PW-Sat2

PRELIMINARY REQUIREMENTS REVIEW

Attitude Determination and Control System

Phase A of the PW-Sat2 project

1.1 EN

pw-sat.pl

2014-05-08

Abstract

The following paper is a part of Phase A Summary of student satellite project PW-Sat2. The document presents a comparison of various systems used in different CubeSats, describes elements of PW-Sat2's Attitude Determination and Control System and other details such as working modes and future plans.

The document is published as a part of:

PW-Sat2 – Preliminary Requirements Review

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Revisions

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		Polish version of the document.	Paweł Jaworski
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Attention Phase A documentation may be outdated in many points. Please do not depend on Phase B or Phase A documents only. Current documentation is available on the project website pw-sat.pl

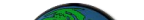This document is also available in Polish.

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1 INTRODUCTION

1.1 FUNCTIONAL REQUIREMENTS OF THE SYSTEM

The necessity of the ADCS is determined by the basic requirements of the mission and the proper performance of other subsystems. The motive of designing the ADCS on-board the PW-Sat2 leads to the following functional criteria:

- Slowing down the angular rate of the satellite after placing on orbit by the rocket (*detumbling*);
- Optimal performance of the Electrical Power System requires pointing the solar panels to the Sun in order to get as much solar energy as possible;
- Angular rate of the satellite cannot exceed the predetermined threshold in order to assure a stable UHF/VHF communication link. External disturbance torques can lead to significant rise of the angular rate which can result in high frequency fading in UHF/VHF (based on the analysis of the communication problems with AAUSat-II tumbling at the rate of 2,5 revs/s [1]);
- Relatively small angular rate of the satellite must be assured so that deploying the solar panels and the sail on orbit would be possible. The exact value of the angular rate will be determined in the future as the result of the tests conducted by the Deployment Team;
- Adding the camera on-board the satellite is considered in order to take the pictures of the Earth. This requires pointing down the satellite (*Nadir Pointing)* and assuring relatively small angular rate to achieve the determined resolution of the pictures.

1.2 REQUIREMENTS OF THE ADCS

Basing on the functional requirements, the team has specified the basic overview of the ADCS system:

- Assuring the high reliability of the system by eliminating the moving parts and relying on bought components (COTS);
- The ADCS system must be able to automatically detumble the satellite after placing on orbit ;
- To avoid the unpredicted rise of the angular rate which can lead to dissatisfaction of the mission requirements, autonomous change of the ADCS mode to the *Detumbling Mode* must take place after exceeding the predetermined angular rate threshold;

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- Taking into account the above requirement, it is recommended to improve the reliability and the robustness to failure by the redundancy of the particular sensors – especially the magnetometers, because they are used during *detumbling*;

- The ADCS system must be able to orient the satellite in the desired direction within the acceptable error;

- The ADCS system must be fully compatible with the others subsystems on-board the satellite;

- In the case of failure of the main satellite's computer or low battery level, switching to the *Safe Mode* must take place automatically;

- Due to the significant role of the *detumbling*, it is recommended to double the *Detumbling Mode* on the satellite's backup computer.

Taking into account all the requirements above and relying on the others CubeSats' ADCS requirements with the similar mission profile (EstCube-1, AAUSat3, NUTS) and the analysis of the simulations assuring fulfilling the requirements, the performance requirements can be summed up ([1], [2], [10], [11]):

- The ADCS must be able to detumble the satellite from the angular rate at the range of $\pm 20\ ^o/s$ to below $\pm 0.3\ ^o/s$ in the Satellite Body Reference Frame within 4 orbits;

1.2.1 REMARK:

The angular rate of the satellite after detumbling should theoretically be equal to the rate of the rotation of the Earth's Magnetic Field vector $\vec{B}$. Taking the simplified model, an assumption of one revolution per 45 mins on LEO orbit can be made, which leads to approximately $0.13\ ^o/s$ [12]. Considering the local changes of the magnetic field, sensors' errors and possible oscillations of the satellite, the value of $0.3\ ^o/s$ has been accepted. The threshold of the number of the orbits within which detumbling should be completed, results in the time of updating the TLE data of the PW-Sat2, which will be sent during the communication session, however it is not the parameter of the highest priority.

