Design Concept for Autonomous Operation of KITSAT-3, an Experimental LEO Microsatellite

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Abstract—KITSAT-3 is a 3-axis stabilized technology demonstration satellite weighing 100 kg and was launched into the 720km altitude sun synchronous circular orbit by Indian PSLV rocket in May, 1999. As we have only one command groundstation, the contact time is limited and hence, satellite operation was required to be highly autonomous. KITSAT-3 is heavily dependent on a centralized on-board computer(OBC) for its autonomous in-orbit operation. Autonomous operation of KITSAT-3 is implemented in the normal mode housekeeping and the safe mode operation. Battery charge control, operation mode based attitude control, scenario based payload operation and flexible on-board software management are the techniques used for the normal mode operation. For the safe mode operation, two levels of power safe mode control, OBC back-up mode and attitude safe mode control are used. Initial in-orbit operation was successful and the autonomous operation has been achieved by the implemented design concepts.

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1. INTRODUCTION

KITSAT-3 is a technology demonstration microsatellite launched by Indian PSLV rocket in May, 1999. Its primary objective is to provide an opportunity to elaborate various technologies for high performance microsatellite and to qualify them in the space environment. In addition, it has payloads for the remote sensing and space science. The satellite was designed in a *"Faster, Better, Cheaper"* approach.

KITSAT-3 is a newly designed 3-axis stabilized microsatellite and as its solar panel is installed at one side (**Figure 1**), there was a requirement to point the panel toward the sun in any condition. As a low earth orbit (LEO) satellite with single groundstation located in South Korea, the ground contact time is limited as short as 5 minutes in a normal pass. To minimize communication traffic between the spacecraft and the groundstaion, much of the housekeeping were required to be carried out autonomously on board. For other requirements for the mission safety, such as heater control of CCD camera and charge control of battery, on-board software was implemented which monitors and controls the hardware.

To meet the requirements listed above, the autonomy was implemented mainly in the OBC and they were implemented in the normal mode and safe mode operation.

The autonomy design of the OBC included :

Normal mode operation
- Operation mode based attitude control
- Scenario based payload operation
- Flexible OBC software management
- Battery Charge Control
- CCD Camera heater control

Safe mode operation
- Power safe mode
- OBC back-up mode
- Attitude control safe mode

This paper focuses on the autonomy aspects of the OBC software of KITSAT-3. In section 2, KITSAT-3 system is explained. In section 3 and 4, each autonomy method is described. Some of the initial operation results are shown in section 5 and we conclude in section 6.

2. DESCRIPTION OF KITSAT-3 SYSTEM

From the successful development and operation of two micro-satellites, KITSAT-1 and KITSAT-2, Satellite Technology Research Center(SaTReC) has acquired technologies for small satellite. Based on the experience, KITSAT-3 was designed to demonstrate advanced concepts and technologies.

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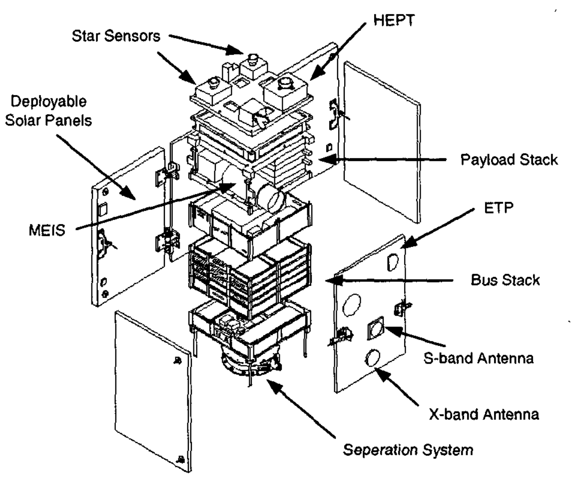

Figure 1. Exploded View of KITSAT-3

New technological features of KITSAT-3 are summarized as follows.

