Attitude Determination and Control System for ESTCube-1

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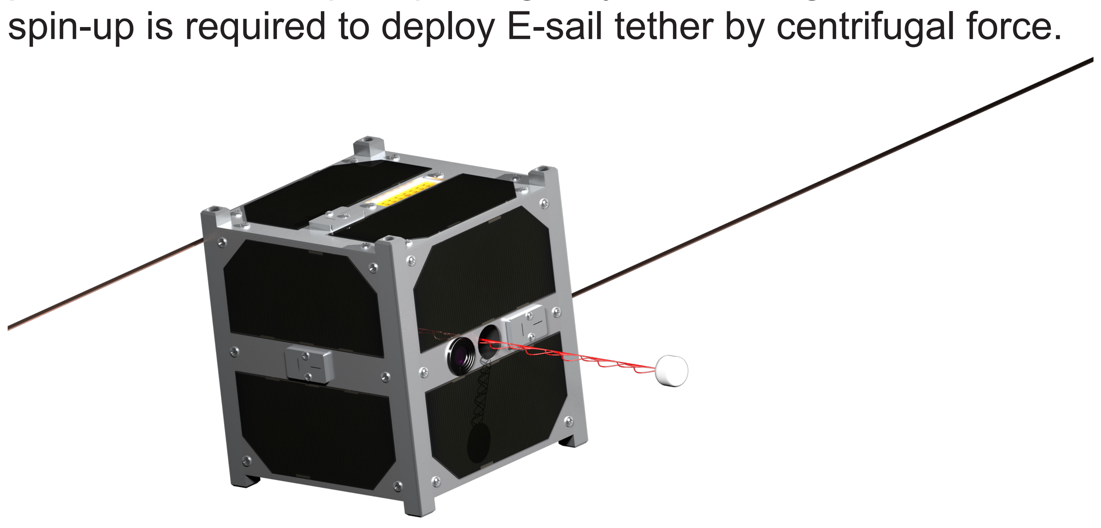
Introduction

ESTCube-1, developed mainly by students in Estonia, will be the first satellite performing the electric solar wind sail (E-sail) experiment in space. E-sail is a novel space propulsion concept which uses the dynamic solar wind pressure to propel the the satellite. During the ESTCube-1 mission, one 50 μm thick 10-meter long heytether will be deployed and E-sail effect will be measured.[1]

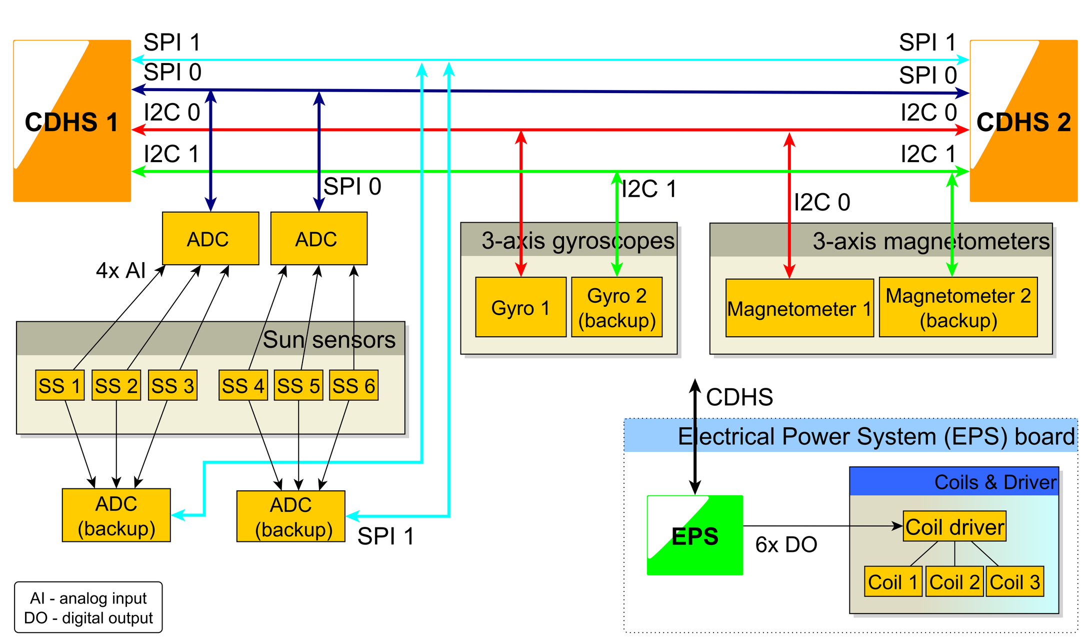
Attitude Determination and Control System (ADCS) aims to perform one axis spin-up using only electromagnetic coils. The spin-up is required to deploy E-sail tether by centrifugal force.



