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X-SAT MISSION PROGRESS

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ABSTRACT

X-Sat is a micro-satellite project with the objective to design, build, test and operate Singapore's first domestic satellite. The mission's main aim is to provide imaging capability for earth observation and environmental monitoring over Singapore and the South East Asian region with daily coverage and downlink of the acquired imagery within the same orbit. Secondary objectives are satellite-based advanced data acquisition and messaging over the Indian and Pacific Ocean as well as high performance fault tolerant on-board data processing using commercial off-the-shelf components. This flagship project of the Centre for Research in Satellite Technology was started officially in 2002 and seeks to foster national and international collaborations among various educational, research and commercial partners. At the time of publication the development and testing of the engineering model is almost completed, while the piggyback launch is scheduled for 2007.

1. INTRODUCTION

The X-Sat mission is a technology capability demonstration project with multi-mission support capability undertaken by the Centre for Research in Satellite Technology (CREST) as collaboration between the Nanyang Technological University (NTU) and the DSO National Laboratories. The three-axis stabilised micro-satellite carries three payloads [1]. The opto-electronic push-broom camera IRIS provides a 10 m ground sampling resolution in the visible and near-infrared wavelength range and has been contracted to be built by SaTReC*i* from South Korea. The secondary payload is the Advanced Data Acquisition and Messaging (ADAM), a communication system adapted from the original ADAM payload designed by the Institute of Telecommunication Research (ITR) of the University of South Australia and DSpace for FedSat, Australia's first micro-satellite mission [2]. The third payload, named the Parallel Processing Unit (PPU) is designed and developed by CREST for the demonstration of on-board data processing, such as real-time image compression and image analysis [3], [4].

X-Sat is designed for a three year lifetime to fly on a sun-synchronous orbit at a nominal altitude of 685 km whereby the mean local equatorial crossing time is 10:30 am. The orbit inclination of 98.13° with an orbit period of 98.58 min results in a repeat cycle of 409 orbits within 28 days. To achieve this objective the PSLV-C2 rocket from the Indian Space Research Organisation (ISRO) was selected as launch vehicle for early 2007. The actual control and operation of X-Sat will be performed from NTU's

ground station while the Centre for Remote Imaging, Sensing & Processing (CRISP) from the National University of Singapore will handle the image downlink [5].

2. BUS ARCHITECTURE

X-Sat is a low earth orbit micro-satellite with a mass of approximately 100 kg and the dimension of $600 \times 600 \times 850$ mm^3 according to the envelope constraints for the piggy-back launch. For the structure a hybrid concept was utilised to achieve high stiffness and maintain a low structural mass budget. The envelope is made from honeycomb panels mounted on a solid aluminium base-plate, which has eight ribs to increase the stiffness and to serve as a heat sink [6]. A central column of 16 module trays with four go-through bolts for housing the subsystems provides the backbone of the bus and the foundation for a central deck that is firmly connected to the envelope side panels. The optical instruments (camera and star tracker) are mounted both on this central deck to allow perfect pre-flight alignment. A finite element analysis of this configuration showed that the first lateral and longitudinal frequencies are 158 Hz and 253 Hz, respectively. In particular, the stress level of the honeycomb panels and random vibration response of the IRIS camera are relatively low. A schematic representation of the in-flight configuration with the two deployed solar panels is shown in Figure 1(a) while Figure 1(b) depicts the internal configuration with its tray structure.
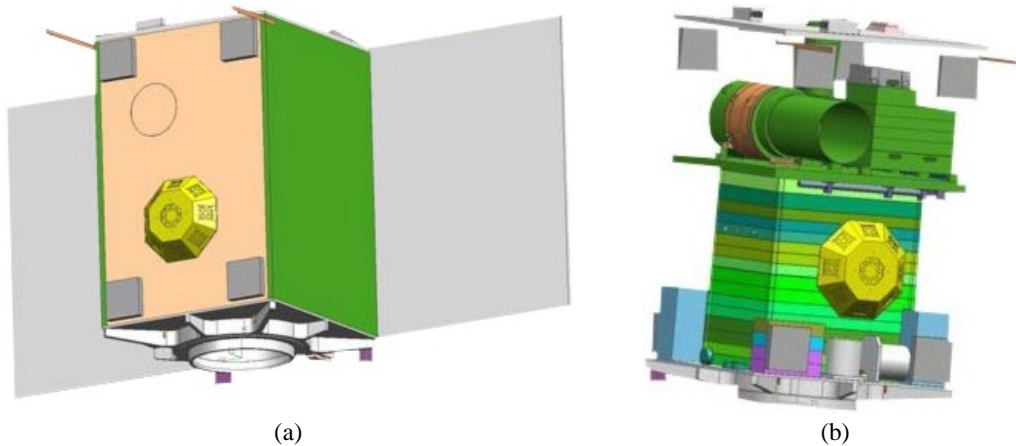