- Common bus architecture
- Deployable solar panel
- Three-axis stabilized attitude control subsystem
- High speed data transmission system
- Solid state mass memory

Common bus architecture with Deployable Solar Panel

Mechanically, KITSAT-3 has a modular structure composed of external and solar panels, launcher separation system, bus stack, payload stack, and sensor platform as shown in **Figure 1**. The command and data handling system was designed based on modular concept to have common bus architecture by employing a number of identical MTC(modular telemetry and command) modules. Each MTC module has the capability to handle telecommands, telemetry, and sub-system data communication either alone or jointly with other MTC modules. Therefore, the functionality of a microsatellite such as KITSAT-3 can be readily expanded by adding more MTC modules. This common bus architecture of KITSAT-3 is cost-effective and suitable for micro-satellites. KITSAT-3 has three identical solar panels made of GaAs cells, one of which body-fixed and others deployable. Accelerometers are attached to monitor its shock and release mechanism.

3-Axis Stabilized Attitude Control Subsystem

The attitude control system performs the attitude maneuvering and stabilization of KITSAT-3 to generate sufficient power from solar panels, to point antennas for communication with the ground station, and to keep the temperature inside and outside of the bus within specified limits. It also supports the operation of mission payloads. MEIS(multi-spectral earth imaging system) imposes the most stringent requirements on the control system. On the planned KITSAT-3 altitude of 720 km, MEIS gives the geometric instantaneous field-of-view (FOV) of 13.8 m at nadir and the swath width of 46.5 km. It requires the pointing accuracy better than 0.5 degree to cover more than 86 % of the target area and the stability better than 0.016 degree/sec to keep the bus within 3 % of the instantaneous FOV during imaging. The attitude control system consists of various sensors and actuators as shown in **Figure** 2. The attitude control system uses the sun sensor and two flux-gate type magnetometers as its fundamental sensors for coarse control. The star sensor and the infrared earth horizon sensor were developed as engineering test sensors and they are used for fine attitude control together with fiber optic gyros.

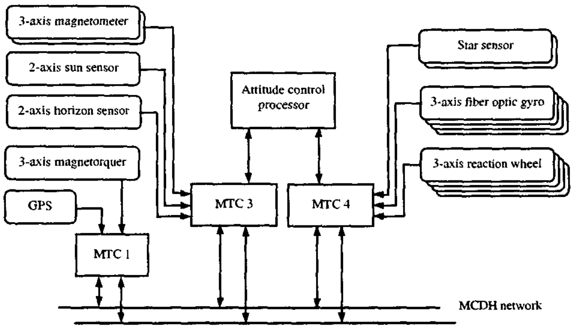

Figure 2. Block Diagram of Attitude Control Subsystem

The horizon sensor employs pyro electric devices and the mechanical chopping is used instead of cooling. The star sensor was designed based on wide FOV imaging systems flown on KITSAT-1 and 2.

The combination of three-axis reaction wheels and fiber optic gyros are used for large angular maneuvering and stabilization in high-speed. The magnetorquer is used for the momentum dumping of reaction wheels. In addition, the attitude control system incorporates an accelerometer and a GPS navigator.

Communication Subsystem

The communication system consists of telemetry transmitters, command receivers, and the image data transmitter (IDTX). For telemetry transmission to the ground station, UHF transmitters are used. The communication subsystem also incorporates two S-band transmitters for downlink to ensure the acquisition and tracking of the S or X band signal for payload data transmission. One of them gives 38.4 kbps with FSK and the other does 9.6 kbps with FSK. For command reception from the ground station, two VHF receivers are used (9.6 kbps/FSK and 1.2 kbps/AFSK). The data communication system has four mono-pole antennas for the UHF transmitter, a microstrip patch antenna for S-band transmitters, and a mono-pole antenna for VHF receivers. The ground contact during the initial commissioning phase of KITSAT-3 is accomplished with the UHF transmitter, which is also used in attitude control anomaly and sun tracking. Once the platform is stabilized, S-band transmitters are used.

IDTX is a part of the image data transmission system that was developed to manipulate and store high-speed image data streams produced by MEIS and to transmit them to the ground station at high-speed. IDT consists of two X-band transmitters (8.0 ~ 8.4 GHz) for redundancy, each of which uses the QPSK modulation and gives the data transmission rate of 3.2 Mbps. The input I and Q data to their QPSK modulators are provided by camera payload for the direct transmission of image data to the ground station.

There are two payloads on-board KITSAT-3. They are the MEIS and the space environment scientific experiment (SENSE) package.

