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UWE-3, IN-ORBIT PERFORMANCE AND LESSONS LEARNED OF A MODULAR AND FLEXIBLE SATELLITE BUS FOR FUTURE PICOSATELLITE FORMATIONS

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Formations of small satellites offer promising perspectives due to improved temporal and spatial coverage and resolution at reasonable costs. The UWE-program addresses in-orbit demonstrations of key technologies to enable formations of cooperating distributed spacecraft at pico-satellite level. In this context, the CubeSat UWE-3 addresses experiments for calibration and evaluation of real-time attitude determination and control.

UWE-3 introduces also a modular and flexible pico-satellite bus as a robust and extensible base for future missions. Technical objective was a very low power consumption of the COTS-based system, nevertheless providing a robust performance of this miniature satellite by advanced microprocessor redundancy and fault detection, identification and recovery software. This contribution addresses the UWE-3 design and mission results with emphasis on the operational experiences of the attitude determination and control system.

I. INTRODUCTION

Modern miniaturisation technologies enable realisation of satellites at continuously decreasing masses. In an extreme case pico-satellites provide at about 1 kg of mass a fully functional satellites. Inherent limitations of performance and increased susceptibility to noise effects are to be compensated by an advanced control and filtering software, as well as by integrating multiple distributed, cooperating pico-satellites [10, 11].

The UWE-program (University Würzburg’s Experimental satellites) develops step-by-step the relevant technologies for such formation flying capabilities at pico-satellite level [12]. The first German pico-satellite UWE-1 (launched 2005) addressed as scientific objective the optimization of Internet Protocol parameters to the space environment as a basis for the future networked satellites [2]. UWE-2 (launched 2009) focussed on attitude determination techniques, while UWE-3 (launched 2013) extended this approach to attitude control. Future formations of satellites use a closed loop control in orbit to keep an appropriate topology for efficient measurements with minimum ground control interaction [8].

The niche market of pico-satellites exhibits dramatic growth with about 100 pico- and nano-satellites launched in 2013, and becomes a technology innovation driver in order to enable robust and reliable operations [7].

Figure 1: UWE-3 flight model after integration in Jan. 2013.

This contribution addresses at the example of UWE-3 capabilities of the new generation of advanced pico-satellites, offering a flexible and robust design, as well as a performance [4, 5, 6], which supports future operational missions. Figure 2 displays the building blocks from which according to mission needs related satellite designs can be flexibly assembled. Standardized connector interfaces replace here the traditional harness.
UWE-3 had specific emphasis on implementation of an efficient attitude determination and control system at minimum mass [9]. Its demonstrated in-orbit performance will be described in details, as this will be a crucial component for future pico-satellite formations, promising very good potential to complement as a distributed sensor network the traditional large, multifunctional satellites.

II. EARLY OPERATIONS

UWE-3 was launched on Nov. 21st at 07:10:11 UTC on board a Dnepr rocket. Within the first months of operations all subsystems and redundancies have been tested, both antennas have been successfully deployed and communication with ground could be established with both radio configurations.

From beginning of operations UWE-3 shows excellent health state. Maximum temperatures vary within ±30°C showing a mean temperature of +4°C. During normal operations battery charge states remain stable above 90%. Several radiation-induced failures have been observed in the redundant on-board computer since launch. The SEU rate observed in a 8kB unused RAM region is in the order of 1 upset per month. Various faults states of the active processing unit were recovered by automated fail-over to the redundant processing unit, thus ensuring continuous operation without significant interruptions.

Operations with the attitude determination and control systems started about a week after launch with a long scale analysis of the satellite’s motion after deployment. The satellite was rotating at a rate of about 23 deg/s on Dec. 3rd with its main contribution on the body z-axis. This rotation was found to decline naturally by about 0.5 deg/s/day until the active detumbling was initiated on Dec. 17th. The ADCS decelerated the satellite from 16.5 deg/s within 7 minutes of active control to about 1 deg/s.

ADCS operations initially focused on characterizing the attitude estimation performance, for which an in-orbit calibration of the magnetic field sensors was the first necessary step. With sufficiently calibrated sensors an attitude estimation accuracy of a few degrees could be demonstrated, rendering more advanced attitude control experiments possible. Furthermore, a natural alignment of the satellite with the Earth’s magnetic field could be identified, implying the presence of a residual magnetic dipole within the satellite. This magnetic field following behaviour in the absence of active control was further investigated as described in section V.I and marked the beginning of the attitude control experimenting phase.