- The ADCS must be able to track the desired attitude within the error of $\pm 20^o$ outside the eclipse and $\pm 25^o$ in the eclipse;

1.2.2 REMARK:

The accuracy of tracking the desired attitude results in gaining no less than 90% of the maximum solar energy (when the solar panels are perfectly perpendicular to the Sun direction),

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the possibility of taking the pictures of the Earth, and the capabilities of the magnetic ADCS and the performance of the algorithms. After further analysis, the predetermined values can slightly change. The steady-state error of the pitch/roll angle should make taking the pictures of the Earth possible. This will be relevant only if the team will decide to put the camera on-board to take the pictures of the Earth. The possibility of keeping the determined error of the attitude is confirmed by the simulations made for the CubeSats which work properly (EstCube-1, AAUSat-3 [1], [2], [10], [11]). The team must confirm the requirements by performing its own simulations of the ADCS algorithms.

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2 COMPARISON OF THE ADCS CONFIGURATION ON-BOARD OTHER CUBESATS

The analysis of the ADCS systems on-board other CubeSats has been made. The emphasis on the similar mission profile to the PW-Sat2 mission plan and the success of the project has been put. The data was collected on the grounds of [15], [10], [11], [3], [1], [16], [4], [7], [2], [5], [8], [9]:

Satellite	Size	Success	Sensors	Type	Actuators
EstCube1	1U	+	6x 2-axis SunSensor	-	3x coils
			Magnetometers	-	
			Gyroscopes	-	
Orsted	34x	+	1x 3-axis magnetometer	from DTU	3x coils
	45x		1x 3-axis magnetometer	from CNES	Gravity
	72 cm		Star Tracker	from DTU	Boom
			8x SunSensor	-	
AAUSat2	1U	-	1x 3-axis magnetometer	HMC1023	3x coils
			Photodiodes	SLCD-61N8	3x RW
			6x 1-axis gyroscope	ADXRS401	
AAUSat3	1U	+	1x 3-axis magnetometer	HMC6343	3x coils
			24x SunSensor	SLCD-61N8	1x magnet
			(photodiodes)	IDG1215	
			1x 2-axis gyroscope	ISZ1215	
			1x 1-axis gyroscope		
MaSat1	1U	+	1x 3-axis magnetometer	-	3x coils
			1x 3-axis accelerometer	-	
			1x 3-axis gyroscope	-	
			Photodiodes	-	
NSO	3U	+	1x 3-axis magnetometer	-	3x coils
			Sun Sensors	-	3x RW
			Gyroscopes	-	
ΔD-Sat	2U	Launch 2015	1-axis Gyroscopes	ADIS16260	3x coils
			1x 3-axis magnetometer	HMC5843	4x 'Sail'

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NTNU	2U	Launch 2014	Solar Panels	-	3x coils
			Magnetometers	-	
			Gyroscopes	-	
SwissCube	1U	**+**	1x 3-axis magnetometer	HMC1043	3x coils
			6x SunSensor	from DTU	
			3x 1-axis gyroscope	ADXRS401	
RAX-2	2U	**+**	1x 3-axis magnetometer	PNI MicroMag3	1x magnet
			1x 3-axis magnetometer	ADIS16405	
			1x 3-axis gyroscope		
			Photodiodes	SFH2430	

Table 2-1 Configuration of the ADCS of ten CubeSats

One of the main goals of the EstCube1, AAUSat3, MaSat1, NSO and SwissCube missions is taking the pictures of the Earth and sending them during the communication session. Based on the Table 2-1, the elements used in listed missions are:

- 3-axis magnetometers;
- Configuration of the gyroscopes giving the information about the 3-axis angular rate;
- Sun Sensors;
- Electromagnetic Coils (Magnetorquers).

In order to calculate the attitude of the satellite from the data from the photodiodes and the magnetometers, the information about the satellite's position on orbit must be available to compare the measured vectors with the reference values. Orsted, AAUSat3 and NPSat1 missions used the TLE data ([3], [1], [6]), updated within the specified time interval during the communication sessions (more precise description in chapter 4).