ESTCube-1 artist's impression

Hardware

ADCS includes magnetometers, sun sensors, gyros, analog-to-digital converters, coil drivers and magnetic coils. Command and Data Handling System (CDHS) microcontrollers are used for interfacing ADCS sensors and running algorithms.

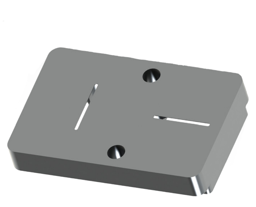


Overview of ADCS sensor and actuator interfaces

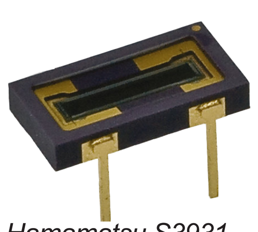
Magnetometer is used to measure the strength and direction of Earth's magnetic field. Digital, 3-axis sensor Honeywell HMC5883L with I²C bus is used.

Gyroscope will measure the angular rate of the satellite. Digital, 3-axis sensor Invensense ITG-3200 with I²C bus is used.

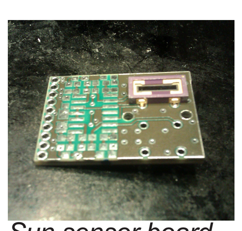
Sun sensor is used to measure the direction of the Sun. Two Hamamatsu S3931 Position-Sensitive-Detectors on each side of the satellite are used. They are mounted on a PCB, attached under a custom aluminium mask with two slits.



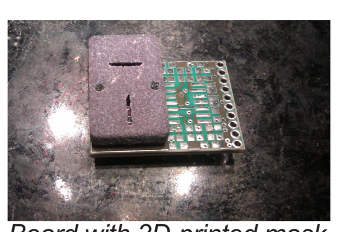
Sun sensor mask



Hamamatsu S3931



Sun sensor board

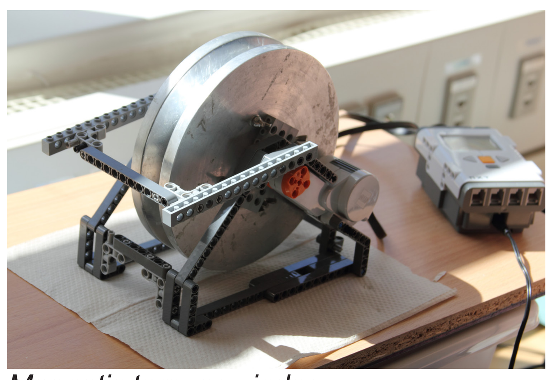


Board with 3D-printed mask

Main board includes redundant sets of magnetometers, gyroscopes and analog-to-digital converters (ADC) on SPI bus, which are used to read signals from sun sensors.

Coil driver is used to control the voltage and duty cycle of coils. They are on Electrical Power System (EPS) board, powered directly from the battery. EPS microcontroller generates pulse-width modulation based on commands from CDHS.

Coils or magnetic torquers are used to control the attitude of the satellite by producing torque in interaction with Earth's magnetic field. ESTCube-1 will accommodate 3 perpendicular coils, each having 400 turns of 0.19 mm copper wire and outer dimensions of 91 mm x 69 mm. That produces 0.11 Am² at 4 V, while consuming 280 mW.



Magnetic torquer winder

Magnetic torquers

Mission Phases

Detumbling

After deployment from the Picosatellite-Orbital-Deployer (POD) the Cubesat will be tumbling randomly. As part of the initial comissioning the satellite will automatically detumble.

Nadir and Inertial Pointing

Pointing algorithms are needed for efficent communications and photographing Estonia, these will be based on Linear-Quadratic Regulator (LQR).[5]