Multi-spectral Earth Imaging System(MEIS)

The MEIS consists of a catadioptic telescope, prism blocks, focal plane assembly, video signal processing electronics, controller, and solid-state mass memory units. It was developed to test various technologies required to build a sophisticated high-resolution optical camera for remote sensing. The electro-optical camera of MEIS is a pushbroom camera that produces images of the earth's surface in three spectral bands. It was developed in collaboration with the University of Stellenbosch in the Republic of South Africa. Its main characteristics are summarized as follows.

- weight : 6.5 kg (3 kg for telescope)
- power : 15 W
- detector : three linear CCDs with 3456 pixels
- IFOV : 19.1 μrad
- FOV : 3.8 degrees
- spectral bands : 520-620, 620-690, 730-900 nm
- effective focal length : 570 mm
- F number : 5.7
- MTF : 20 % at Nyquist frequency

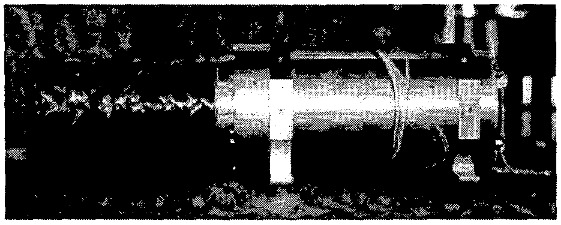

Figure 3. Photograph of MEIS Telescope

Figure 3 is the photograph of the MEIS.
To protect the telescope against large temperature variations, electrical heaters are employed. The camera electronics system includes gain control, clock speed control, and black reference adjustment units along with other CCD signal processing units. The gain control unit provides eight levels of video gain with temperature compensation. With the clock speed control unit, the CCD readout speed can be tailored to accommodate altitude variation.

Space Environment Scientific Experiment

The space environment scientific experiment (SENSE) package was developed with various scientific objectives. It consists of following four sub-systems.

- high-energy particle telescope (HEPT)
- radiation effects on micro-electronics (REME)
- scientific magnetometer (SMAG)
- electron temperature probe (ETP).

Unlike the radiation detector on KITSAT-1 that measured only indirect particle energies, HEPT measures the particle energy entering the telescope and has the capability to identify the particle species. Four silicon sensors are used along with blocking materials of aluminum and copper, which are used to control the particle energy reaching each sensor. It can also measure the pitch angle distribution of particle energies by spinning KITSAT-3 along its pitch axis. The pitch angle distribution is calculated with the accuracy of about 1 degree using the sensor look-angle and the magnetic field direction provided by SMAG.

REME consists of TDE(total dose experiment) monitor and SEU(single event upset) monitor units. The TDE monitor measures the long-term accumulated ionizing radiation dose in SiO_2 for three locations in the KITSAT-3 bus. Sensing elements are RADFET dosimeters. With the SEU monitor, a series of testing will be performed to measure the SEU characteristics within memory devices. Components under testing are connected to measurement electronic circuits and the variation of their characteristics will be measured together with TDE.

SMAG measures the magnetic field based on the flux-gate principle and is used as a diagnostic tool of global and local geomagnetic disturbance and current systems, of low-frequency waves in the ambient environment, and of the wave-particle interaction. It provides the information on the magnetic field direction for HEPT and plasma gyro-frequencies. It is also used as a secondary source of attitude determination. ETP measures the electron temperature in high latitude regions. It was developed in order to study the anomalous heating phenomenon found in the South Atlantic Anomaly and to find any relationships with other plasma parameters such as energetic particles and plasma waves.

3. NORMAL MODE OPERATION

Autonomy during the normal mode operation was designed to complement the short ground contact time. The idea behind is to maximize on-board automation with minimum ground communication. This ground control will overrule the on-board autonomy. Major operations during the normal mode are attitude control, battery charge control and CCD camera heater control.

Operation Mode Based Attitude Control

The KITSAT-3 attitude control modes are complicated. KITSAT-3 achieves an attitude by tilting the spacecraft body. To generate enough power for the spacecraft operation, it should point the spacecraft toward the sun during the sunlight period. For the thermal control purpose, it might have to tilt the spacecraft from the sun with some angle. When the satellite takes a picture of the earth, it should of course target the spacecraft toward some specific direction. To transmit the image data, transmitters must point towards the groundstation antenna.
Figure 4 shows the attitude control mode of KITSAT-3.