![SKA logo]	PW-Sat2	Attitude Determination and Control System	![PW-SAT2 logo]
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3 ADCS COMPONENTS SELECTION

Basing on ADCS structures of various CubeSats which aim and mission character were similar to PW-Sat2's, the following components were chosen. In the selection process the following features were taken into consideration:

- proper work during previous missions and fulfilling the guidelines
- precision
- mass
- size
- costs
- power demand

3.1 SPATIAL ATTITUDE AND ORIENTATION SENSORS

3.1.1 3-AXIS MAGNETOMETER

(i.e. Honeywell HMC6343 [20] or HMC5843)

Figure 3-1 Honeywell HMC6343 - 3-axis compass module with algorithms

Advantages
- Temperature sensors will allow to reduce errors due to thermal conditions' impact on dynamic characteristic of the magnetometer;
- Built-in Self-Test allows to detect any possible failure;;
- Low cost allows to multiply the number of the sensors without heavy impact on overall costs;
- Small size (MEMS) does not affect the structure of the satellite;
- Always accessible read mode.

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Disadvantages

- Susceptibility to electronic noise – necessity of compensating the errors and filtering the noise by low-pass filter with adequate boundary frequency in order to not decrease the precision of the sensor by phase inversion;

- Sensitive to temperature changes – necessity of compensating their impact on sensor readings.

Digital sensors have built-in low-pass filter and temperature compensation module. The above disadvantages might be justified in case of analogue sensor.

Magnetometer gives the information about the spatial attitude when the satellite stays in the Earth's shadow. It is crucial in the detumbling phase and it allows to slowing down the angular velocity. The errors resulting from the incomplete model of Earth's magnetic field, possible electric noise or limited accuracy of PCB structure may cause errors in determining the attitude no larger than 4° ([14], [24]), so such magnetometer may be used on board of PW-Sat2.

3.1.2 PHOTODIODES

Photodiodes with directional characteristics as Sun Sensors

(OSRAM SFH2430 [23] lub Farnell SLCD61N8)

Figure 3-2 Photodiode OSRAM SFH2430

Advantages

- 3-4 photodiodes placed on each wall will allow determine the direction to Sun, when only one wall is illuminated [1];

- Simplicity of design;

- Low cost.

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Disadvantages

- Coarse measurement of the angle, estimated at *10°* [14];

- The need to eliminate the Earth albedo influence by taking into account the measurements with the highest values. Also infrared absorbing coating on surfaces of the photodiodes is considered;

- The need to eliminate the influence of UV radiation, which results in surface darkening; for this purpose it is necessary to cover the surface with a glass coverslip [8];

- No measurement in the shade;

- As in the case of magnetometer it is necessary to compensate the temperature and measurement noise influence on the sensor indications; for this purpose temperature sensor and low-pass filter will be used.

Due to necessity of knowing two reference vectors to determine the attitude (TRIAD algorithm), it is required to integrate the measurements from photodiodes with the magnetometer. Because of high unit cost (2,500 €), our team cannot buy 6 Sun Sensors with accuracy not lower than *0.5°* (based on documentation). Relying on the other CubeSat missions, photodiodes have been selected as sensors for attitude determination. The optimized photodiodes configuration allowing to cover the whole sphere around the satellite will be achieved after tests and simulations. The photodiodes measurements will be normalized and the influence of the dark current will be taken into account.