Spin-up

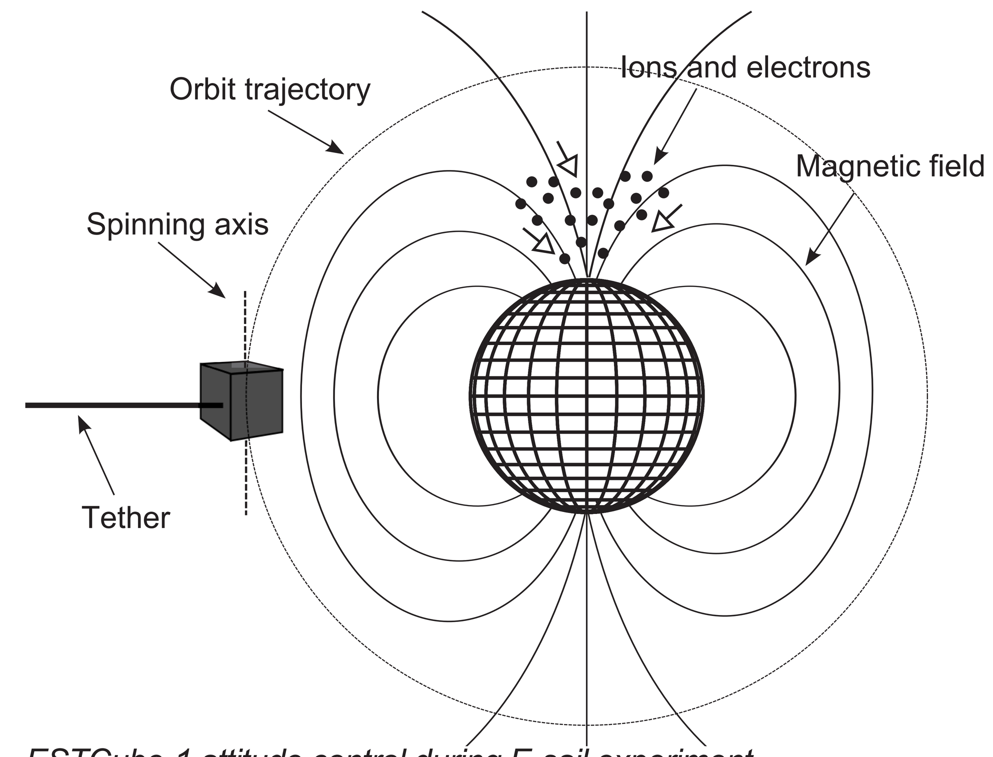
The centrifugal deployment of the tether requires a spin rate of 1 revolution per second around the satellite's z-axis and an alignment of the spin axis with the Earth's polar axis.

Measuring E-sail Force

E-Sail effect will be verified by measuring the change in satellite's angular velocity during the experiment.

Plasma Brake

The long term deorbiting effect of the plasma brake results in change of orbital altitude[2]. This can be seen by comparing the orbit of ESTCube-1 to other Cubesats from the same launch.



ESTCube-1 attitude control during E-sail experiment

Models & Simulation Environment

Orbit Propagator

Predicting the orbit is essential to simulating environment and disturbances. Two-line-elements (TLE) are used to convey orbital parameters into simplified perturbations model SGP4, which calculates satellite position at a particular time.

Ephemeris Model

The rotation of the Earth is required to determine the magnetic field and to calculate how the satellite should point in order to track targets on Earth.

Eclipse and Earth Albedo Models

Eclipse indication is used to disregard sun sensor measurements during an eclipse and determining Earth's albedo gives the possibility of making more realistic sun sensor models.

Magnetic Field Model

International Geomagnetic Reference Field (IGRF) model is used for the emulation of magnetometers and calculating the control torque of the coils.

Environment Disturbances

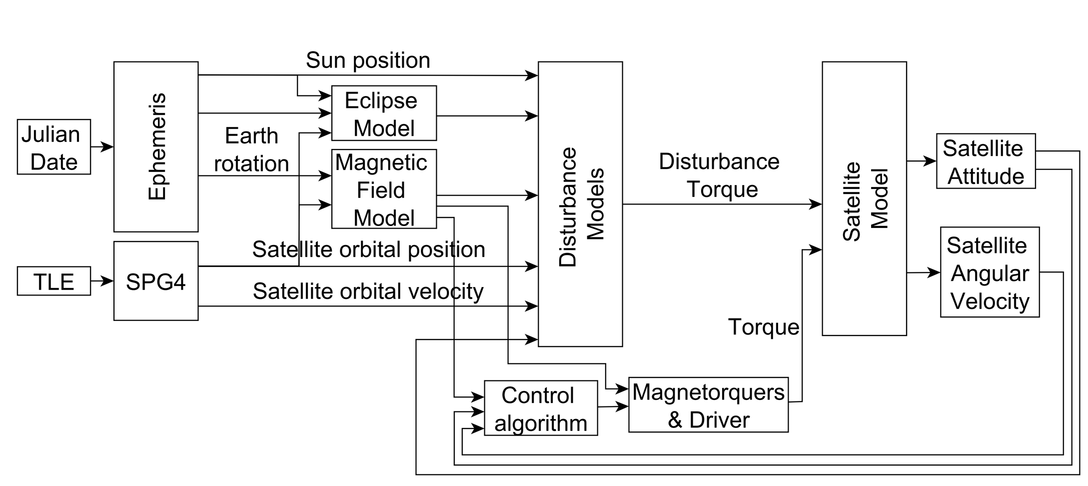
Spacecraft orbit and attitude are disturbed by atmospheric drag and torque from solar radiation and gravity gradient.

