A Conceptual Design of HAUSAT-1(CubeSat) Satellite

Joon-Tae Kim*, Young-Suk Kim*, Seung-Won Seo*, Young-Hyun Kim* and Young-Keun Chang**

Space System Research Lab.

Hankuk Aviation University, Koyang, Korea 412-791

Abstract

This paper addresses the conceptual design results of the HAUSAT-1 (Hankuk Aviation University SATellite-1), developed by Space System Research Lab. of Hankuk Aviation Univ., which is a new generation picosatellite. This project has been funded by Korean Government for the purpose of developing the space core technology. This is the first attempt at the level of university in Korea to develop the satellite weighing less than 1kg and accelerates opportunities with low construction, low launch cost space experiment platforms. The purpose of the HAUSAT-1 project is to offer graduate and undergraduate students great opportunities to be able to understand the design process of satellite development as a team member. Its mission objectives are to track its position by the GPS receiver system, to deploy the thin film solar cell panel to generate extra power, and to measure plasma density and temperature with the plasma sensor. The HAUSAT-1 will orbit at the altitude of 650 km with 65 degree inclination angle with 12 months of design mission life. It is planned to be launched on November 2003 by Russian launch vehicle "Dnepr".

Key Word : HAUSAT-1, GPS, Picosatellite, Plasma Sensor, Thin Film Solar Cell, Li-Ion

Introduction

In recent years, the trend of the satellite development is toward "smaller, faster, cheaper, better". [1] Many countries are focusing on developing small satellites like microsatellite for the improvement of space technology, and several universities in the world are also developing nanosatellite and picosatellite for the purpose of educating space science. Among those satellites, the CubeSat is a picosatellite weighing less than 1kg with $10cm \times 10cm \times 10cm$ cubic configuration. [2] The CubeSat is carried by P-POD (Poly Picosatellite Orbital Deployer) which is adapted at MPA (Multiple Payload Adapter). Its first launch is going to be conducted June, 2002 by Russian launch vehicle "Dnepr". The configuration of P-POD and MPA is represented in Fig. 1. [3]

The HAUSAT-1, a CubeSat which is being developed by Space System Research Laboratory, is low cost satellite for education and space technology verification. The team member is made up of professors and a variety of majors of students such as Aerospace Engineering, Mechanical Engineering, Electric & Electronic Engineering, Computer Engineering, and so on. The CubeSat, briefly speaking, is easy to develop at university level because it has a lot of advantages as followings; low construction cost, short development period, easiness to apply new technology and great educational opportunities for students studying satellite design. This paper addresses the conceptual design and trade-off results of HAUSAT-1 satellite.

* Graduate Student, Department of Aerospace Engineering

** Professor, School of Aerospace and Mechanical Engineering

E-mail : ykchang@mail.hangkong.ac.kr , TEL : 02-300-0286 , FAX : 02-3158-3189

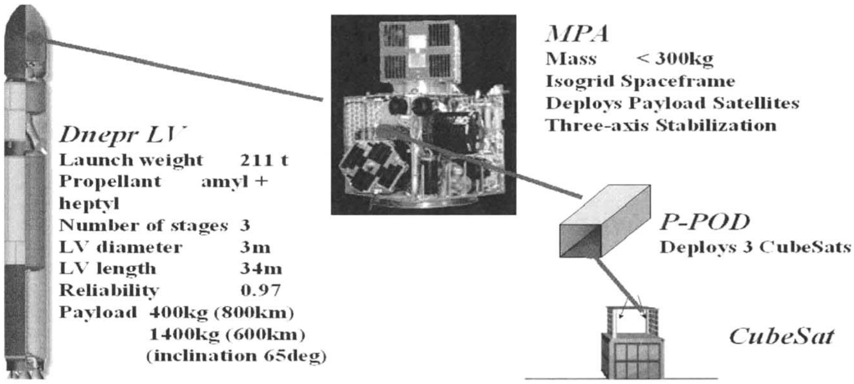


Fig. 1. Launch Configuration

Mission Analysis

Mission and Payload

The primary mission objective of HAUSAT-1 satellite is to offer graduate and undergraduate students great opportunities and help them understand the whole development process of satellite design, analysis, manufacturing, assembly, integration, test, launch and operation, and consequently make them specialists in the field of satellite development. Actual mission objectives in accordance with on-board payload are as follows; tracking the satellite with GPS receiver, deployment of thin film solar cell panel to get extra power, space environment measurement and getting data related to health of satellite from various sensors, whose data will be used to design HAUSAT-2 nanosatellite in the future. Building and operating the satellite in a desired orbit can help students provide the hands-on experience for overall satellite development process. Among the additional mission objectives, the thin film solar cell panel deployment requires the panel deployment mechanism. The plasma sensor will measure the plasma density and temperature for space experiment. The payload configuration is illustrated in Fig. 2.

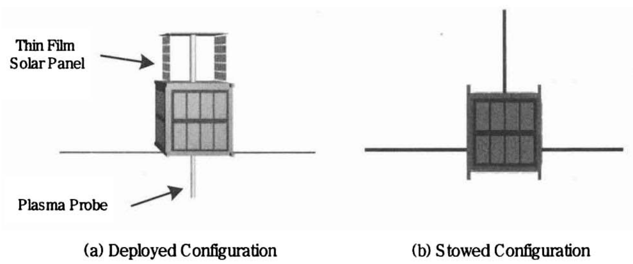


Fig. 2. Payload Configuration

Mission Life

The major factors to determine the mission life of the LEO satellite are as follows; battery charging/discharging cycle, solar cell degradation, part failure due to total dose effect, and so on. The COTS(Commercial-Off-The Shelf) parts will be utilized to minimize the development cost for the HAUSAT-1 electronic modules except radiation-sensitive items like microcontroller. The radiation environment for total dose and single event effects will be analyzed to ensure the satellite's extended mission life. [4] The HAUSAT-1 will implement shielding technology to avoid any failures due to total dose accumulation and select its components to meet twelve months of design mission life.