(a)   (b)
Figure 1: X-Sat model: (a) external in-flight configuration, (b) internal configuration

Most of its orbit time X-Sat is in sun-pointing mode, while imaging or downlinking with different orientations occurs less frequent. Hence, for the resulting orbit parameters the values for direct solar flux, Albedo and IR emission from Earth are estimated to be 1309 W/m^2, 445 W/m^2 and 208 W/m^2, respectively, with the worst hot cases expected not to exceed 1400 W/m^2, 588 W/m^2 and 233 W/m^2. Based on these values and an initial temperature for X-Sat between 10–15°C in the launcher's transport bay, a detailed analysis in the form of simulations was conducted for the internal heat loads of various subsystems and the payloads [6]. As a result it was found that four L-shaped aluminium channels have to be attached to the four corners of the 16-level tray stack to facilitate a smooth temperature gradient through an increased thermal conductance. Moreover, due to the temperature sensitivity of the batteries, a multilayer insulation of 20 aluminised Kapton layers was incorporated. Only one titanium bolt with 4.5 mm diameter and

5 mm length is used to conductively connect the entire battery unit to the base-plate. In order to meet the temperature requirements for the lower and upper compartments, which are separated by the central deck, the side panels and the back panel are coated with two different types of material on their outer and inner surfaces. For a detailed overview refer to reference [6]. In summary, the simulations indicated that the temperature range for all internal subsystems is within -10°C to 40°C, while for the most critical payload, i.e. the IRIS camera, temperature variations from 0°C to 15°C are anticipated. Therefore, only a passive thermal control scheme based on surface coatings, insulation blankets and metallic conductors is utilised.

The space bus system architecture follows a distributed system design in which all subsystems and payloads are connected by dual redundant control area networks (CAN) with 80 kb/s bandwidth. The individual CAN interfaces consist of a CAN micro-controller (Infineon C515C), a fault-tolerant transceiver (Philips TJA1054) and a bus-switching relay (Teledyne 422D) to select one of the two hot-redundant CAN networks [7]. Dedicated direct serial links are provided for mission critical subsystems such as the power system and the telemetry and command system. High speed data exchanges between the bus, camera and processing payload are supported by 100 Mb/s and 200 Mb/s low voltage differential signalling (LVDS) links. Figure 2 shows an overview of the wiring harness for communication and power supply of the entire system.
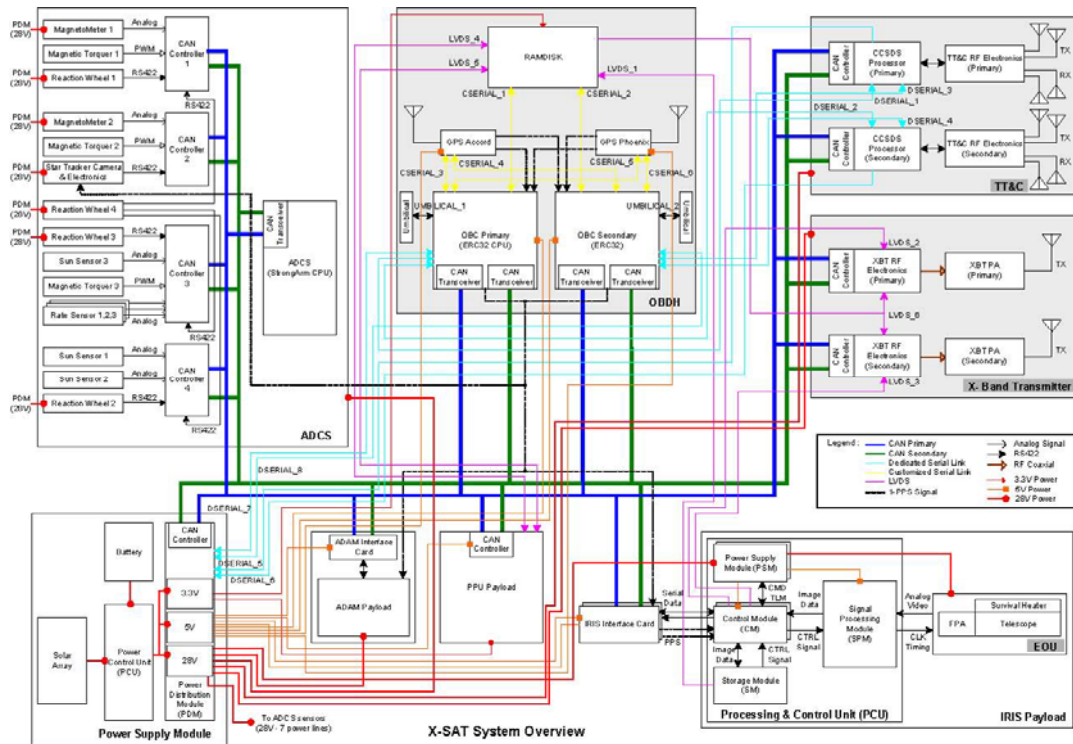