3.1.3 GYROSCOPE

3-axis MEMS or integration of 2-axis with 1-axis (InvenSense IDG1215 [21], ISZ1215 [22] or AnalogDevices ADIS16260
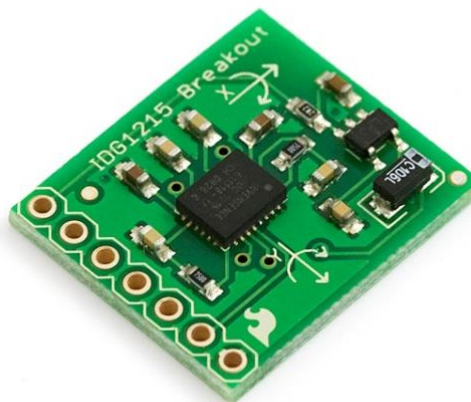

Figure 3-3 IDG1215Analog 2-axis MEMS gyroscope

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Advantages

- The possibility of satellite angular velocity determination gives the information of attitude when satellite is in the shade and determination from photodiodes is incorrect;
- Small size;
- Low cost;
- Build-in auto-zero function, temperature sensor and low-pass filter.

Disadvantages

- Drift increasing in time;
- Large relative measurement errors at small angular velocities due to drift, large absolute measurement errors at high angular velocities and the influence of the temperature on the sensor characteristics; required compensation of abovementioned effects;
- Necessary noise compensation using a low-pass filter.

ADCS simulations, testing PD and PID controllers to obtain desired attitude of CubeSats, have shown, that in the case of changing the Euler angles more than 20° using the coils the time for obtaining desired attitude is about 4 orbits for LEO (~600 km) [2]. Therefore it is necessary to control the satellite in the shade and quite accurate knowledge about attitude and angular velocity. In the case of 2U CubeSat with a mass of *2,7 kg* influenced by disturbing momentum order *10^{-5} Nm* (there were assumed aerodynamic drag, inhomogeneity of gravitational field and solar radiation on the altitude *600 km*; value is the largest total value used in literature) for about *50 min* leads to angular velocity change around the axis of the smallest moment of inertia of about *360°/s.*

It is possible to determine the satellite state vector with sufficient accuracy using only information from the magnetometers and Kalman filter. The advantage of using the gyroscope is instant measurement, when the angular velocity is required by the control algorithm (i.e. when satellite has high angular velocity). In the case of determining the angular velocity from magnetometers indications, in the early phase of work of Kalman filter there will not be supplied information about angular velocity, because the filter is stabilized after a certain time. The final decision on the choice of gyroscope will be taken after simulations.

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3.2 ACTUATORS

3.2.1 MAGNET COILS

3 magnet coils called *magnetorquers* (ISIS MagneTorquer Board [19]);
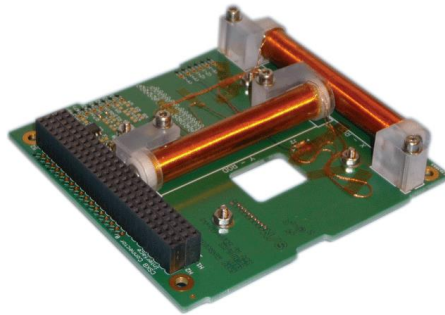

Figure 3-4 ISIS MagneTorquer Board

Advantages

- System fits on a PCB;
- No moving parts;
- Relatively low cost and small size – in comparison to the reaction wheels;
- Two coils with ferromagnetic core provides lower power consumption, while one coil without a core is less vulnerable to the influence of the hysteresis in the control;
- Simplicity of design.

Disadvantages

- Small torque control value;
- Possibility of obtaining a control torque only in a plane perpendicular to vector $\vec{B}$;
- Relatively high power consumption ~1W [19];
- It is required to take into account the influence of magnetic moment generated by the coils on the sensors and electronic devices.

The system of solenoid coils is the most popular solution for CubeSat attitude control on LEO. Due to financial, mass and size limitations our team is not considering other actuators on board of the satellite PW-Sat2. Simulations performed for all of the CubeSats with only magnetic control of attitude has shown, that obtaining the desired attitude error within the limits defined in Point 1.2 is achievable [15], [10], [11], [1], [2].

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3.3 MICROCONTROLLER

The computing unit for ADCS will be the main OBC device with 32-bit architecture and 72MHz clock (STM32F103ZGT6). Basic ADCS modes (see point 6.): Detumbling, Safe Mode and Pointing will be mirrored on the backup 8-bit microcontroller with 32MHz clock (ATXMEGA128A1).

