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System Design and Control Aspect of a Novel Satellite Concept "Panel Extension Satellite (PETSAT)"

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A novel concept of satellite design, named "PETSAT," is proposed and its system design and control aspect is discussed in this paper. In this concept, a satellite is made of several "Functional Panels" such as "Communication panel," "Attitude control panel," "Thruster panel," and "Mission Panel," each of which has a special dedicated function. By connecting these panels by reliable connection mechanism in "plug-in" fashion, the total integrated system as a whole has a satellite function. The satellite is configured by multiple panels with hinges, which poses unique problems on system design, information management and dynamics and control, such as design of function distributions into panels, inter-/intra-panel communication systems architecture, moment of inertia management, flexibility, distributed control and so on. The paper will describe the basic concept of PETSAT, result of system design and subsystem development with focus on information management system and Attitude Control Panel. In-orbit demonstration plan which is now scheduled in 2008 – 2009 will also be given.

1. INTRODUCTION

A novel concept of satellite design, named "PETSAT," is proposed in this paper. In this concept, a satellite is made of several "Functional Panels" each of which has a special dedicated function (Nakasuka, et.al., 2004a,b). By connecting these panels by reliable connection mechanism in "plug-in" fashion, the total integrated system as a whole has a satellite function. Various combinations of different kinds of functional panels, sometimes in different quantity more than one, provide flexibility to deal with various mission requirements, even though the basic panels are the same for various missions. These panels are stowed during launch into a small volume (left figure in Fig.1), and are extended on orbit (right figure in Fig.1), realizing a satellite which requires a long boom part or a large area.

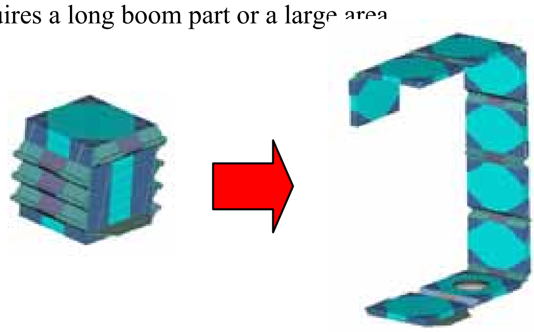

Fig.1 Concept of PETSAT before deployment (left) and after deployment (right)

PETSAT intends to change the satellite development cycle in the following way:

1) Each functional panel can be produced in mass quantity to reduce cost and improve reliability. And the produced panels are to be stocked.
2) When a certain mission is given, the satellite bus suitable for the mission requirements can be configured only by connecting the appropriate panels in appropriate quantity in "plug-in" fashion without much effort on ground test of the total system.

This "semi-customize" type satellite production process is expected to reduce required time and workload dramatically, resulting in a drastic reduction of the satellite cost and development time.

Mass production of the panels is the key to reduce cost and to improve reliability, but in the conventional satellite concept, mass production is difficult even in subsystem level due to the wide variety of the mission requirements. PETSAT tries to make this possible by modularizing the various basic subsystem functions into "Functional Panels," and by dealing with the variety of mission requirements with the quantity of the utilized panels of different functions.

The concept of PETSAT was initially proposed at the Satellite Design Contest in 2002, where the concept and design was awarded "the Best Design Award." Five year research project of PETSAT started in 2003, supported by NEDO subsidy, in collaboration of University of Tokyo, Osaka University and manufacturers' community of Higashi Osaka, and JAXA. In addition to the basic concept refinement and technology development, we are also examining commercial applications of PETSAT, one of which is lightning observation system described later.

In the following sections, first, some technical issues to be solved to realize PETSAT will be shown, followed by the results of study on system design. Then the developed subsystems are described in more detail, with emphasis on the information management and the attitude control system. Finally, in-orbit technology test and demonstration satellite named "SOHLA-2" will be briefly described, which is now planned to be launched in 2008 - 2009.

2. TECHNICAL ISSUES

2.1 Overall Technical Issues

The key technical issues to realize PETSAT include:
1) How to modularize the satellite bus functions into different panels: for example, whether battery and solar cells should be implemented in a separate functional panel such as "an electric panel" or should be equipped in every panel as standard components.
2) The standard panel structure which provides enough thermal and structural environment to different kinds of functional panels: for mass production and cost saving, a standard design should be applied to different functional panels.
3) Interface between panels: four kinds of interface, mechanical, electrical, information, and thermal interfaces should be carefully designed so that the plug-in simplicity of PETSAT can be achieved.