Operation Modes

From launch to the end of life, the HAUSAT-1 should be normally operated without malfunction. The HAUSAT-1 has four types of operating modes as shown in Fig. 3 ; Initial Mode, Communication Mode, Mission Mode, and Safe Mode. The power requirement at individual mode is different and calculated by considering average and maximum power consumption. In the case of initial mode, system power is supplied only by battery before the solar cell starts to generate power. Therefore it is required to charge the battery fully prior to launch. Table 1 shows the power requirement budget each modes.

Table 1. Power Requirement Each Mode (mW)

	Initial	Mission	Communication	Safe
Payload	0	400	10	10
ADCS	175	175	20	20
EPS	30	50	50	50
OBC	130	60	60	60
Communication	465	465	3,500	165
TCS	200	200	10	10
System Margin	100	150	70	70
Total	**1,100**	**1,500**	**3,720**	**385**

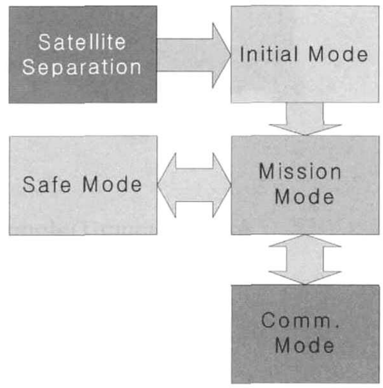


Fig. 3. Operation Modes

Spacecraft Bus Design

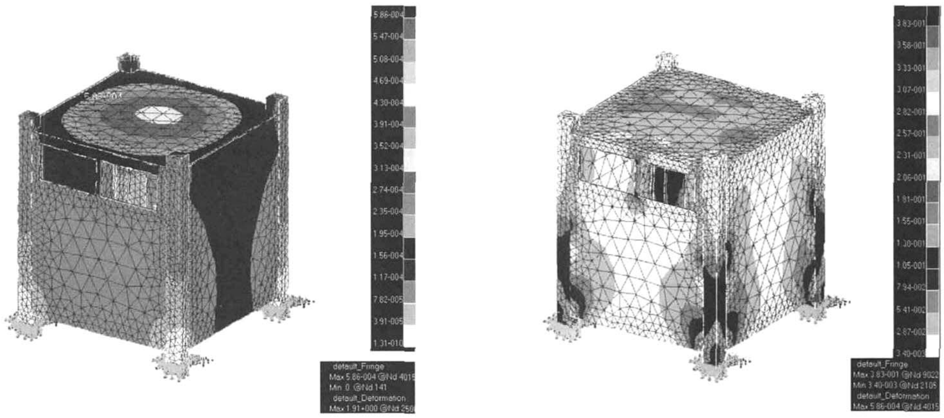
Structure Subsystem

The consideration of launch environment is an important factor in designing the satellite structure. It is stated in the Dnepr user's guide that "The spacecraft should be designed with a structural stiffness, which ensures that the values of fundamental frequency of the spacecraft, hard mounted at the separation plane, are not less than 20 Hz in the longitudinal axis and 10 Hz in the lateral axis." There are additional requirements suggested by "CUBESAT Design Specifications Document"; The CubeSat center of mass must be within 2cm of the geometric center. The CubeSat should not exceed 1 kg of mass and its dimension is 10 cubic centimeters.[2] Especially, the mass budget of structure subsystem is allocated to be 270 g as shown in Table 2. To assure proper sliding and release from the P-POD, all edges contacting rails must be rounded. CubeSats must have at least 75 %(85.125 cm) of flat rail contact with the deployer. Raw metal is not allowed as the contact surface of the bottom standoff to prevent cold-welding.[2] The use of Aluminum 7075 or 6061-T6 is suggested for the main structure.[5] To avoid jamming, internal P-POD walls cannot contact any part of the CubeSat. To maintain spacing and to prevent CubeSats from sticking together, a standoff contact or feet must exist at the ends of the rails. To assure the separation of CubeSats after release, a separation spring must be included at designated contact points.[2]

Table 2. Total Mass Allocation

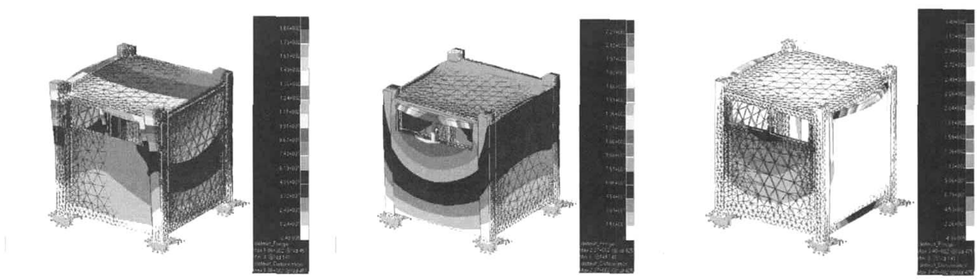
	Mass (g)
Payload	200
ADCS	60
EPS	145
OBC	70
Communication	140
TCS	30
Structure	270
System Margin	85
Total	**1,000**

