to the SPI bus.

Besides of the power lines and data bus connection, the magnetometer is directly connected to the microcontroller on two lines, the magnetometer reset line (*MAG_RST*) and the magnetometer “data ready” line (*MAG_DRDY*). The former is used before every measurement to reset the measurement circuit of the device, the later one is used by the magnetometer to signal an end of measurement to the microcontroller.

To reduce the impact of currents, generated trough the electronics, no signal lines or power lines have been routed underneath the magnetometer board. Also, the ground and power layer, that is filling unused portions of both board sides, are restricted from the area near the magnetometer board.

3.3.3 Gyrometer

The gyrometer is only available as a 5V device whereas all other components of the ADS are using 3.3V as a power supply voltage. For the interface of the gyrometer sensors to the data bus, which is running on 3.3V, a level-shifting circuitry is implemented.

3.3.4 Data bus implementation

It was decided to have one data bus that is common for all sensors, the SPI bus. For connecting the ADS to the OBDH, TWI was used as this interface is already provided. The microcontroller, which is the central part of the ADS, is connected to the sensors over SPI and, for sending the data after preprocessing, interfaced to the TWI bus.

SPI-bus Many sensor devices are available with SPI connection as this interface provides very high transmission speeds (clock frequency in MHz range) with low protocol overhead and feasible hardware connection requirements. Therefore the reasonable choice has been made for the SPI bus as the connection between the sensor devices and the controlling microcontroller.

TWI-bus The microcontroller is providing the main interface of the ADS to other systems, in this case the OBDH of the satellite, using the TWI (or *Inter-Integrated Circuit (I^2C)*) bus. The OBDH acts as the master and is controlling the ADS as slave.

4 SYSTEM PERFORMANCE ANALYSIS

During setup of a test environment and after the implementation of the sensors in the prototype hardware, experiments have been conducted to judge about the achievable accuracy of the whole system when using the sensors for which the decision was made to integrate them. Results of this considerations can be used for judging about the performance of the system and should give insight into the expectable accuracy levels.

4.1 Power budget

An important step for integration into the picosatellite structure is the power that is consumed by the ADS system. This is outlined in the *power budget* which was derived by estimations and afterwards confirmed by measurements that have been conducted using the prototype. For this, four modes of operation have been defined, integrated and compared:

Table 1: Measurement of the power consumption (in mW) of the ADS prototype hardware in the different power modes. Measurements have been conducted with a *FLUKE 80 V True RMS Multimeter*.

mode	NOM	MAX	PS1	OFF
Power/mW	274.08	274.49	116.88	22.72

NOM: Nominal Operation with idle periods

MAX: Maximum power consumption, busy all-time, worst-case calculation

PS1: PowerSave Mode 1: lowered measurement frequency (10Hz), Active during measurement, power down during idle

OFF: All off/PowerDown, if available

The result of the measurements are shown in table 1. Overall, the estimation has been undercut with a power requirement of about $274\,\mathrm{mW}$ during normal operation. When the system is switched off in software it needs $P_{\text{off}} = 23\,\mathrm{mW}$.

4.2 Calibration results

For the usage of sensors in an application, they have to be calibrated at some time. This can be done in various ways and is very much dependent on the kind of sensor. For the presented sensor platform included in the ADS, there was the need to calibrate the gyrometer, the accelerometer, the magnetometer and the sun sensor(s). A precise calibration should be done in orbit while the satellite is conducting its mission objectives. This requires a good knowledge about the models describing the position of the sun and a model of the magnetic field of the earth for using the sun sensors and magnetometer. Using them, rotations of the satellite can be detected and measured and subsequently compared to the gyrometer readings for further calibration processes.

On ground calibration in the first place requires the existence of a simulation environment or the presence of attitude sensors whose characteristics are known. Already present and calibrated sensors can then be used for also calibrating subsequent sensors, like the ones included in the ADS. A simulation environment can represent part of the environment that would be encountered in the orbit. If the model of the simulation is known to a good extent, the sensors can be calibrated using the predefined situation. For example, a point source of illumination simulating the sun can be used for calibrating the sun sensors, a defined rotation in multiple axes can calibrate the gyrometer.