Figure 2: Communication and power harness of X-Sat

2.1. S-band Communication Systems

The dual redundant telemetry, tracking and telecommand (TT&C) system conforms to the CCSDC's recommendations and is based on 3.5 W S-band transceivers. The system

enables a 4 kb/s uplink with a binary phase shift keying (BPSK) modulated signal on a 16 kHz subcarrier. The receiver input port supports a dynamic range of -70 dBm to -120 dBm to accommodate horizon-to-horizon variations in link margin as well as different sizes of ground station antenna. The downlink signal is a BPSK root raised cosine at 125 kb/s and 500 kb/s for contingency and normal operation, respectively, using Reed Solomon coding. To ensure highly reliable communication even for a non-stabilised attitude, a near omni-directional antenna pattern on the front and back panels was selected [8]. In this mission, the CCSDS baseband processing up to the packet layer is performed using a radiation-tolerant field programmable gate array (FPGA) (Actel RTAX1000S).

2.2. X-band Communication Systems

The dual redundant X-band transmitters at 8.3025 GHz with an RF power output of 10.5 W support 12.5 Mb/s, 25 Mb/s and 50 Mb/s data downlink rates with quadrature phase shift keying (QPSK) modulation using root raised cosine filtering in a dedicated FPGA. The system accepts data through its two LVDS links directly from the multispectral camera's internal 1 GB solid state recorder or from X-Sat's additional RAM-Disk. The actual antenna consists of an eight patch antenna, whereby the patches are mounted on the surfaces of a cut-through octahedron. Hence, the number of re-orientation manoeuvres is reduced through automatic selection of the switch beam facing the ground station most directly. For redundancy purposes a canonical beam antenna resides in the centre of the inclined platform.

2.3. On-Board Data Handling

The On-Board Data Handling (OBDH) system consists of the On-Board Computer (OBC) and a mass storage device called RAM-Disk. The system is responsible for reception, execution and relay of telecommands, collection, storage and transmittal of telemetry data, and continuous supervision of all subsystems [7]. Moreover, the OBDH supports the execution of the attitude determination and control [9].

The dual-redundant OBC is based on a radiation-tolerant EDAC aware ERC32 processor (Atmel TSC695F, 8 MHz) and has 8 MB cold redundant SRAM (Toshiba TC55VBM416) as well as 8 MB flash memory (Intel 28F016). The communication interface over CAN is provided by hot redundant CAN pairs of controllers (Intel AS82527) and transceivers (Philips TJA1054), while all other interfaces are handled by an FPGA (Actel RT54SX32S), EIA-422 transceivers (Linear LTC1480) and conventional signal lines. To protect the processing core from any single event latch-up (SEL) events in the peripheral devices, the design incorporates tri-state octal buffers (TI 54AC244/245) and FPGA controlled MOSFET switches in order to isolate the power supply of each memory bank. As operating system VxWorks was chosen due to its space heritage.