0.5 g and 7.7 g are given as the dynamic and static load, respectively. These loads are generated by Dnepr launch vehicle. If the thermal expansion is not similar to the P-POD material (Aluminum 7075-T73) the satellite may be jammed



(a) Maximum Deformation (b) Maximum Stress

Fig. 4. Maximum Deformation and Stress



(a) Mode 1 (1859.8 Hz) (b) Mode 2 (2154.8 Hz) (c) Mode 3 (2801.1 Hz)

Fig. 5. HAUSAT-1 Mode Shapes

when it is released from P-POD due to deformation and change of shape by thermal effect. The material having similar thermal expansion should be selected as that of P-POD such as Al 7075 and Al 6061-T6.

The HAUSAT-1 satellite consists of four pillar, eight side-beams and six panels. Two holes which are required exist on the side-panel to provide test port like flight pin and communication port on the ground. It must not exceed $35mm \times 20mm$.[2] Fig. 4 and 5 are results of static load and modal analysis, which is performed by FEA (Finite Element Analysis). It was assumed that the factor of safety is 2 for maximum load, whose load is applied to only Z-direction. Fig. 4 (a) and (b) shows the maximum stress and deformation under static load condition, respectively. The maximum deformation($5.86 \times 10^{-4} mm$) occurs at the center of top and bottom plate, while the maximum stress($3.83 \times {}^{-1} MPa$) occurs at the lower end of vertical beam. Fig. 5 illustrates the three kinds of mode shapes of HAUSAT-1 by modal analysis.

The HAUSAT-1 requires deployment mechanism to deploy the thin film solar cell panel. A geared motor is being considered as a panel deployment mechanism.

Electrical Power Subsystem (EPS)

The HAUSAT-1 EPS is composed of solar panel, battery pack, power regulation and power distribution circuits. The power distribution is controlled by the on-board computer.

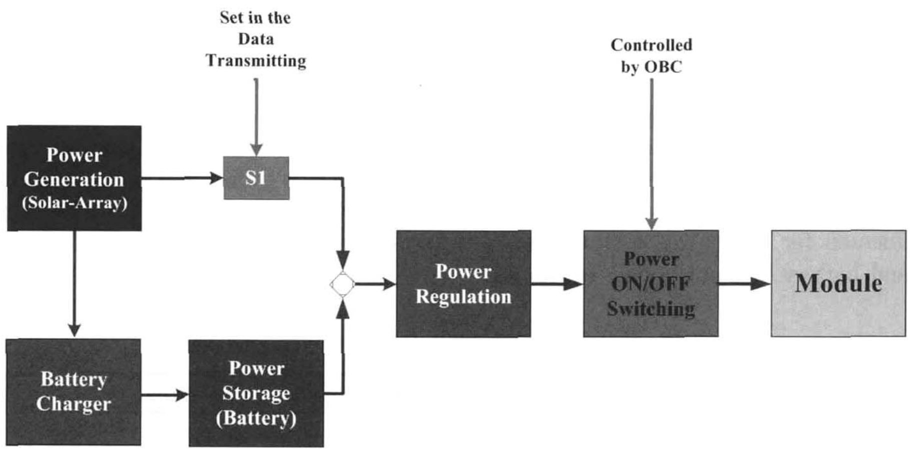


Fig. 6. EPS Flow Chart

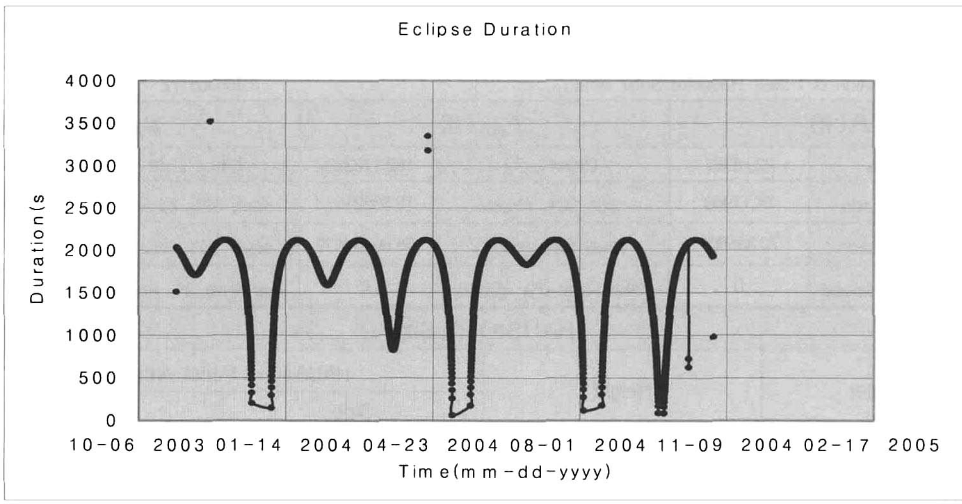


Fig. 7. Eclipse Duration at 650km Altitude and 65° Inclination Angle

Basically the power is generated by the body mounted-solar cell. Separated power regulation circuit converts primary bus voltage into suitable voltage demanded by each module. Fig. 6 illustrates the EPS flow diagram of the HAUSAT-1. All the power generated by solar cell is used to charge the battery packs except the communication mode, whose mode needs more power to transfer data. When the satellite is under the communication mode, the power generated by solar cell goes to each module directly without passing battery. Such method is implemented because of the low power (about 1.5W) generation capability with limited solar panel area.