First results from UWE-3 early operations and first attitude determination and control experiments have been published in [1] and [3].

III. AUTOMATED GROUNDSTATION OPERATIONS

A typical operations workday of the UWE team members begins at 7:00 UTC and ends at 16:00 UTC (summer time). During this period three to four satellite overpasses can be used to perform operations. However, there are another three to four overpasses during the night period (20:00 – 01:00 UTC) such that a remote accessibility of the university’s ground station was mandatory to enable operations from the outside.

The ground segment software is build up of two main parts: ground station server and operations client. The server is basically responsible for proper hardware setup (e.g. antenna orientation, transceiver) and is able to broadcast received satellite packets along the connected clients. It transmits client packets (e.g. tele commands, requests) via the radio and synchronizes all clients among themselves, providing the operator an insight into the actions of his collaborators. The client software can be executed on arbitrary workstations presupposed that the server is reachable within the available network (e.g. via SSH tunnel). Typically multiple workstations are simultaneously engaged during the operations.

The operations process mainly consists of: receive housekeeping data, send tele commands, request remote files and uplink files (e.g. configuration). The commanding interface has a wide functional range - inter alia file system operations, ADCS controlling, enquire and change system states, script execution etc. During the initial operations phase all actions had to be initiated manually as soon as the satellite was within the range. It has been discovered that a significant amount of time during an overpass remained unused – especially when the operator had to react dynamically to the current satellite’s system state (reaction time). Consequently, many night overpasses were completely unused.

The on board data handling system of the UWE-3 was designed in such a way as to enable the software
being replaced in-orbit. The size of a software image is about 140 kB; the theoretical AFSK uplink rate is 9.600 baud with AX.25 data layer protocol on top. Considering the occurred uplink throughput issues, the maximum AX.25 packet size (250 bytes hardware limitation) and the protocol overhead, the image uplink would take up to one week of manual operations.

In order to resolve these issues and to increase the data throughput, the operations had to be automatized. That is to enable a predefinition of all necessary operation tasks, which are automatically executed as soon as the desired satellite is reachable. Furthermore, each task can be executed periodically – e.g. daily or during every overpass. Based on these requirements an operations scheduler has been implemented. To allow auto-operations without connected clients, the scheduler is located on the ground station server.

The server has been extensively updated to fulfill the requirements of the scheduler. That is fast orbit prediction of a single or multiple satellites, rapid detection of all currently set hardware settings, straightforward exchangeability of the hardware components (e.g. for debug purposes).

With the new software design a frequency sweep test could be performed. During every overpass this task was continuously adding a random offset within the predefined range to the uplink frequency with subsequent message uplink. Later all messages were downlinked and mapped to the frequencies at which they have been transmitted. This way a superior frequency was determined at which most packets were received.

Using the optimized uplink frequency an updated software image could be transmitted with the new uplink task. This task continuously transmits file packets and periodically asks for chunks which need to be transmitted again as a consequence of link errors. The image uplink was accomplished after 7 overpasses.

A further downlink yield improvement was achieved by involving the radio amateurs. For this purpose a web server was introduced to enable external submission of received UWE-3 packets. In order to automate this process, the auto-submission was integrated into the software which is commonly used by the radio amateurs. This way the UWE-3 team is able to receive packets even if the satellite is not within range. As it can be seen in Figure 3, the amount of received packets was drastically increased after the web server kick-off in April 2014.

![Figure 3](image_url)  
**Figure 3:** Number of UWE-3 packets submitted by radio amateurs.

In order to test the scheduler ability of multiple tracking, the UNISAT-6 satellite from GAUSS-Team was added as the additional target. In case of simultaneous reachability of multiple targets, the one with the higher priority is privileged. During every overpass of UNISAT-6, a listener task is activated such that all received packets can be saved and forwarded to a remote server. For this purpose the GAUSS team has established a web server with the same interface, which has been defined for the radio-amateurs. Hereby the new downlink-only ground station network approach has been successfully verified. Every ground station which is capable of multiple satellite tracking can be easily integrated into this network. To also share the uplink capabilities of a ground station a joint project with the WARR team of the University of Munich (TUM) is currently in progress. The developed ground station server software allows simple and straightforward hardware adaptation. Multiple servers can be connected to a grid network, within which every node can grant hardware access to other nodes. The access rules are described within the centralized node scheduler.