Sensor and Actuator Models

Sensor signals are introduced with realistic noise patterns to provide input for attitude estimators during simulations.[4]

Simulation Environment

These simulation models with attitude estimators and different attitude control algorithms are implemented in Matlab/Simulink environment.



ADCS simulation environment

Spin-up Algorithm

Magnetic control law is $\boldsymbol{m} = \mathrm{sat}\left[-\frac{k}{|\boldsymbol{B}|^2}\boldsymbol{A}, \boldsymbol{m}_{\max}\right]$

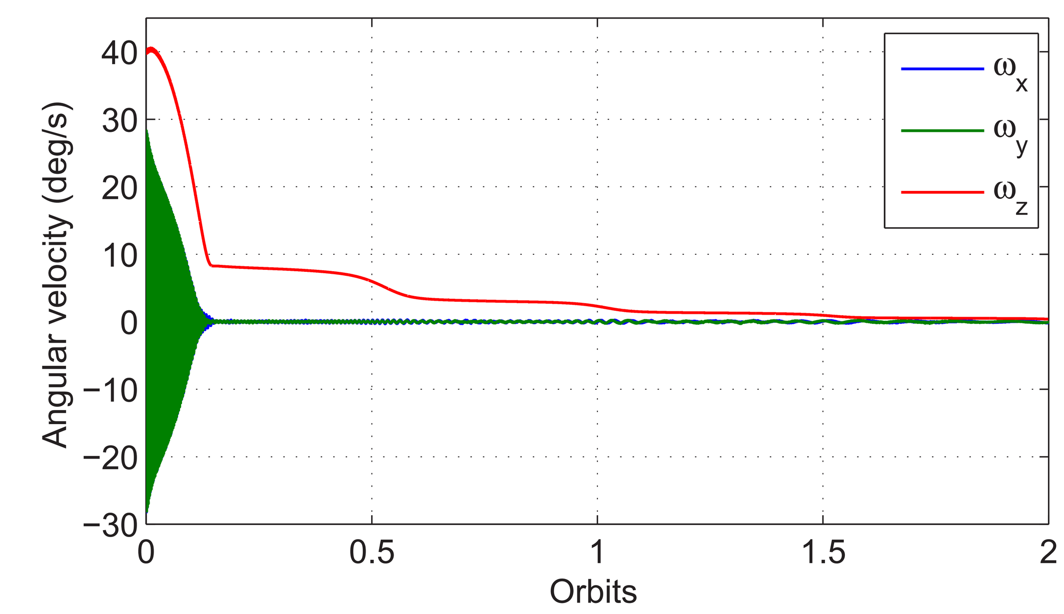
where $k > 0$, and $\boldsymbol{A} = \boldsymbol{W}\boldsymbol{B}^{\times}\left(\tilde{\boldsymbol{h}} + k_1 e_{hz}[0\ \ 0\ \ 1]^T + k_2\boldsymbol{P}\boldsymbol{\omega}\right)$;