After separation from the launcher, the on-board computer will randomly spin up the spacecraft using magnetorquers(A1.1). Once the ground contact has been made, OBC runs the detumbling algorithm to reduce the tumbling rate in every axis(A2.1). When the tumbling rate slows down, ground control sends commands to stop the tumbling motion of the spacecraft using wheels(A3.1). After the attitude capture, attitude mode can be switched to *sun tracking mode, imaging mode, automatic ground targeting mode, thermal/power control mode* and *earth pointing mode.*In **Figure 4**, all the upward attitude mode change occurs by ground command and the downward attitude mode change, which is a safe mode fall back, occurs automatically. All the control modes were implemented in the on-board computer and the mode change can be achieved as simple as sending a command byte instead of transmitting complicated parameters. This was made possible by the reliable ground-proven attitude determination and control subsystem(ADCS) software on-board. In this way, the amount of communication between groundstation has been greatly reduced. The attitude safe mode operation is explained in the section 5.

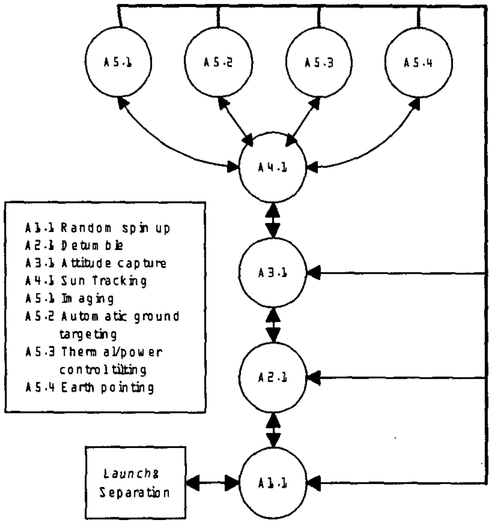

Figure 4. Attitude Control Modes

Scenario Based Payload Control

A scenario file was defined for the scheduled operation of the payloads. A scenario file consists of command block numbers and parameters. A command block consists of micro commands. Those command blocks are listed with time information. The on-board action scheduler checks all the time tagged action items and executes according to the schedule. The scenario file is prepared by the payload operator. The file is then compiled to create a binary command file to be transmitted to spacecraft. This file contains scenario information in packed binary format. Once the OBC receives scenario files, the ground controller can edit, delete and update the scenario.

The command blocks can be edited and newly defined. This feature gives extra flexibility to the simple payload operation.

Flexible OBC Software Management

In our previous two microsatellites, we have only a simple bootstrap loader in the OBC ROM. This was because the OBC software was not ready by the time and it caused us to upload large amount of run time codes for the normal mode operation. For the low earth orbit(LEO) satellites which has short ground contact time, it is very costly and even dangerous if the minimal codes on-board could not secure the spacecraft.

Hence, in KITSAT-3 we had all the operational software burned in the *on-board program storage(OBPS)* EPROM. When OBC is turned on after separation from the launcher, it reads codes from the OBPS and copies codes into the on-board task storage area(OBTSA). Then OBC executes all the system tasks and by doing that, spacecraft can secure its minimum survival including power control and thermal control. During the normal mode, OBC software can be selectively updated by uploading new codes into OBC *file system* or directly to the OBTSA. Those uploaded software codes are registered into the OBTSA. The OBC loader maintains OBPS and OBTSA and any software codes can be run with simple ground user interface.

If the OBC got reset for some unknown reason, it has the OBTSA intact unless its power turned off. In this way, we have implemented a programmable ROM capability in the program RAM area. With this feature, we could remarkably reduce the OBC recovery time after software crash. **Figure 5** shows the OBC software code management hierarchy.