![Figure 4](image_url)  
**Figure 4:** Receive locations of UWE-3 packets submitted by radio amateurs.
IV. ANALYSIS OF GLOBAL INTERFERENCES IN AMATEUR RADIO BAND

UWE-3 employs two fully redundant UHF transceivers with separate omnidirectional monopole antennas operating in the 70cm amateur radio band (435.000 MHz – 438.000 MHz). While the satellite’s transceivers provide about 1 Watt transmit power, the universities groundstation operates at 70W on a 3m cross-yagi antenna with 14dB gain.

From beginning on the downlink quality from the satellite to ground was excellent, showing high signal strengthes even at low elevations. However, the telecommand uplink was initially difficult with transmission failure rates between 80% and 90%. From beginning of 2014 the uplink quality degraded further, resulting in average failure rates between 90-95%, which could sporadically extend to 98-100% for several passes, while still providing excellent downlink quality.

Both, ground and space borne hardware defects could be excluded from potential failure sources as the problems remained when operating on the redundant devices. The problem has been further analyzed by performing various automated uplink tests. In order to efficiently identify the uplink success rate, short data frames containing a unique id have been frequently uplinked directly to a file in the satellites flash memory without acknowledgement requests. In the course of the test, parameters such as offsets in antenna pointing or uplink frequency have been altered randomly. After downloading the file, the received frame ids could be directly compared with the uplinked frame ids to correlate the success rate with instantaneous frequency offset, satellite position, etc. As it can be seen in Figure 5, a potential frequency drift, e.g. caused by temperature variations at the satellites receiver, could also be excluded as failure source, as the success rate is not affected by slight frequency deviations. However, it could be identified that the uplink quality significantly changes in general within the amateur frequency band and further slightly varies with the satellites relative location.

Following a trial-and-error search on different frequencies, a good candidate has been found such that the uplink quality could be improved significantly and the satellite operations and experiments could be conducted more efficiently again.

In beginning of June 2014 a software update has been uploaded to one of the redundant onboard-computers of UWE-3. Among other features, the update included several new experiments targeting the analysis of the link quality. In order to further analyze the spatial distribution of in-situ interference levels for the whole amateur radio spectrum, an RSSI frequency sweep experiment has been implemented. The experiment allows to monitor and log measured RSSI noise levels, while automatically scanning over a specified frequency range. Beside start and stop time, the experiment allows to configure target frequency range and scan interval \( C_i = (f_{start}, f_{stop}, \Delta f_{scan}) \). Further, the data acquisition can be controlled with parameters for RSSI sampling rate, number of averaged samples in a measurement and number of repeated measurements for a single frequency \( C_a = (t_s, t_b, n_m) \).

As the on-board radio is used for the RSSI sampling, first the device response to a single carrier has been determined on the engineering model on ground. As can be seen in Figure 6, the RSSI measurement is sensitive to a range of \( f_{base} \pm 110 \text{ kHz} \) when the radio is configured to a specific receive frequency \( f_{base} \).

Figure 6: RSSI frequency sweep showing response to a constant carrier signal at 437.400 MHz. \( C_i = (437.100 \text{ MHz, 437.800 MHz, 20 kHz}), C_a = (1000 \text{ ms, 1, 3}) \).

**Figure 5: Exemplary uplink quality analysis based on a ground based frequency sweep around 435.000 MHz ± 150 kHz from 15/16 April 2014.**

Figure 7 shows an in-orbit frequency sweep recording from 15th of June when UWE-3 had a high elevation pass-over in the west of Wuerzburg. Throughout the entire measurement the signal emission from our groundstation has been deactivated. It can be seen that the background noise level increases about 5-10 dB on both observed frequencies when the satellite passes Europe. Further, it can be noticed that the 437.385 MHz is exposed to severe interferences over central Europe with RSSI peak levels ranging up to -70 dBm while the 436.400 MHz is not affected by this source. These measurements could be repeated several times and are representative for the observed time frame in third quarter of 2014.
Described observations lead to further experiments targeting the global spatial distribution of interferences on the entire UHF amateur radio band used for satellite operations. Several frequency sweeps have been recorded in third quarter of 2014, each lasting several days to ensure global coverage. The results discussed in the following are based on measurements recorded between 06.08.2014 and 11.08.2014, and are representative for the performed observations. The recording comprises more than 100,000 data points downloaded from the satellite in a 1.5 MB compressed data file. The measurements have been recorded with the following configuration: \( C_{\text{f}} = (435.000 \text{ MHz}, 438.000 \text{ MHz}, 200 \text{ kHz}) \), \( C_{\text{s}} = (250 \text{ ms}, 10, 2) \). In order to ensure the observation of sporadic short interference peaks, a high sampling rate of 250 ms has been chosen. Each recorded measurement represents the average of 10 samples, thus reducing the amount of data produced. Figure 8 shows the mean RSSI level from an exemplary data set versus base frequency \( f_{\text{base}} \) and time.