3.4 THE MOST IMPORTANT ELEMENTS/ELEMENTS WITH THE HIGHEST RISK

Magnetometers are the most important sensors in ADCS system. In the case of their failure it is impossible to:

- optimize deceleration of the satellite (detumbling);
- determine exact spatial orientation angles because the magnetometer is the most accurate sensor on-board PW-Sat2;
- control the orientation of the satellite, because each time before coils are powered on (which are working with a certain frequency, depending on the time of coils discharging , measurement time, the time required to calculate and duration of action of coils) the vector $\vec{B}$ is measured.

It is considered to provide redundancy in the form of two additional three-axis magnetometers. If all magnetometers are effective, simultaneous 3 measurements will allow to average indications and eliminate gross errors, such as those resulting from transmission in I^2C bus. In case of damage, the algorithm will reject the non-matching information, which is beyond the acceptable range.

Simultaneous failure of two magnetometers, resulting in the rejection of information from properly functioning sensor, is not considered due to the low level of probability. At least one magnetometer should be installed outside the satellite.

Doubling of the basic modes algorithms of the ADCS system on the reserve OBC microcontroller will provide ADCS resistance to failure of the main microcontroller (see section 3.3).

Elements bearing the most risk are photodiodes, due to low reliability and accuracy. In case of insufficient protection against UV radiation, the indications are accordingly smaller and the orientation error increases significantly [8].

In case of photodiodes' failure:

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- TRIAD algorithm cannot be used to determine the spatial orientation as an input to the Kalman filter; it becomes necessary to determine the state vector using magnetometers indications and eventually gyroscope;

- Pointing mode implementation (see section 8) cannot be based on indications from the photodiodes; it becomes necessary to estimate orientation using magnetometers and gyroscope.

Due to the number of wires and complexity of the whole algorithm (necessity to analyze the indications from 72 sensors) the redundancy of photodiodes is not considered.

However, it is considered to develop an algorithm which will detect the failure of photodiodes, resulting in cessation of the use of the TRIAD algorithm and then reliance on indications of gyroscope and magnetometers.

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4 DETERMINATION OF THE SATELLITE POSITION BY MEANS OF TLE DATA

In order to determine the satellite position in the orbital frame based on measurements made with magnetometer and photodiodes, a comparison of the measured values with those of the model predictions is needed. Thus it is necessary to know the satellite position in orbit, to know the magnetic field vector at the satellite position. There are two common methods in use: having a GPS receiver on board, or an implementation of the orbit propagator on board, which will update the TLE of the SGP4.

	Advantages	*Disadvantages*
GPS receiver	- accuracy ~10m; - ionospheric errors can be corrected by software;	- expensive; - separate PCB board; - additional antenna; - mass and size; - antenna pointing to GPS constellation;
TLE	- no costs; - no space needed; - simple algorithm which takes into account a number of factors;	- position error grows exponentially with time; - need to update data.

Table 4-1 Comparison of GPS receiver and TLE data as the position determination method for satellite in orbit.

NPSat1, Orsted and AAUSat3 missions had the orbit propagator implemented ([6], [3], [1]). During the latter two missions it was used for providing the necessary redundancy in case of GPS receiver failure. For the NPSat1 mission, the TLE data was updated every 7 days. The data which was collected during Orsted mission (10-17.02.2002) confirmed the exponentially increasing position error, which was determined by comparing SGP4 to GPS.