2.2 Requirements on Panel Interface

As to the interfaces, the following requirements should be satisfied.
(a) Mechanical Interface
Panel connection and deployment/latch mechanism, which is very reliable, fault tolerant, soft and with high accuracy is required. Also it is required that the panels can be easily plugged-in. The accuracy of the angles between panels after deployment should be a certain level so that the initially planned satellite shape can be achieved. Finally, in order to achieve various shape of the satellite (see Fig.2), the sequence of the panel deployment should be carefully designed because otherwise the deployment becomes stacked.

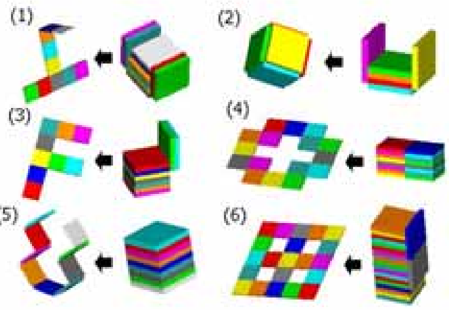

Fig.2 Various shape realizable by PETSAT

(b) Electric (power) Interface
In principle, the electric power required in each panel should be generated by solar cells of the same panel, but in many cases power should be transferred from one panel to another panel. PETSAT should have the capability to autonomously transfer power between panels. Reliability of power line is another important issue, which should be realized by carefully designed redundancy.

(c) Information Interface
Communication between panels is essential for PETSAT. The information line should be very reliable and should have enough communication capacity to deal with the flow of house keeping data as well as mission data. Each panel should have a certain level microprocessor for controlling this information traffic as well as managing the information flow inside the panel. So the total system becomes a multi-processor system and the architecture to manage such large number of CPUs should be carefully designed so that the strength of the distributed system such as fault tolerance or capability of grid-computing can be pursued as much as possible. The information line can be either wired bus line or RF line, but after careful considerations, wired bus line has been adopted. The detailed design will be given later.

(d) Thermal Interface
Thermal coupling within and between panels should be made very strong so that the temperature difference between each part of satellite should be as small as possible (Nakasuka, et.al. 2004a). the paper indicated that this is the best "general" strategy for thermal control because (1) the thermal environment is different from missions to missions, and (2) there are not many design freedom for PETSAT thermal control because the surface of the panel is almost covered by solar cells.

2.3 Distributing Functions into Panels

In PETSAT, some satellite functions may be implemented as "specialized components" in only a certain panel, and other functions may be implemented as "standard components" in all the types of panels. Therefore, one of the important system design issues is how to distribute various satellite functions into different type of panels.

To determine this, the following requirements coming from PETSAT features should be observed:

1) Interface simplicity: panels of different types can be plugged-in in any quantity while satisfying the requirements on the four type of interfaces as described before.
2) Functions enforced by increasing the number of panels: for example, the attitude control capability should be enforced by the number of ACS panels employed
3) Standard panel structure: the structures of different panels should be almost the same so that the mass production of the panel structure is possible.
4) Flat shape of the panels: in order to be deployable, the panels should be flat, which requires that, for example,

only one axis wheel can be implemented in one panel.

5) Fault tolerance and graceful degradation: the satellite functions can be maintained in degraded level even in case of failures of certain panels or interface component (such as information line, power line, hinge, etc).

After the examinations taking into account how several example missions can be achieved by PETSAT, the following distribution strategy has been found appropriate.

1) The variety of panels are as follows: ( ) shows the specialized components implemented in each panel

(a) Communication Panel (transmitter, receiver and antenna)
(b) Attitude Control Panel (one axis reaction or momentum wheel and three axis magnetic torquers, gyros, and sun sensors, realizing minimum three axis stabilizing capability in one panel.
(c) Thruster Panel (thruster, valve, pipe and propellant tank, Sahara, et.al. 2006)
(d) Mission Panel (different for different missions)

2) The following components are implemented as "standard components" to be implemented in all types of panels.