- $\{\mathrm{sat}[\boldsymbol{x}, \boldsymbol{x}_{\max}]\}_i = \begin{cases}\{\boldsymbol{x}\}_i, & |\{\boldsymbol{x}\}_i| \le \{\boldsymbol{x}_{\max}\}_i \\ \{\boldsymbol{x}_{\max}\}_i \mathrm{sign}(\{\boldsymbol{x}\}_i), & |\{\boldsymbol{x}\}_i| > \{\boldsymbol{x}_{\max}\}_i\end{cases}$ is the saturation function;
- $\boldsymbol{m}_{\max} = [m_{x\max}\ \ m_{y\max}\ \ m_{z\max}]^T$ is the maximum dipole moment for each magnetic torquer;
- $|\boldsymbol{B}|$ is the norm function of the magnetic field vector;
- $\boldsymbol{W} = \mathrm{diag}(1,1,1)$ selects the coils and $\boldsymbol{P} = \mathrm{diag}(1,1,0)$;
- $\boldsymbol{B}^{\times} = \begin{bmatrix} 0 & -B_z & B_y \\ B_z & 0 & -B_x \\ -B_y & B_x & 0 \end{bmatrix}$ is the cross product matrix associated with the vector $\boldsymbol{B} = [B_x\ \ B_y\ \ B_z]^T$;
- $k_1,\ k_2 > 0$ are tunable gain values;
- $\boldsymbol{\omega}$ is the satellite angular velocity vector;
- $\tilde{\boldsymbol{h}} = \boldsymbol{h} - \boldsymbol{h}_d = \boldsymbol{I}[\omega_x\ \ \omega_y\ \ \omega_z]^T - \boldsymbol{I}[\omega_{dx}\ \ \omega_{dy}\ \ abs(\omega_{dz})]^T$ is the angular momentum error;
- $\boldsymbol{h} = \boldsymbol{I}\omega$ is the angular mometum, where $\boldsymbol{I}$ is the moment of inertia matrix;
- $e_{hz} = h_z - h_{dz}$ is the angular momentum error about z-axis.[3]

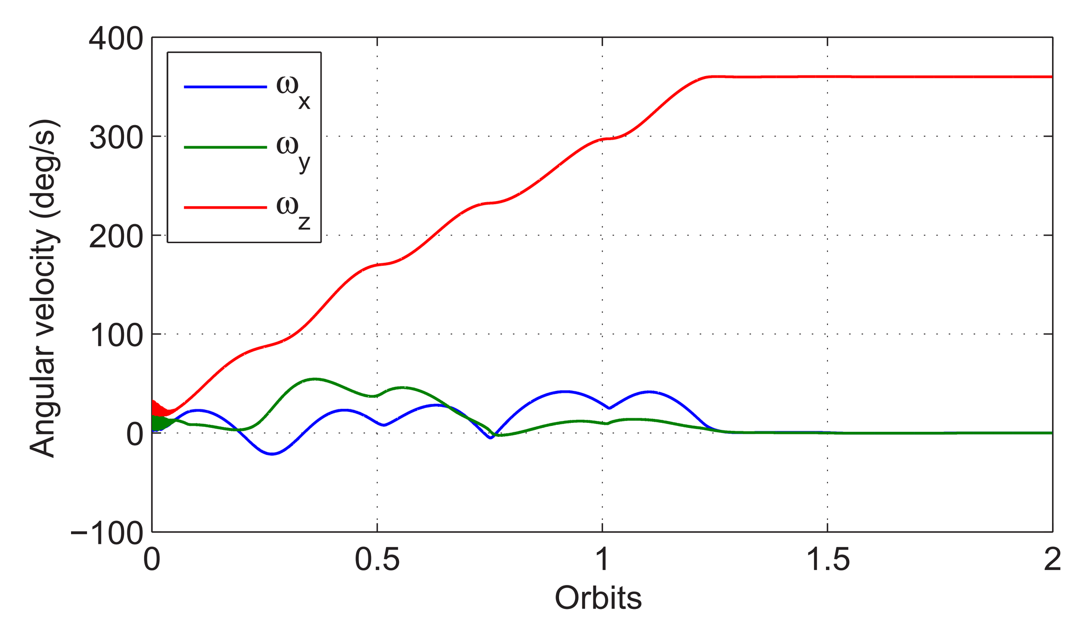
The original algorithm has been improved for ESTCube-1 mission specific requirements of aligning spin axis and satellite with the Earth's polar axis. Desired angular velocity is now transformed from Earth-centered inertial coordinate frame to spacecraft body reference frame and the desired angular velocity in z-axis is now always positive.

Simulation Results

Attitude control algorithms for detumbling, pointing and spin-up have been developed and tested in a simulation environment to estimate and measure the controller time response, error tolerance, accuracy and stability.



Detumbling from initial angular velocity of (20,20,40) deg/s with B-dot controller



Spin-up from initial angular velocity of (20,20,20) deg/s to (0,0,360) deg/s

References

1. Janhunen, P., et al. Electric solar wind sail: Towards test missions. *Review of Scientific Instruments.*, 81, 111301, 2010.
2. Janhunen, P.,. Electrostatic Plasma Brake for Deorbiting a Satellite. *Journal of Propulsion and Power* 26 (2), 370372.
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4. Jensen, K., Vinther, K., 2010. Attitude determination and control system for AAUSAT3. Master's thesis, Aalborg University, Department of Electronic Systems.
5. ESTCube-1. Space System and Mission Description. Phase-A document, 2009.

Acknowledgments

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