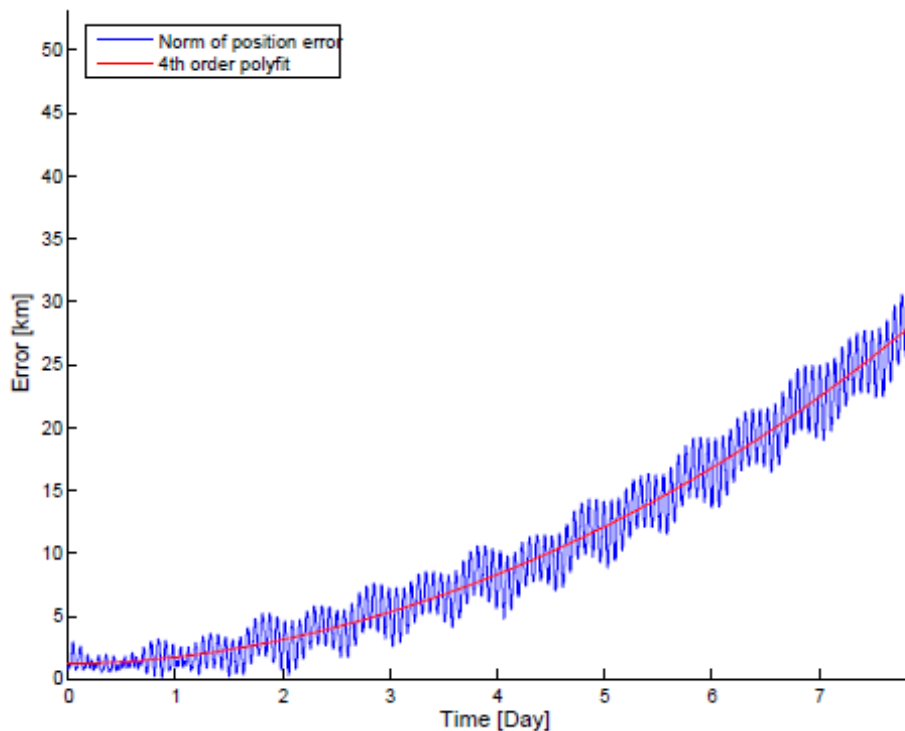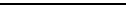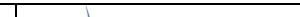| ![SKA logo]	PW-Sat2	Attitude Determination and Control System	![PW-Sat2 logo]
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Figure 4-1 Norm of position error for SGP4 and GPS data.[3]

In order to keep the magnitude of the relative position error below 5 km, a 3-day TLE update frequency is required. It is also important to keep in mind the importance of properly updating on-board timekeeping, seeing as how during LEO orbit, a 1-second error results in a position error of about 7.5 km, and translates to an attitude error of ~0.5°. The value of the attitude error has been estimated by use of the IGRF model [24] in the most variable magnetic field area at 600 km above the north hemisphere; 80°N, 110°W. The angle between the horizontal components of the vector $\vec{B}$, at the distance of 7.5 km along the meridian translates to a latitude difference of 0.06°. The resulting 0.23° is multiplied by 2, to take into account the model.
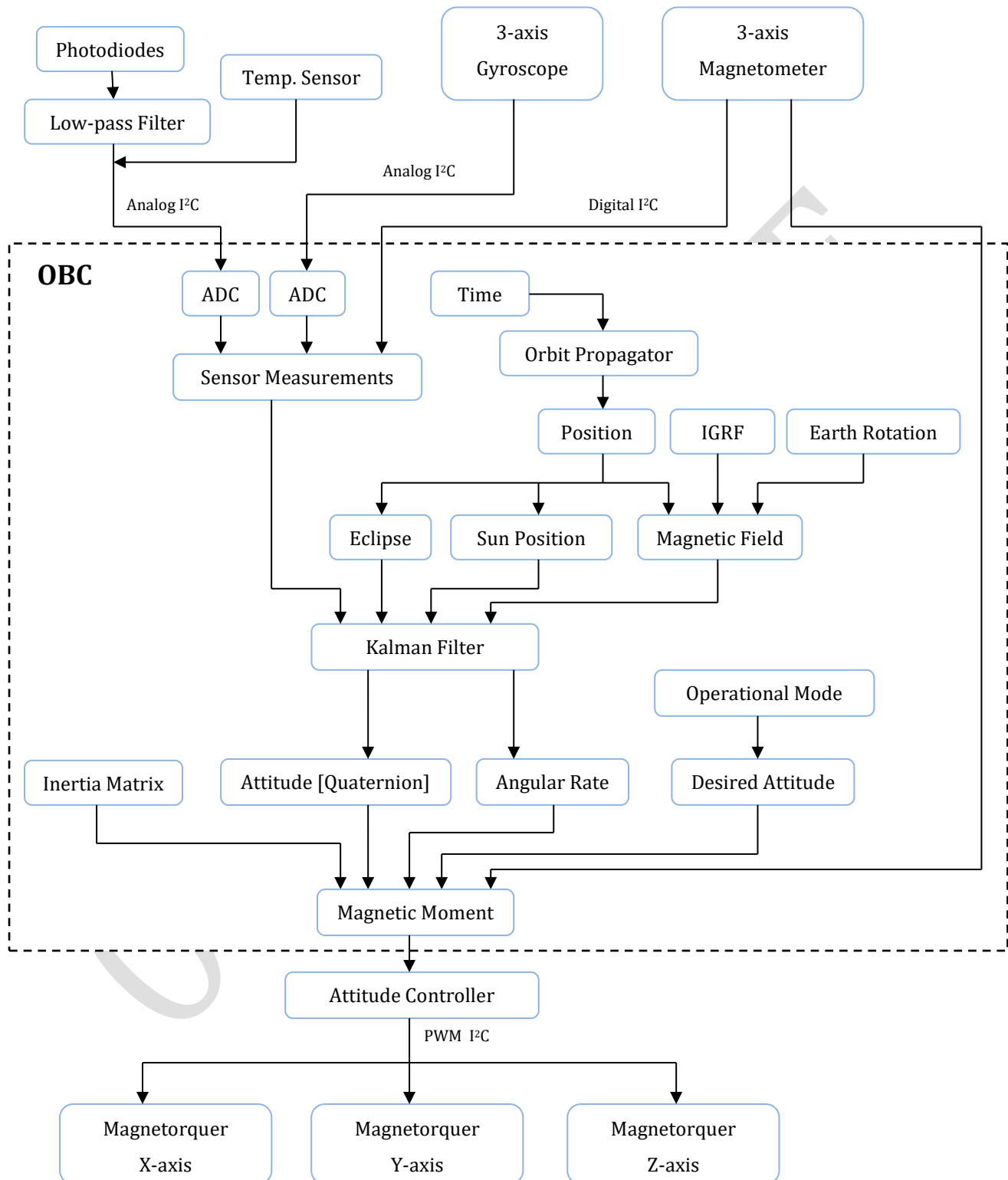
SGP4 model takes into account [17], [18]:

- atmospheric drag;
- Earth gravity harmonics (J2, J3, J4);
- Sun radiation;
- Lunisolar gravitational attractions.

Due to acceptable accuracy, the ability to send updated data during the communication session, saving cost, weight and space, the team have decided to use the SGP4 model for determining the position of the satellite in orbit.

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5 BLOCK DIAGRAM OF ADCS

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A sample HMC6343 magnetometer is a digital sensor with integrated temperature sensor. IDG1215 gyroscope has an analogue output, yet it also features a low-pass filter and a temperature sensor. The ADCS system block diagram will change depending on the mode of operation. The diagram above illustrates the pointing mode, utilizing information from all available.

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6 ADCS WORKING MODES

The following 7 modes of ADCS have been defined. Future simulations and test will show whether the presented architecture of the system is justified, so the number and characteristic of modes may be changed significantly.

- OFF

  The ADCS is turned off in the very first phase of the mission. It is turned on after the Electric Power Supply and On-Board Computer systems check run by a specific command. In OFF mode the power supply is not supplied to the system, so there is no data collected from the sensors, the orientation is not being determined and there is no possibility of attitude correction. If the battery level is critical, the ADCS should go into OFF mode automatically.

- CHECK

  During this mode there is a sensors and actuators test carried out by built-in functions or voting algorithm in case of redundancy. If the failure is registered, the actuators will be turned off and the system will be set to SLEEP mode.

- SLEEP

  In case of positive result of sensors and actuators test or if any problems are registered, the system should go into SLEEP mode. During this mode the data from sensors is registered with smaller frequency in order to reduce power demand.

- STANDBY

  The attitude is determined, but there is no active control over the satellite's orientation. This mode should be activated in case of coils' failure. Determining the attitude has its reasons due to SunSensor experiment and its aims.