The downloaded measurements have been mapped to their instantaneous sub-satellite points as visualized in Figure 9. The recorded data points show sufficient coverage of the entire globe and can properly be used as a grid for spatial interpolation to generate a global interference map for each frequency under investigation. The map interpolation results are shown in Figure 12. It can be seen that the average interference levels vary significantly with location and observed frequency. Especially orbital regions connected to central Europe seem to be affected significantly on a wider frequency band between 437.000 MHz and 437.600 MHz.

In order to express these observation with concrete numbers, a local statistical analysis has been made. For this purpose the measurements have been filtered for specific locations and frequencies in order to calculate statistical measures such as median and quartiles of the underlying distribution of observed averaged RSSI levels. Figure 10 depicts the statistical analysis for two different regions. The first region is centered around the sphere of influence around our groundstation in Wuerzburg. The second region is an undisturbed reference with a selected region of similar size located somewhere in the south pacific (see Figure 11).

Figure 7: RSSI noise levels \([\text{dBm}]\) measured on-board UWE-3 during a pass over central Europe without groundstation operations in Wuerzburg. \( C_{\text{f}} = (436.400 \text{ MHz}, 437.385 \text{ MHz}, 985 \text{ kHz}) \), \( C_{\text{s}} = (5000 \text{ ms}, 1, 6) \).

Figure 9: Orbit coverage of measurement recording.

Figure 8: Extract from the raw RSSI \([\text{dBm}]\) measurements over time [UTC]. (Colorbar similar to Figure 9). \( C_{\text{f}} = (435.000 \text{ MHz}, 438.000 \text{ MHz}, 200 \text{ kHz}) \), \( C_{\text{s}} = (250 \text{ ms}, 10, 2) \).

Figure 10: Average interference statistics for each frequency for Europe centered at groundstation in Würzburg (top) and for a reference without interferences over the pacific (middle). (Box: first and third quartiles, median of average RSSI (10 samples in 2.5 s); Whiskers: data in 1.5 interquartile range)

Figure 11: Reference world plots show RSSI levels \([\text{dBm}]\) for 437.400 MHz (corresponding to Figure 10).
Again, the plots clearly show the dependency in location and especially frequency, but it has to be pointed out that the underlying data points represent an average of 10 RSSI samples already. Therefore, the extreme interference levels as present in Figure 7 are not directly visible anymore in terms of their real outlying value. However, it is ensured that these peaks contribute to the statistics such that the different frequencies can be compared with each other for frequency selection.

The results reflect our experiences when operating UWE-3 during the first six month after launch. They further underline the importance of proper frequency selection for satellites using the radio amateur bands. Moreover, the results emphasize the requirement for in-orbit frequency re-configuration to be able to react to changes of inevitable global interferences caused for example by military space surveillance radars.

435.000 MHz 435.200 MHz 435.400 MHz 435.600 MHz
435.800 MHz 436.000 MHz 436.200 MHz 436.400 MHz
436.600 MHz 436.800 MHz 437.000 MHz 437.200 MHz
437.400 MHz 437.600 MHz 437.800 MHz 438.000 MHz

Figure 12: RSSI [dBm] average interference world plot between 06.08.2014 and 11.08.2014.

V. ADCS OPERATIONS

UWE-3 has been launched to demonstrate real-time attitude determination and to achieve first attitude control for the UWE platform. The former has been accomplished, its performance characterized and the results have been published. While working to further improve the attitude estimation capabilities of the satellite, the focus has shifted towards active attitude control. Preceding work comprises the satellites active detumbling in Dec. 2013 [1] and functionality tests of the reaction wheel [3]. Furthermore, the presence of a residual magnetic dipole has been found, which affects directly attitude control. In the following sections the approach to attitude control of UWE-3 as well as results of experiments with a spin controller are described.

V.I Residual Magnetic Moment

Identifying certain features in the natural movement of the satellite, it became apparent that its rotation is dominated by the interaction of the Earth’s magnetic field and an inherent residual magnetic dipole $\mu$ within the satellite. In order to prepare attitude control for absolute pointing, it was essential to distinguish the magnetic dipole’s orientation and strength.