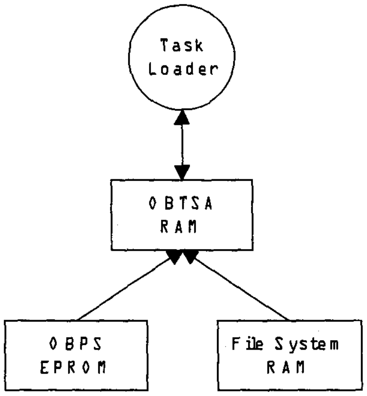

Figure 5. OBC Software Code Management

Battery Charge Control

A battery charge control software was implemented as a back up for the hard wired charge control circuitry. The charge control circuit controls the output power from the solar panels to generate peak power during sun light period. While the hardware circuit controls in voltage mode, the software implementation controls the output current from the panels. The hardware control circuit is simple and works well during normal operation. However, as it controls only the output voltage, there is a danger of not controlling the battery charge current which may rise up to 2A. High rate overcharge of NiCd battery may cause serious damage. The software task can set maximum and minimum output current band. The OBC monitors the solar panel status and output currents and sets the output duty of the FET switch in the hardware control circuit.

CCD Camera Heater Control

The MEIS components are sensitive to the thermal unbalance which may result in the crack or distortion of the optomechanical system. There are two heaters for the thermal control. A 12W low power heater is used for the temperature increase of 0.4°C/min. A 18W high power heater is used for faster control. OBC housekeeping task monitors the CCD temperature every minute and turns on the low power heater when the temperature goes down under 0°C. Heater will be turned on and off every 10 seconds to reduce thermal shock to the system.

4. SAFE MODE OPERATION

Safing on KITSAT-3 is defined as the situation when spacecraft can continue its normal operation with reduced functionality on the occurrence of event. *Safehold* is defined as the situation when spacecraft cannot continue its normal operation and have to reconfigure the spacecraft into minimum survival mode. **Table 1** shows the safe mode definitions.

Power Safe Mode

Two level power safe mode was implemented with the OBC software and power subsystem hardware. OBC housekeeping task monitors battery pack voltage and if the value is lower than the preset threshold, then it stops scenario operation and turn off all the payloads. In this level 1 power safehold, bus subsystems have power supplied and OBC can control attitude with on-board storage intact. In the level 1 power safehold, attitude control task will change to sun tracking (A4.1 in **Figure 4**) mode.

In the event the attitude control fails, the battery will be discharged more and reach its power shutdown voltage threshold of approximately 20 volts. This will shut off all the power supply to the subsystems. The spacecraft will recover from this level 2 power safehold when the battery voltage reaches the threshold level.

Attitude Control Safe Mode

Attitude control in KITSAT-3 is a crucial operation as without attitude control, the spacecraft will die within 24 hours with battery discharge. It is critical in thermal and power control aspects. Attitude control task in OBC maintains spacecraft safety even when failure occurs in the attitude control subsystem. Reaction wheels, gyroscope, and magnetorquers are the critical equipments to control the spacecraft. If any of those attituce control items experiences a failure the spacecraft mission could be in danger. Hence, those equipments have redundancy. If any of the equipment has unavoidable failure, the attitude control mode falls back from normal mode into random spin up mode(A1.1 in **Figure 4**). While keeping spacecraft in this mode, ground operators should fix the problem and move upward into normal mode.

OBC Back-up Mode

The OBC is located at the center of the KITSAT-3 autonomy. The OBC has full function redundancy and uses an Intel 80960 as its CPU while OBC2 uses and Intel 80C186. OBC2 was intended to be used as hot standby. While OBC1 is running, OBC1 sends life sign continuously to OBC2 over the on-board data handling network. OBC2 listens to the OBC1's message and if the message stops for some period, it takes over the whole control of spacecraft. When an OBC1 failure is detected, the OBC2 runs a very simple algorithm to stabilize the spacecraft. If the failure was a temporary one and was recoverable, OBC1 should take the control back from OBC2 by the ground commanding. If the failure can not be fixed, then OBC2 will be used as the primary computer with reduced performance. This method is expected to reduce the recovery time of the spacecraft attitude after an OBC failure occurs. Instead of