Table 3 shows the power generated during one orbit cycle. The worst case eclipse time and sunlight time were assumed to calculate the power generated during the mission life. Fig. 7 represents the graph of eclipse time duration. Other conditions are shown in Table 3. The discontinuous dots illustrated in Fig. 7 represent eclipses by the moon. It is assumed that the solar cell efficiency at the end of life is 19%. The calculation results in Table 3 indicates that the power generated during one orbit cycle is insufficient to operate the HAUSAT-1. Since the HAUSAT-1 is small and light picosatellite, the solar cell having higher efficiency should be selected to generate the required power. The HAUSAT-1 will use triple-junction CIC(Cell Interconnect Cover) type cell, showing more than 19% of solar cell efficiency at EOL. Currently, we are in the process of selecting and sizing the solar cell. Since the battery should satisfy the bus voltage of 5V and have low mass, the cell should have high energy density and nominal voltage. The cell material selected will be either Li-ion or Li-polymer cell. Table 4 shows the calculation results of battery capacity required for the HAUSAT-1 operation.

The bus voltage of 5V is implemented for the HAUSAT-1 design. Either the home-made circuit or purchased IC will be selected for the battery charge circuit and bus voltage regulator design. Power distribution is controlled by OBC and the DET(Direct Energy Transfer) method will be implemented for the power architecture. The power will be directly transfered to subsystem module and battery without power tracking.

Table 3. HAUSAT-1 Power Generation Calculation

HAUSAT-1 Power Generation Calculation

Input Parameter

Required Power in Eclipse	Required Power in Daylight	Eclipse Time	Daylight Time	Eclipse Time Efficiency	Daylight Time Efficiency	Life Time	Cell Efficiency	Degradation	Sun Angle	Degradation Solar Array
1.5 W	1.5 W	0.5597 hr	1.043 hr	0.6264	0.72	1 yr	0.19	0.77	23.5 deg	0.9725

Calculation in Worst Case

Calculation of Power Required Solar Array	3.368355172

$P_0(W)$		$P_{BOL}(W)$		$P_{EOL}(W)$	
Direct Light	229.8387	Direct Light	162.1702337	Direct Light	157.7105522
Side 30% Albedo	24.11969	Side 30% Albedo	18.56621613	Side 30% Albedo	18.05564519
Nadir 90% Albedo	72.335907	Nadir 90% Albedo	55.69864839	Nadir 90% Albedo	54.15893555
Anti-Nadir 0% Albedo	0	Anti-Nadir 0% Albedo	0	Anti-Nadir 0% Albedo	0

HAUSAT-1 Size

Diameter	Height	HAUSAT-1 Panel Area (m^2)	
		Side	0.01
0.2	0.1	Nadir	0.01
		Anti-Nadir	0.01

HAUSAT-1 Total Cell Size

Number of Cell per Each Panel Area (0.0064 m^2)		Total Solar Cell Area (TSCA)	
Side	18	Two Sides Facing the Sun	0.009050967
Nadir	12	One Side Facing the Sun	0.0064
Anti-Nadir	30	Anti-Nadir Facing the Sun	0.004523681

HAUSAT-1 Total Power Generation by Cell

Power Generation Only Direct Light (Watt)		Power Generation as Only Albedo		Total Power Generation in HAUSAT-1 (Watt)		
Two Sides Facing the Sun Case	1.427432972	Side	0.462224517	Best Case	2.94975813	Two Sides+Anti-Nadir+Albedo
One Side Facing the Sun Case	1.009347534	Nadir	0.346668388	Normal Case	2.531672693	One Side+Anti-Nadir+Albedo
Anti-Nadir Facing the Sun Case	0.713432254	Anti-Nadir	0	Worst Case	1.818240439	Two Sides+Albedo
				Average	2.433223754	

Result of Analysis

Required Power (W)	3.368355172	Available Power (W)	2.433223754

Table 4. HAUSAT-1 Battery Capacity Calculation

Battery Capacity Calculation					
Input Parameter					
Required Power in Eclipse	Eclipse Time	DOD	Number of Battery Pack	Charging Efficiency	Bus Voltage
1.5 W	0.5597 hr	0.3	1	0.82 %	5 V
Power Calculation					
Battery Power	3.4128 Wh		Battery Capacity	284.4 mAh	
Analysis Result					
Cell Capacity	300 mAh		Cell C-rate	0.5	

Communication Subsystem and Ground Station

The requirement of frequency used for communication subsystem should be highly reliable, wide bandwidth and little traffic. It is so important to select frequency bandwidth due to the possibility of getting lost the satellite. By using HAM frequency, HAM can support to find out the position of satellite. It is hard to track the picosatellite on the ground station because of small size and the signal transferred with lower power compared to other satellites.

Communication subsystem of the HAUSAT-1 consists of transmitter, receiver, TNC (Terminal Control Node) including modem, and antenna. Since the communication equipment such as transmitter and receiver is expensive, the cost should be considered for the component selection. It should be also considered to rebuild, optimize and use the amateur band and HAM without interference from other HAMs in selecting the communications equipment. Since the HAUSAT-1 is so small and cannot generate high power from the solar cell, it definitely reveals the weakness point in the communication subsystem. The receiving power is weak on the ground station, on the contrary the transmitting power should be strong. The receiving traffic could be recovered by the transmitting power. The HAUSAT-1 will choose 145 MHz for uplink and 450 MHz for downlink, amateur J mode, whose frequency is HAM bandwidth. The ground station will be designed and established based on the configuration of AMSAT standard ground station.