- DETUMBLING

  When the magnetometer and coils are in working order, going into DETUMBLING mode is taking place after EPS and OBC test automatically. In case of exceeding the boundary value of angular velocity the satellite goes into DETUMBLING mode provided that

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gyroscopes are operable. In case of gyroscopes failure only, the angular velocity is determined based on magnetometer readings.

- SAFE MODE

Safe Mode is related to all systems' work. When the battery level drops below some level, the SAFE MODE should be activated. In case of such event the ADCS is set to OFF mode.

- POINTING

This mode should be activated only after DETUMBLING. The data from all the sensors is received and the active control of the satellite attitude supported.

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7 COURSE OF WORK AND CONSIDERED SOLUTIONS

The team will conduct simulations of proposed solutions with Matlab/Simulink software. These tests should show that system corresponds with requirements (see point 1.2).

Tasks for the team:

- Test of the proposed ADCS configuration – the simulation should check whether it is possible to keep specific attitude by coils only providing that there are no disturbances and the state vector is precisely known.

- Optimal photodiodes configuration test in order to cover full sphere around the satellite. Designing the algorithms of determining the Sun-pointed vector on the basis of photodiodes' readings.

- Simulation of disturbing moments on LEO (atmospheric drag, nonhomogeneousity of gravitational field and solar radiation impact).

- Further development of simulation software by implementing the IGRF module and real factors emulation (biasing, drifting, noise) with Kalman filter.

- B-Dot algorithm simulation. Determining the gain value. Estimation of IGRF precision.

- Verification of theoretical precision of the gain value. Verification of optimal value real-time calculations of the gain in order to shorten the detumbling time.

- TLE data precision verification.

- Control algorithms simulation. PD controller test. Requirements verification (see point 1.2).

- Failure states test. Implementation of corresponding algorithms.

- Test of all ADCS modes.

- Choice and purchase of system components.

- Algorithms test on purchased components (Processor/Software In The Loop).

- Tests during the integration of the satellite (sensor errors, communication status, polarisation tests).

Purchase of commercial reference sun sensor is considered in order to compare SunSensor experiment's readings which are used in determining the attitude and orientation.

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8 MASS BUDGET AND COSTS ESTIMATION

The following table shows the comparison of cost and mass budgets of ADCS in different configurations. Specified devices are just an example and may be changed in the future

Version 1 (basic): ISIS Magnetorquer Board, magnetometer HMC6343, 2-axis gyroscope IDG1215, 1-axe gyroscope ISZ1215, 24 photodiodes OSRAM SFD2430;

Version 2 (basic + redundancy): elements from basic version + 2 redundant magnetometers;

Version 3 (basic + reference SunSensor):): elements from basic version + reference SunSensor;

Version 4 (full): elements from basic version + 2 redundant magnetometers + reference SunSensor.

	Version 1		Version 2		Version 3		Version 4	
	Mass [g]	Price	Mass [g]	Price	Mass [g]	Price	Mass [g]	Price
ISIS MagneTorquer Board	195	7500€	195	7500€	195	7500€	195	7500€
Magnetometer HMC6343[1]	5	80$	15	240$	5	80$	15	240$
Gyroscope IDG1215[1]	3	25$	3	25$	3	25$	3	25$
Gyroscope ISZ1215[1]	2	2$	2	2$	2	2$	2	2$
Photodiode SFD2430[1]	24*3=72	24*1,5=36€	24*3=72	24*1,5=36€	24*3=72	24*1,5=36€	24*3=72	24*1,5=36€
Reference SunSensor	-	-	-	-	5	2500€	5	2500€
Suma[2]	**277 g**	**7812€**	**287 g**	**7926€**	**282 g**	**10312€**	**292 g**	**10426€**

Table 8-1 Mass and cost comparison of different ADCS configurations

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[1] Mass of wiring system and soldering added
[2] Shipping costs added (200€). In $ to € exchange the 0.71 ratio was assumed (20.03.2014).

	PW-Sat2	Attitude Determination and Control System	
	1.1 EN	pw-sat.pl	
	Phase A of the PW-Sat2 project		

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