High resolution recordings of the satellite’s rotational rate show that the rate vector lies in a plane, such that its changes also lie in the same plane. For small rotation rates and an inertia tensor with small off-diagonal entries, Euler’s equation simplifies to $T_{\text{external}} = T_{\mu} = \mu \times B = I \omega + \omega \times (I \omega) \approx I \omega$, [1] which means that for these cases $\mu$ is perpendicular to the plane spanned by the rotation vector.
In order to find the magnetic dipole the differential rotation rate, $\dot{\omega}$, was numerically found and inserted into Euler’s equation together with an estimated inertia tensor $I$ and $\omega$ to give an expected torque $T_{\text{external}}$ in Body coordinates. With simultaneous recordings of the magnetic field $B$ in Body coordinates, a magnetic torque $T_\mu = \mu \times B$ can be calculated for any constant $\mu$. Using the error function $E = \sum (T_{\text{external}} - T_\mu)^2$, a magnetic dipole could be found that produces a torque which matches the experienced torque as shown in Figure 14.

The estimated magnetic dipole was found using several recordings to be on the order of $\mu \approx [-0.0005, +0.0115, -0.0386] \text{ Am}^2$. This dipole is shown in Figure 13 where its perpendicularity onto the plane of $\dot{\omega}$ is clearly visible. Furthermore, the magnetic field in Body coordinates naturally swings about this dipole, which is shown in Figure 15.

The dipole mainly lies in the satellite’s z-axis which limits the list of potential causes to internal magnetic fields in the batteries, the reaction wheel and the satellite’s antennas. During ground-testing with the engineering model, the reaction wheel and batteries could be eliminated which leaves the strong assumption that the antennas, made out of stainless steel, have been magnetized after launch.

Since the dipole is in the order of the one produced by the magnetic torquers, measures to demagnetize the dipole have been investigated, ranging from applying a constant magnetic field in its opposite direction using the torquers, to fast and random magnetic fields. Unfortunately, none of the experiments could significantly change the residual magnetic dipole.

However, precise attitude control appears feasible taking spin-stabilization into account. During an experiment with very high rotational speeds of up to 90 deg/s, the satellite’s stability against the magnetic dipole became apparent. This is shown in Figure 16 and Figure 17, where the satellite’s angular velocity in ECI coordinates is plotted. In Figure 16 the satellite spins at about 80 deg/s which stabilizes the satellite, such that its rotation vector in ECI coordinates shows only minor changes in direction over the course of one orbit. During eclipse the attitude estimation is not precise enough, such that the gyroscopic rate cannot be transformed into ECI coordinates and therefore no data points are shown for this period.
Figure 16: Angular velocity direction in ECI coordinates during a slow rotation of about 1 deg/s. The rate vector changes direction in ECI coordinates throughout the orbit, indicating that an external torque dominates the satellite’s motion.

Figure 17: Angular velocity direction in ECI coordinates during a fast rotation of about 80 deg/s. The rate vector retains its direction in ECI coordinates throughout the orbit, indicating that the satellite’s motion is spin stabilized.

V.II High rotation rate attitude determination

Spin-stabilized attitude control poses the requirement on the attitude determination system to be capable of estimating the attitude even at high rotational rates. Especially for CubeSat systems employing low power micro-controllers as computational platform this requirement is not easily fulfilled. Very accurate timing of the sensors’ measurements as well as efficient algorithms are necessary to have a reliable attitude estimation at high rotational speeds.

The UWE-3 attitude determination has previously been characterized [1] using the estimated orientation and transferring the measurements into the ECI frame. The angular difference between the reference models and the measurements gives an estimate of the attitude determination accuracy, still containing the sensors’ noise and therefore serving as a worst case estimate. It was previously found to be on the order of 2.4 deg and 6.9 deg for the magnetic field and the sun-sensor measurements, respectively (RMS deviation from reference data).

Using the same analysis on a recording during which the satellite was spinning at 80 deg/s with the rate vector being \( \omega = [73, -2, -32] \) deg/s, the attitude determination accuracy is given in Table 1 and the results are also shown in Figure 18 and Figure 19. The deviations are slightly increased compared to the case of a slowly spinning satellite. Especially for the sun-sensors this increase is due to small uncertainties in timing of the sensors.