(e) solar cell, small battery and power management system
(f) microprocessor to play as C&DH system within the panel as well as manage inter-panel communication

3) As to the power, each panel's solar cell supplies solar power to the panel, and the residual power can be transported to any other panel automatically

4) As to the information management, many CPUs in different panels had better be efficiently utilized for realizing fault tolerance, graceful degradation, and for grid computing if a certain panel requires heavy information processing.

3. EXAMPLES OF PETSAT APPLICATIONS

3.1 Interferometric Positioning System

If a certain RF wave arrives at the antennae located with proper separation on PETSAT, then the difference of the arriving time or "phase difference" provide the information as to the relative direction of the RF signal source in respect to the PETSAT. If there are three antennae which are not located in one line, then the direction of the signal source in 3D space can be estimated. The accuracy of the direction estimation depends on the distance between the antennae (base line) and the knowledge about the relative positions of these antennae in respect to the satellite body frame. The long base line can be achieved in PETSAT by extension of several panels between the panels which implement these antennae (Fig.3) or by extending booms, and the relative positions of antennae can be estimated by calibrating this sensor system using the generated signal from a certain point of PETSAT. Figure 3 shows one example; interferometric observation of where lightning occurs. Lightning causes clusters of impulsive electro-magnetic waves in VHF (very high frequency) band, and by detecting the direction of VHF sources, which is equivalent to the lightning monitoring, we may be able to predict where lightning will possibly occur in near future (Mardiana et al., 2000, Morimoto et al., 2004).

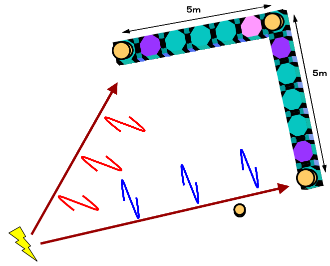

Fig.3. Lightning Observation PETSAT (Panel)

If we want to obtain the geo-location of the RF source on the Earth, then the PETSAT should know its attitude precisely. Several type of navigation sensors for attitude can be employed, including IRU (gyros), magnetometers, Earth sensor, sun sensor and star sensors. However this interferometric sensor itself can be also a precise navigation sensor, i.e., attitude can be estimated by obtaining with this interferometric antennae a RF signal generated by the ground station whose position is known. This calibration method is now under study.

4. INFORMATION NETWORK DESIGN

4.1 Requirement

Information network of PETSAT has been designed by considering the following factors.
(a)High reliability
(b)Usage of COTS hardware/software which is widely utilized with efficient development support tools and software library.
(c)Two layer (inter-panel and intra-panel) structure in nature.

4.2 System Overview

Taking these factors into consideration, Renesas's SH series microprocessor, CAN (Controller Area Network) bus system and I2C have been adopted as the back bone. Figure 4 shows the overall architecture of the information network and Fig.5 shows the information management system inside each panel.

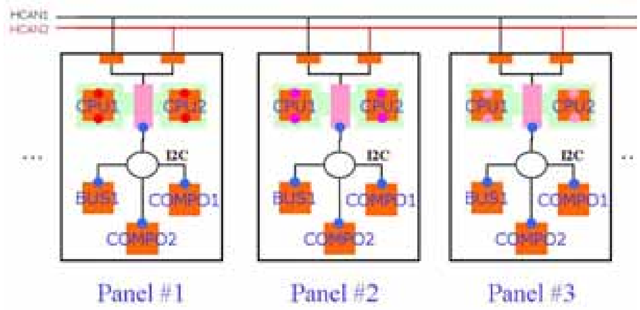

Fig.4 Overall Information Architecture

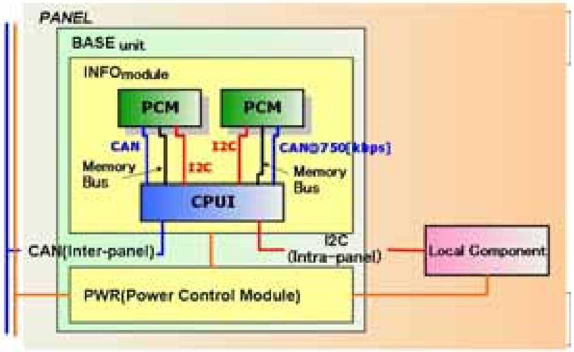

Fig.5 Inside-panel Information Management System

As the information bus, a two-layer hierarchical structure is adopted; CAN bus manages information flow between panels and I2C manages flow inside each panel. In each panel, "Base unit" manages the overall information flow and common functions, and "Local Component" manages the specialized functions such as attitude control, thruster control, communication (to/from the ground), etc. Local components usually have low power CPU such as H8 or H8S which have I2C controller inside.