Attitude Determination Control Subsystem (ADCS)

There exist various sensors used for satellite attitude determination control subsystem ; Sun sensor, Earth/Horizon sensor, Star sensor, Magnetometer and IMU(Inertial Measurement Unit ; Gyro & Accelerometer). The sensor has to point a desirable orientation to be properly utilized. The actuator is needed to control the satellite attitude and orientation by providing some torques. When the thin film solar cell panel and antenna are deployed, the vibration will be generated absolutely. ADCS should stabilize the vibration which can influence the satellite performance. The HAUSAT-1 satellite will require low accuracy about 5° to 7°. The mass and power allocated for ADCS are 60 g and 175 mW, respectively. The ADCS will take semi-autonomous judgment by installed sensors and command by ground station. Fig. 8 & 9 represent the ADCS block diagram and flow architecture.

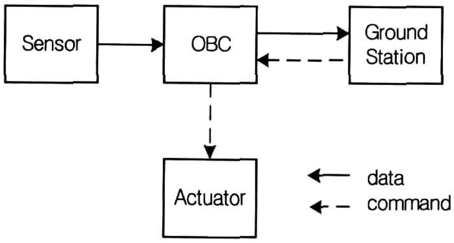


Fig. 8. ADCS Block Diagram

During the HAUSAT-1 trade-off study, the sun sensor, horizon sensor, magnetometer and gyro have been considered as a sensor candidate. However, the horizon sensor was discarded due to the limitation of mass 20 g and power 30 mW. There are also installation and narrow field of view problems. The HAUSAT-1 selects sun sensor and magnetometer because of light mass and low power requirement. The small and light sun sensor will be designed and manufactured by SSRL.

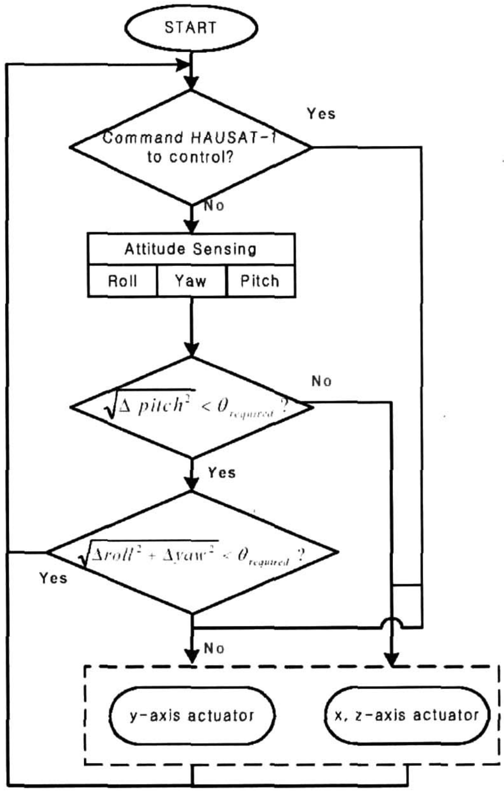


Fig. 9. ADCS Flow Architecture

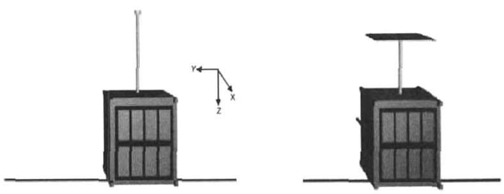


Fig. 10. Deployed Thin Film Solar Cell Panel and Gravity Gradient Boom

Table 5. Maximum and Total Disturbance Torque

Type of disturbance	Max. torque(N-m)
Magnetic field	2.11×10^{-10}
Gravity field	8.17×10^{-10}
Solar pressure	4.00×10^{-10}
Atmosphere	1.04×10^{-6}
Total disturbance	1.04×10^{-6}

Table 6. Magnetic Coil Specification

	Copper	Aluminum
Mass (g)	10	5
Number of turns	265	430
Diameter of coils (cm)	0.015	0.015
Area (cm^2)	6 × 6	6 × 6
Magnetic moment	0.022	0.022

On orbit, the external disturbances are caused by space environment; magnetic field, earth gravity, earth atmosphere, solar activity, etc. [6] Various disturbances can occur at the same time. These disturbances can be piled up one on another and counterbalanced. Table 5 indicates the maximum torque of disturbance. The capacity and size of actuator will be selected based on maximum torque and type of disturbance.

There exist two methods to stabilize the satellite; active and passive methods. The HAUSAT-1 implements 3-axis stabilization technique which is an active method. Magnetic coils are incorporated for 3-axis stabilization, and gravity gradient boom as a design baseline, since the HAUSAT-1 satellite doesn't require high accuracy of attitude control.[7] The thin film solar panel, which is one of the HAUSAT-1 payloads, will be operated as a gravity gradient boom as shown in Fig. 10.

The magnetic moment required is estimated to be $0.02A-m^2$ [8] to counterbalance the torque by disturbance. The magnetic torque generated is varied depending on the selected material of magnetic coil. Table 6 illustrates the magnetic coil specification for copper and aluminum materials. It is seen that aluminum can generate more torque per mass than copper. Aluminum magnetic coil will be selected for the HAUSAT-1 application. The direction of magnetic torque is ±x, y and z and controlled by the on-board computer.