However, it should be noted that these deviations still contain the sensor’s internal noise. The sun-sensors have an accuracy according to their datasheet, of ±5 deg and the magnetometers have been shown during tests to be precise to better than 3 deg.

<table>
<thead>
<tr>
<th>Deviation of measurements from predicted reference models while spinning at 80 deg/s.</th>
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<tbody>
<tr>
<td>Reference Magnetic Vector RMS: 2.9 deg</td>
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<tr>
<td>Reference Sun Vector RMS: 9.6 deg</td>
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Table 1: Deviations of sensor measurements from predicted reference models while spinning at 80 deg/s.

Figure 18: Magnetic Field vector in ECI coordinates compared to the IGRF model.
V.III Detumbling

Another requirement for safe spin-stabilized control is that the ADCS is capable of slowing down high spin rates reliably. Its effectiveness has already been shown in Dec. 2013 during the initial detumbling [1]. Figure 20 shows the detumbling process from an initial spin rate of 80 deg/s, which was completed in about 40 minutes. Shown in Figure 21 is the corresponding 3-D representation of the rotation rate vector in different projections. From this it becomes visible, that the ADCS is capable of slowing down the satellite even at very high spin rates.

Furthermore, the algorithm stabilizes the satellite with an RMS of 0.7353 deg/s about zero (0.3968, 0.4953, 0.3714 deg/s in x, y, z-components respectively).

Figure 20: Rate vector during detumbling from about 80 deg/s. The satellite reaches its stable state after 40 minutes and remains with an RMS of 0.7353 deg/s about zero afterwards.

Figure 21: 3-D representation of the angular rate vector during detumbling.

V.IV Spin-Z Controller

Spinning up the satellite about one defined axis precisely, has been the next step towards spin-stabilized attitude control. In Figure 22 an experiment is shown during which the satellite was spun up from an initial set-point of -10 deg/s about its z-axis to +10 deg/s about its z-axis. The controller intends to minimize the rotation about the x- and y-axes simultaneously.

Figure 22: Angular rate vector during spin-up to setpoint 10 deg/s from an initial setpoint of -10 deg/s about the body z-axis.
The controller is able to perform the transition of 20 deg/s about the z-axis within 18 minutes, after which it retains the intended spin rates. The corresponding 3-D trace of the angular velocity is shown in Figure 23.

![Figure 23: 3-D representation of the angular rate vector during a spin-up experiment to setpoint [0, 0, 10] deg/s.](image)

However, there are two periods during which the y-axis rate significantly moves away from its set-value. A correlation with the measured magnetic field reveals that during this period the magnetic field along the satellite’s z-axis vanishes (i.e. the magnetic field lies within the xy-plane) and thus, the controller is not able to produce efficiently torques in the xy-plane, leaving these axes underactuated. During the rest of its activation time the controller retains an RMS of [0.1196, 0.25077, 0.0892] deg/s for the x-, y-, and z-axis about their set-points respectively.

The successful test of this spin-z controller has confirmed the effectivity of a stepwise approach to spin stabilized attitude control. A controller allowing an arbitrary spin axis is in preparation, targeting a spin axis perpendicular to the residual dipole such that effects of the latter onto the satellite’s attitude can be minimized. Furthermore, the improved controller shall retain the spin axis constant in ECI coordinates, such that Sun-pointing for instance can be achieved.

![Figure 24: The top shows the magnetic field’s body z-component throughout the spin-z experiment whereas the bottom graph shows the angular rate vector. Note that the periods in which \( \omega_y \) deviates significantly from its set-point coincide with very low magnetic field strengths in the body z-direction, leaving the body xy-plane underactuated.](image)

VI. CONCLUSIONS

Pico-satellite formations offer excellent potential for efficient applications in Earth observation and telecommunication missions. Essential enabling technologies related to modular, flexible system design approaches, to robust on-board data handling systems based on advanced FDIR-software, as well as to miniature attitude determination and control system implementation are addressed in the UWE-3 project. Key subsystems and components have successfully been demonstrated in orbit, preparing the subsequent formation demonstration mission “NetSat”.

As an important milestone related to attitude determination and control, an internal residual magnetic moment could be found by analysing gyroscopic and magnetic measurements. It could be shown, that the ADCS is capable of reliably estimating the satellite’s attitude even at high spin rates, enabling spin stabilized control. Furthermore, efficient spin-up and detumbling could be demonstrated, laying ground for further control experiments targeting inertial spin stabilized control.

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