Two CPUs named "Panel Control Modules (PCM)" manage the information inside the panel and information flow between panels. The outputs of these two PCMs are compared in CPUI (CPU Interface), which monitors health status of PCMs. When CPUI detects some discrepancy between the outputs, it reset both the PCMs. In addition to that, PCM has self-test functions, and when it detects its own anomaly, it resets itself. CPUI records the number of resets for two PCMs, and if the number of resets exceeds a certain threshold, this specific PCM will never be powered-on. CPUI is configured using a small scale FPGA.

4.3 CAN Bus System

CAN bus has been developed since 1980s and standardized in the 1990s, and is currently one of the standards in the automotive industry. Can bus has network layer model based on OSI (Open Systems Interconnection) reference model.

Typical features of CAN bus are as follows:
- Automatic error detection and message retransmission
- Multi-master layer has network architecture
- Transmission of all messages by broadcast method to improve the integrity of data

By introducing CAN, PETSAT can keep high reliability, redundancy, and easiness to realize inter-panel communication functions. Communication speed of CAN bus is now set as 650 kbps, considering "derating".

4.4 Semi-distributed network system

Network system is constructed with use of CAN that transmits all messages by broadcast method and has the function of automatic message retransmission. Each data is not transmitted from each panels in random order, but handled under less-restricted control to use core functions (communication, mission, power and so on) effectively.
A set of PCMs in a certain panel is assigned with "OBC" role, which manages the whole satellite, including sequencing the multiple missions, treating anomalous situations, and commanding attitude/orbit control requirements, etc. If some anomaly is found in the operation of this OBC, then the OBC function is taken over by the second prioritized PCM sets in different panel.

5. DESIGN OF ATTITUDE CONTROL SYSTEM

The attitude control function is implemented in Attitude Control Panel (ACS-P). The philosophy employed in the control systems' architecture for PETSAT is that:

1) One ACS-P has 3-axis coarse attitude estimation and control functions using sun sensor, gyros, magnetic sensor and magnetic torquers, so that implementing only one panel still can provide enough capability of 3 axis control, even though it is coarse.

2) One ACS-P has one axis momentum wheel so that one axis can hold angular momentum or have capability of precise control. Additional ACS-Ps will provide additional axes to be precisely controlled. "One wheel in one panel" is also suitable for a panel structure to accommodate a wheel which usually has a flat shape.

The 2nd philosophy comes from the basic PETSAT concept that the system performance can be tuned by changing the number of panels to be used.

Fig. 6 shows the overall control systems' architecture implemented in one ACS-P. The specifications of each sensor and actuator have been decided to provide 1-3 degree coarse attitude control capability. The magnetic torquers are also used for unloading the one axis wheel's momentum which may be accumulated because of external torque such as gravity gradient torque. Two-axis sun sensors have been developed in our laboratory and three of them are implemented in one panel to enhance observability.

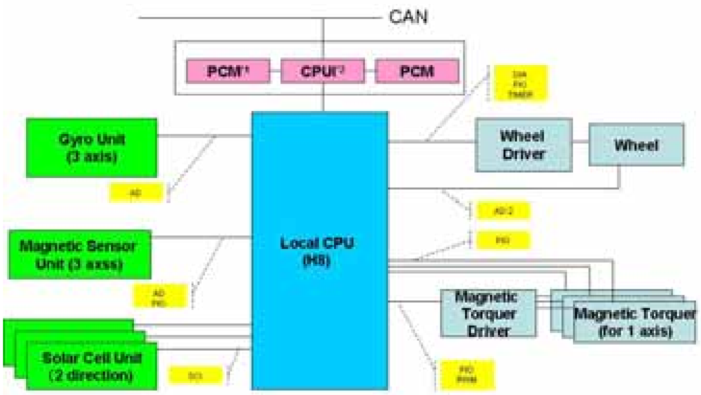

Fig.6 Control System in One ACS-P

Fig. 7 shows several components to be used for the control system. Magnetic torquers with 1ATm^2 magnetic momentum and a reaction wheel with maximum momentum capacity of 1.23Nms have been developed in-house. The control algorithm is now under development and the simulation results will be presented at the conference.