The simulation study has been performed to investigate the effects of four disturbances(gravity, magnetic, atmosphere and solar radiation pressure effects) for the following cases; effects of x-axis vs. z-axis(Fig. 11) and attitude stabilization of the HAUSAT-1 by using magnetic coils (Fig 12). Fig. 11 shows some simulation results by comparing effects due to x-axis and z-axis rotation. The initial conditions of Fig.11 are assumed to be (a) $\phi=0^\circ$, $\psi=5^\circ$ and (b) $\phi=5^\circ$, $\psi=0^\circ$, respectively (ϕ : rotation angle about x-axis, ψ : rotation angle about z-axis). It is found that the effect by x-axis rotation is greater than that by z-axis.

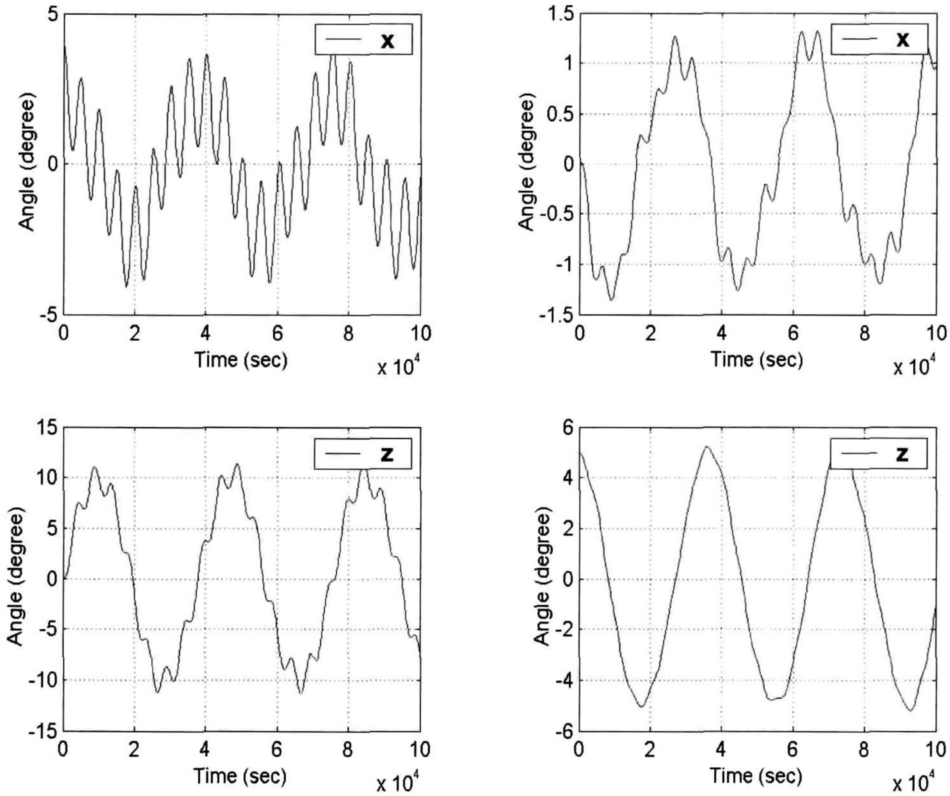


Fig. 11. Comparison of Effects due to X-axis and Z-axis Rotation

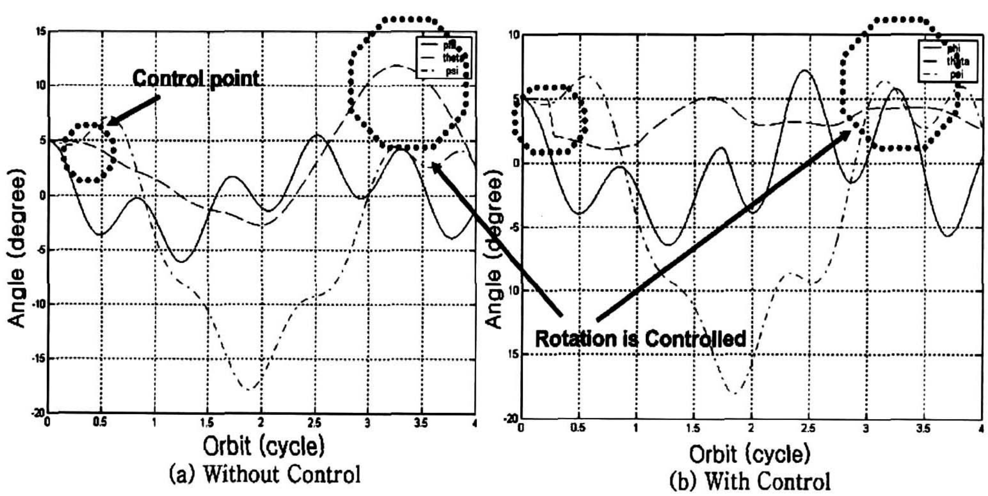


Fig. 12. Attitude Change of HAUSAT-1 Controlled by Using Magnetic Coil

Fig.12 indicates simulation results that the attitude of the HAUSAT-1 is controlled by using magnetic coils when the HAUSAT-1 is tumbled in orbit. Fig. 12 (a) shows the change of rotation angle of the HAUSAT-1 without control and Fig.12-(b) shows the change of rotation angle of the HAUSAT-1 with control which z-axis magnetic coil is operated when the HAUSAT-1 passes through the North Magnetic Pole.