Table 1. Safe Mode Definition

Safing Monitor	Class	Implementation	Action
Battery undervoltage	Safehold	Hardware	Spacecraft shutdown
Low battery state of charge	Safing	Software	OBC1 S/W only monitors and GS shows warning signal
Failures of ADCS sensors or actuators	Safing or Safehold	Software	ADCS task control mode fall back Random spin up in major failure
Operation Fault	Safing	Software	exceptional event handler
System Watchdog	Safing	H/W and S/W	watchdog timer
Power system operation	Safing	H/W	Reconfigure power system
Switched load overcurrent	Safing	H/W	Disconnect load
Transmitter on-time exceeds threshold	Safing	S/W	Automatic transmitter on/off control
Low Battery voltage	Safing	S/W	Non-essential load disconnect
Camera low temperature	Safing	S/W	Heater on
No life sign from OBC1	Safehold	S/W	OBC2 take over

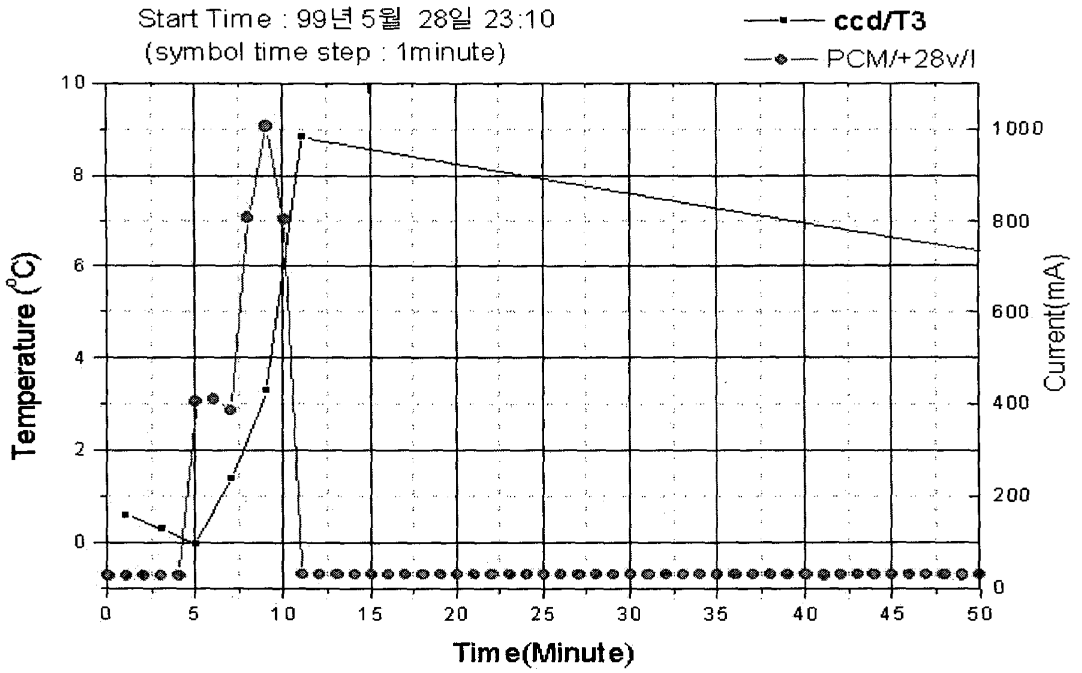

Figure 6. Initial operation result : CCD heater control

implementing a complicated multicomputer network protocol, we made it as simple as possible.

5. INITIAL OPERATION RESULTS

During the initial operation period, all the autonomous operation concepts have been proven to be successful. Normal mode operation autonomy greatly reduced the communication load between satellite and groundstation. Power safe mode and power safehold mode have been experienced during the initial operation due to a communication error and accidental high current discharge. The safe mode and safehold operation mode designed has been working well. **Figure 6** shows the CCD heater operation result. At 5 minute from the measurement, CCD temperature value was recorded to be under 0°C and the heater was turned on. CCD temperature reached 5°C, 5 minutes after heater on. With all the autonomy features, KITSAT-3 is producing high quality multi spectral images from MEIS such as shown in **Figure 7**.

Figure 7. MEIS Image of San Francisco airport

Autonomy design of the spacecraft is crucial for its mission safety. Specially autonomy design plays a more important role for small low cost missions. Normal mode and safe mode autonomy methods were devised for KITSAT-3. Those implementations have shown excellent performance in the initial operation of KITSAT-3. Autonomy for the spacecraft should not be complex. Instead of implementing complicated methods, various simple but reliable ideas were used and these various ways of autonomy would increase mission lifetime.

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