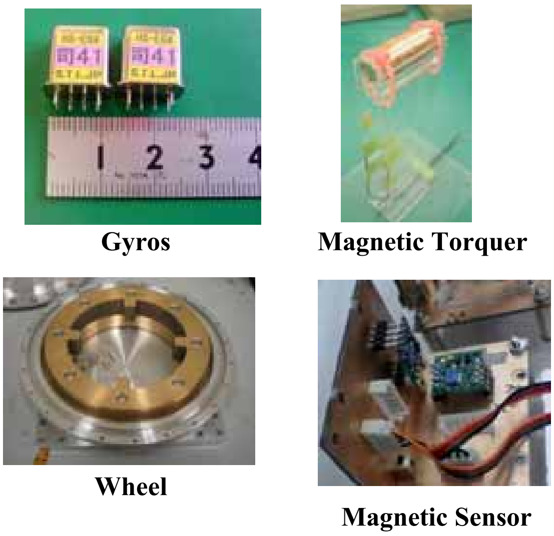

Fig.7 Components for Attitude Control System

6. SOHLA-2 IN-ORBIT DEMONSTRATION PLAN

6.1 Overall Configuration

The research to develop PETSAT technologies has been funded by NEDO, Japanese governmental organization, with an intension to complete SOHLA-2, the first experimental PETSAT, at the end of the 5-year project. Figure 8 shows the current planned configuration of SOHLA-2. It consists of five panels, a bus functional panel(BUS-P), a communication panel(COMM-P), an attitude control panel(ACS-P), a thruster panel(PROP-P) and a mission panel(MISN-P), its main objectives being the experiment and demonstration of the important technologies of PETSAT. In addition, as a scientific mission, lightning monitor experiment using VHF digital interferometer has been adopted.