In Fig.12 (b), the y-axis rotation angle of the HAUSAT-1 is maintained within 7° . The simulation results show that the rotation of pitch axis can be controlled by z-axis magnetic coil.

On-Board Computer Subsystem (OBC)

OBC is one of the important system because the OBC manages and controls the whole system of the HAUSAT-1. The OBC consists of a microcontroller, Analog to Digital converter, Digital to Analog converter, memory, and so on. In the HAUSAT-1, a microcontroller is chosen as core instead of a microprocessor. A microcontroller consumes less power and produces less heat than a microprocessor. The HAUSAT-1 doesn't require any fast compression and process for acquired data because the data will be just converted into digital signal, almost raw data, and then transferred to the ground station. The data processing will be accomplished on the ground station.

The microcontroller as core is to be fast enough to sample data for each sensor and payload. The microcontroller should have enough I/O ports, watchdog timer and serial interface. The factors, such as cost and simplicity, to use development tools and get a vast amount of information will be considered for a microcontroller selection and design. Currently Microchip's PIC controller and AVR 8bit RISC of Atmel is being considered. The flash memory will be implemented as system memories. A variety of memory exists; ROM, PROM, EEPROM, DRAM, SRAM, Flash, and so on. Flash Memory is selected as system memory due to non-volatile feature.

Space environment is also an important element to be considered in designing OBC. Special attention must be paid to the radiation environment. It can cause critical problems to induce mission failure. Total dose and single event phenomena can impact satellite mission life. The board level or part level shielding may be required for core and memory to keep mission life requirement. To protect the single event latch up, OBC will monitor current and voltage. If outbreak of current or voltage should be happened, the single event latch up circuit would detect this and then cut off power temporarily until the system recover from this event. Fig. 13 shows OBC Data Flow Diagram. Table 7 shows acquired data rate per second.

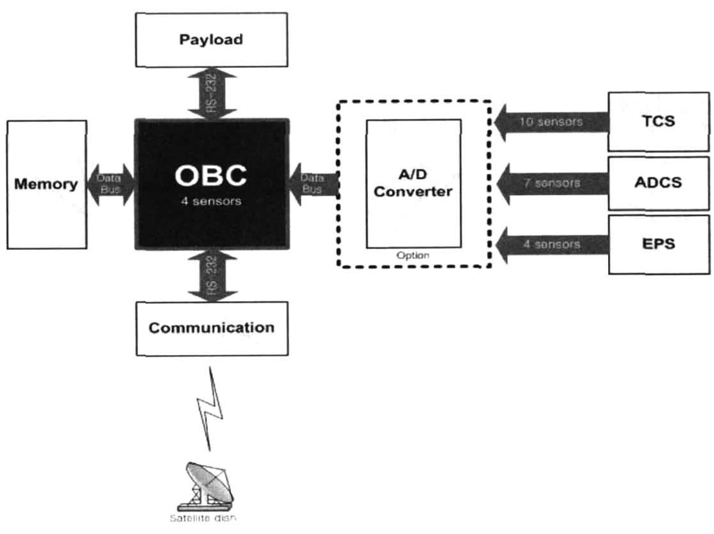


Fig. 13. OBC Data Flow Diagram

Table 7. Acquired Data Rate

Subsystem	Sensor Type	Quantity	Sampling Rate [Hz]	Word Size [bit]	Data Rate [bps]
EPS	Voltage	2	1/8th	8	2
	Current	2	1/8th	8	2
TCS	Thermal(Battery)	4	1	8	32
	Thermal(System)	6	1/4th	8	12
ADCS	Magnetometer	3	1	10	30
	Sun	6	1/4th	10	15
OBC	Voltage	2	1/4th	8	4
	Current	2	1/4th	8	4
PAYLOAD		1	1	10	10
				Total Data Rate (per sec)	**111**
				Daily Data Rate (bit)	**9590400**
				Daily Data Rate (kbit)	**9365.625**

Thermal Control Subsystem (TCS)

The purpose of the TCS is to maintain all satellite components within their specified temperature limits throughout all mission phases. There are some ways to protect satellite from harsher thermal environment; passive and active methods. Because of limited mass and power budget, the HAUSAT-1 must accomplish heat control, making the utmost use of passive method as internal heat conduction, surface finish and body mounted radiator well. If needed, active method will be used. Typical temperature ranges allowed for spacecraft components are given in Table 8. The basic equations of satellite thermal equilibrium can be expressed as

$$q_{Solar} + q_{Albedo} + q_{Earth} + q_{Int.Heat} - q_{Emitted} = 0 \qquad [9]$$

Based on this equation, steady state thermal analysis and transient analysis have been accomplished. In these analyses, the assumptions were that deep space temperature is 3K and the satellite structure material is Al-6061. As shown in Fig. 14 and 15, the maximum and minimum temperature during sunlight and eclipse are about $37\,^{\circ}C$ and $-60\,^{\circ}C$, respectively.

It is assumed that the solar flux illuminates on the right corner of the satellite, and the satellite bottom surface always orients toward the nadir. It is supposed to be difficult to operate the HAUSAT-1, in particular, the battery module without the additional thermal control. The heater is inevitable to protect the battery from cold temperature. Since the satellite temperature is varying depending on orbit cycle and has a latent heat, the temperature doesn't drop directly until steady state temperature. Fig. 16 shows the transient temperature analysis results with assumptions which initial temperature is 300 °K and specific heat of Al-6061 is $962\ J/Kg \cdot K$. The estimated satellite temperature has the range of $-21\,^{\circ}C$ to $20\,^{\circ}C$ and varies periodically according to sunlight time and eclipse time.