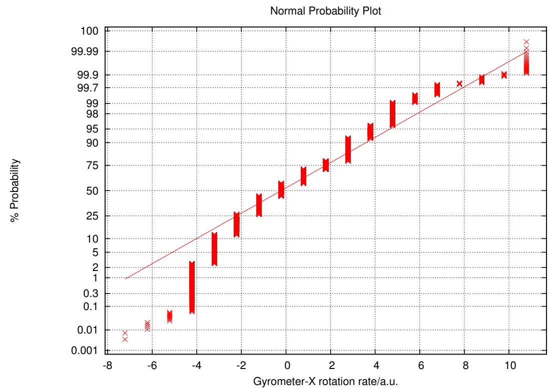


Figure 8: Normal distribution plot, gyrometer x-direction. y- and z-direction show close resemblance.

4.3 Data distribution evaluation

Additionally to calibration alone, the data distribution is quite important. As it is considered to use the ADS in conjunction with a Kalman filter, a crucial prerequisite for the data is the *normal* or *Gaussian* distribution. If it is assumed that the data is normal distributed, then one data sample is also following the same. In this case the mean value and variance of a sample are converging towards the corresponding values of the distribution if the sample size is sufficiently large.

4.3.1 Gyrometer

For the gyrometer the values of measurement have been observed if they follow a normal distribution. It was found, that this relation is given. A qualitative analysis result is shown in the figure 8, where a comparison plot is given, that compares the gyrometer data with the normal distribution with the mean value equal to the measured mean value of the data set and with a variance which is equal to the measured one. A close accordance with the normal distribution, which is depicted by the straight line, can be seen.

Noise characterization One gyrometer sensor on the prototype board was measured in a stable environment with no rotation applied (including no acceleration) in one experiment to derive the statistical noise characteristics of the sensor (Sensor with $\pm 75\,°/\mathrm{s}$ full-range). The standard deviation was computed as $2.1765 \cdot 75\,°/\mathrm{s}/2048 = 0.080\,°/\mathrm{s}$ as the wideband noise.

4.3.2 Magnetometer

The output of the magnetometer was measured in a stable situation with no movement of the sensor and no additional noise sources nearby. The mea-

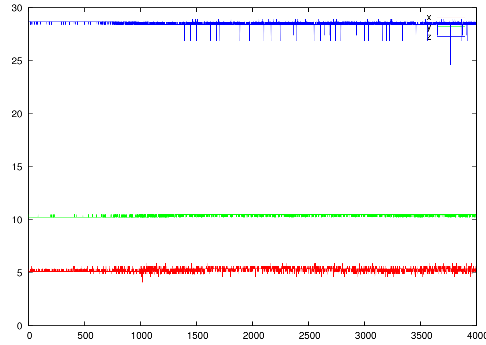


Figure 9: Measurement of magnetic field components in μT in x, y and z direction over time (arbitrary units). Measurement condition: stable location, inside building, no additional noise sources present.

Table 2: Magnetometer statistics in a stability test.

	mean/μT	variance/$(\mu T)^2$
x	20.64	0.62
y	40.59	0.24
z	111.5	0.64

surement over time in the tree components over x, y and z is shown in figure 9.

From the shown data, the mean values and variation values have been derived as stated in table 2.

These value can further be used for attitude determination in on board software as well as in post-processed data in groundstation software.

5 RESULTS

During the course of the thesis work presented here a system for determining the satellite attitude has been developed for a pico satellite platform, especially adapted for the use on board the UWE-2 spacecraft. Referring back to the initial intention of providing the attitude of the satellite, it can be said that the presented system should be capable of providing useful results for the actual UWE mission and as a precursor for following mission.

The design was developed for providing good accuracy attitude determination information while trying to cope with restrictions existing in the actual satellite model but also to accommodate possibilities to change the system easily if it is needed to improve, exchange or extend parts of the ADS system.

It was achieved to manufacture a prototype which is capable of fulfilling the objectives as planned while maintaining a decent power consumption. Experiments have been conducted to judge the goodness of the sensor integration. The flight hardware was produced after minor problem solutions and improvements were made to the system design.

Further results are expected after the launch of the UWE-2 satellite in mid-2008.

ACKNOWLEDGEMENT

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