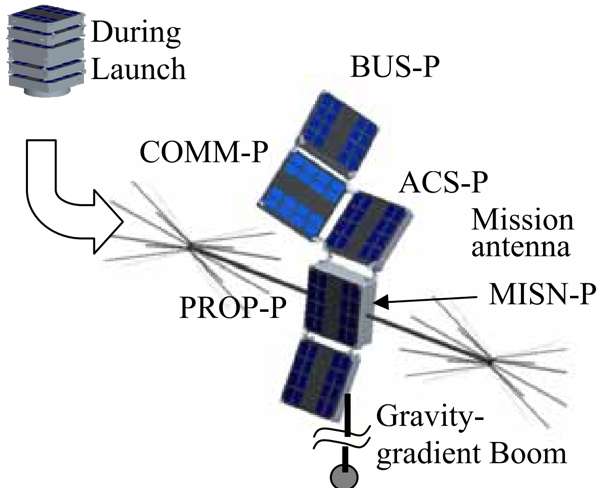

Fig.8 Planned configuration of SOHLA-2

Table1: Basic specifications of SOHLA-2

Items	Values	Comments
OVERALL		
Weight	< 50kg	
Size (stowed)	350x350x500 mm	
Size (deployed)	350x50x1400 mm	(Antenna length is 5m)
Size (one panel)	350x350x50 mm 350x350x100 mm	(four panels) (mission panel)
BUS FUNCTION PANEL (BUS-P)		
Configuration	Same system as CubeSat "XI"	Space proven for over 3 years
Communication	<u>Uplink:</u> (FM) 145MH 1200bps <u>Downlink</u>: (FM,CW) 437MHz 1200bps 437MHz CW	Amateur Frequency Band
LOCAL CPU	PIC16F877	
COMMUNICATION PANEL (COMM-P)		
Downlink (S-band)	0.1W 500 bps PCM-PM 2W 256 kbps BPSK	for H/K for mission
Uplink (S-band)	500 bps PCM-PM	
Antenna	Phased array patch ant. Monopole whip antenna	for BPSK for PSK-PM
ATTITUDE CONTROL PANEL (ACS-P)		
Sensors	Magnetometer 3-axis mechanical gyros 6 sun sensors	Accuracy is roughly 0.5°
Actuators	Magnetic Torquer Reaction Wheel (TBD)	
Local CPU	H8/3694F (Renesas)	
THRUSTER PANEL (PROP-P)		
Fuel	Ethanol (C_2H_5OH)	can be others
Oxidizer	H_2O_2 (stabilizer included)	middle-level concentration (<60%)
Thrust	500 mN / 1 N	For mono / bi-propellant
Total ΔV	50sec / 120sec	mono- / bi-
Local CPU	H8/3694F (Renesas)	
MISSION PANEL (MISN-P)		
A/D Channels	2 (for two antennae)	max 3 possible
Antenna	Conic-shape 2 antennae	Separation: 5m

Table 1 shows the basic specifications of SOHLA-2. The shape and configuration of the five panels is determined considering the gravity gradient torque, solar power generation (assuming operation in a sun-synchronous orbit), required attitude during the lightning observation, position and orientation of communication antennae (in COMM-P and BUS-P), thrust vector direction, and how they can be stowed before separation from the rocket, etc. The five panels are stacked during launch such as in the upper left figure in Fig.8 using a separation mechanism. The column type holders at the four corners will bend and release SOHLA-2 by cutting wires using pyro wire cutters. The length of these column holders can be changed to deal with various number of stacked panels. The planned operation sequence after the separation is as follows.

1) SOHLA-2 detects separation from the rocket, when BUS-P and the Base-unit of each panels is turned on.
2) Soon (such as 30 minutes) after the separation from the rocket, the timer triggers the panel deployment process; the panel connection hinges cut the launch rock wires and start deploying panels with spring forces.
3) BUS-P deploys its antenna and check-out of BUS-P is performed, whose results are sent to the ground using its own communication system.
4) The inter-panel communication between Base-units of each panel and BUS-P over CAN bus starts, whose results will be collected to the BUS-P and sent back to the ground using BUS-P communication system.
5) Mission antenna is deployed, and final configuration is achieved.
6) Each panel performs initial check-out, and based on the results and the amount of really generated power, the experiments of each panel are planned and performed one by one for about 10 weeks.
7) Lightning observation and data downlink experiment is performed using COMM-P's communication system.
8) After all the nominal experiments are completed, additional "advanced" experiments will be performed such as collaborative functioning of PROP-P and ACS-P, etc.

6.2 Bus Functional Panel（BUS-P）

BUS-P acts as "Bus system" for SOHLA-2, performing such tasks as sequencing the experiments, collecting H/K data from each panel and send to the ground, getting commands from the ground and send them to appropriate panels, and especially send back to the ground some data even if SOHLA-2 is in anomalous situation. The reliability and tolerance in space environment is essential, and therefore the bus system of University of Tokyo's CubeSat "XI-IV" and "XI-V" has been adopted with least modification. This very small bus has been surviving in space for more than four years (for XI-IV case) and almost two years (for XI-V case). BUS-P has its own battery and solar cells in addition to those inside the Base-unit common to all the panels, and even if the Base-unit does not function correctly, BUS-P can operate with the same functions as XI-IV and XI-V. Its communication system developed by Nishi-musen, also the same as one demonstrated in XI-IV and XI-V, operates as the primary communication system to/from the ground before the S-band communication link is established. BUS-P also manages the battery voltage of the whole SOHLA-2 and when the severe shortage of the power is detected, BUS-P makes the SOHLA-2 come into safe-mode, in which only BUS-P operates in low power consumption mode.

7. CONCLUSIONS

The concept of PETSAT will open a new way of satellite development, which is expected to reduce the time and cost required for integration and ground test. The unique satellite architecture poses unique problems on system design, information management as well as control system design. One example of such unique problem is that, if PETSAT has three ACS-Ps, then how these panels collaboratively control the satellite. The system design and development of control algorithm to make the most of these unique features as well as information management software is now at the final developmental stage, whose simulation and test results will be presented at the conference.

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