Table 8. Typical Temperature Range (℃)

Component	Operating Temperature Range	Survival Temperature Range
Battery	0 to 40	-15 to 50
Solar Cell	-100 to 30	-100 to 100
Kapton Heater	-200 to 200	-200 to 200
Electronics	-15 to 55	-40 to 80
GPS Antenna	-40 to 105	-40 to 105

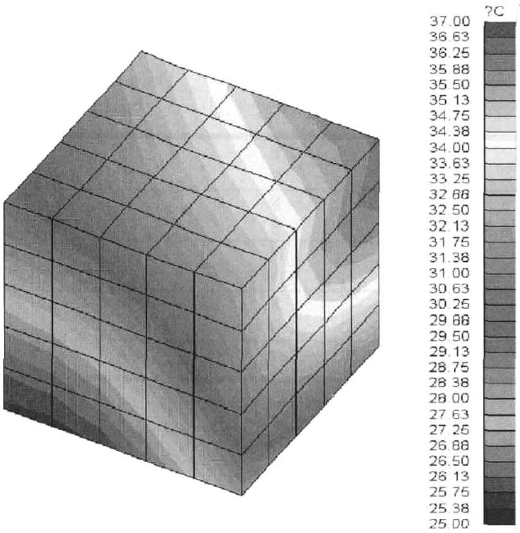


Fig. 14. Temperature Distribution During Sunlight

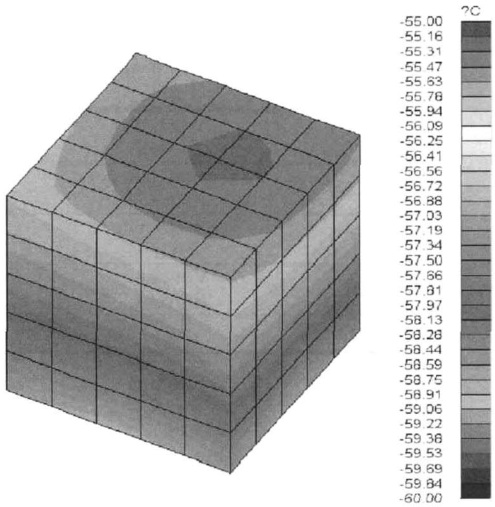


Fig. 15. Temperature Distribution During Eclipse

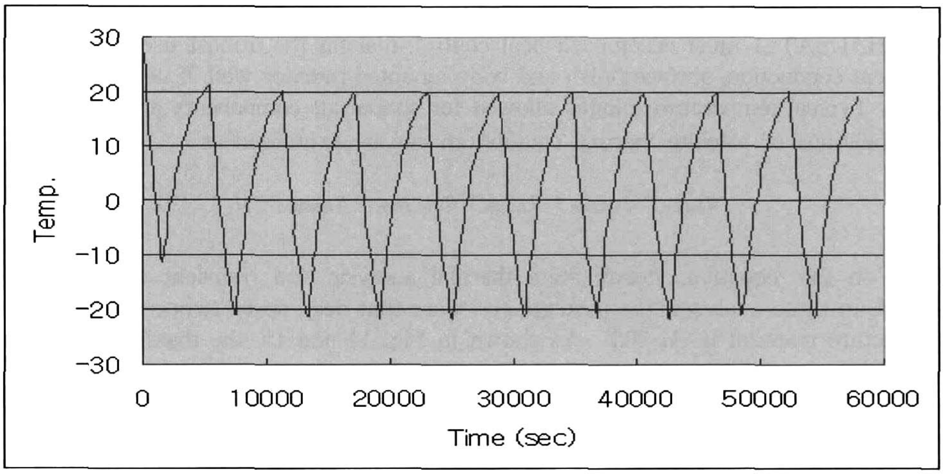


Fig. 16. Transient Analysis Result

By comparing these analysis results to the temperature requirements of the components in Table 8, it is found that some components like battery are not within the specified limits. Additional thermal control may be required for these components by using MLI, heater, thermal isolator to satisfy their temperature limits. It will be also necessary for these components to analyze more detailed models with a consideration of material properties and internal components. Uncertainties will be reduced through the updated assumptions as the design progresses. Based on these analysis data, we can choose proper surface coating material for the HAUSAT-1 and will help lay out the satellite components.

Conclusions

The purpose of the HAUSAT-1 project is to offer graduate and undergraduate students great opportunities to be able to understand the design process of satellite development as a team member. Its mission objectives are to track its position by the GPS receiver system, to deploy the thin film solar cell panel to generate extra power, and to measure plasma density and temperature with the plasma sensor. The HAUSAT-1 will orbit at the altitude of 650 km with 65 degree inclination angle. Its design mission life is estimated to be 12 months.

Several trade-off studies have been carried out during the conceptual design. The preliminary structure and thermal analyses at the system level have been completed. The power and attitude control simulation are being performed to select the optimal power and attitude control architecture for picosatellite. Additional trade-off studies are being continued to clarify the HAUSAT-1 satellite design. We will select an optimal architecture at the subsystem levels based on the simulation and analyses results. A detailed circuit design and parts selection will be also carried out at the module level.

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