The RAM-Disk provides a storage capacity of 2 GB assembled from externally buffered high performance commercial-off-the-shelf (COTS) SDRAM (Samsung K42561632D) chips. The partially triple-redundant firmware resides in a controller FPGA (Actel AX1000, 100 MHz) based on anti-fuse technology with built-in support for the high speed LVDS communication links.

In summary, the design of the OBDH is based on a mixture of reliable radiation-tolerant and less reliable COTS components. In the latter case a high degree of redundancy caters for possible losses [10]. This is coupled with fault detection circuitry for over-current and SELs, which triggers the more reliable radiation-tolerant FPGA to decide on isolating the affected part and switching to redundant components. A periodic heartbeat signal to the power module allows detecting a failure of the entire OBC itself and results in power cycling, whereby multiple consecutive cycles trigger a switchover to the cold redundant OBC. Soft single event errors (SEE) like SEU bit-flips are compensated through a Hamming code based EDAC inside the OBC, while the RAM-Disk firmware employs a robust (255,223) Reed-Solomon encoding mechanism. Both components provide regularly scheduled memory scrubbing operations to avoid accumulation of SEUs beyond the detection and correction limit.

2.4. Attitude Determination and Control System

The mission objectives require a three-axis stabilised attitude with a roll / pitch and yaw pointing accuracy of 0.33° and 1°, respectively, while the attitude determination accuracy during imaging in pitch and roll has to be better than 0.06° and 0.2° for the yaw. Moreover, the satellite is required to support ±40° off-nadir imaging (roll), sun pointing and safety sun pointing in a contingency situation. To fulfil these constraints during the different mission phases the satellite possesses two three-axis magnetometers, three sun sensors, three rate sensors, one star tracker and two Global Positioning System (GPS) receivers as sensors. Control outputs by the ADCS are generated for three magnetic torquers and four reaction wheels, whereby the fourth wheel is for redundancy purposes. The analysis of perturbation torques indicates that a torque capacity of $1 \cdot 10^{-5}$ Nm is sufficient. Hence, the dipole strength of the magnetic torquer coil for the nominal altitude of 685 km with a magnetic field of 45 µT was determined to be at least 2.44 AmpM^2, which is met by the proposed magnetic torquer with a capacity of 6 AmpM^2. Considering the steerability requirement of ±40°, the capacity of the reaction wheels was assessed in detail in [9].

One of the GPS receivers is the Phoenix low-cost GPS receiver developed by DLR/GSOC [11]. The system is based on a Zarlink GP4020 chip making use of a 32 bit ARM7TDMI microprocessor which is completed by 512 kB flash EPROM and 512 kB RAM for storing the receiver software and run-time code as well as data, respectively. The $70 \times 47 \times 11$mm^3 large GPS board has a total mass of less than 250 g and consumes less than 1 W of power. The hardware is complemented by a passive single frequency GPS antenna and a separate preamplifier. This solution provides raw pseudo-range, carrier phase and Doppler measurements with noise levels of 0.3 m, 0.5 mm and 0.06 m/s, respectively, at a carrier-to-noise ratio of 45 db-Hz [11].

The so-called X-Sat Navigation System (XNS) comprises the Phoenix receiver hardware as well as the actual GPS tracking and navigation software. Several hardware-in-the-loop tests using a Spirent STR4760 12-channel signal simulator were conducted. The result for an offline kinematic position solution demonstrated an overall three-dimensional RMS position error of about 0.5 m after two hours of simulated orbit. The velocity error was found to be 0.34 cm/s which is consistent with the corresponding position error.

2.5. Power Supply Unit

The power budget analysis showed that an end-of-life average power generation of 140 W is adequate to meet the intended operational scenarios [6]. Accordingly, triple junction GaAs solar cell strings with an efficiency of 27% were selected for the two deployable solar panels, each providing an area of 780×580 mm^2. Both panels have individually six solar strings with each 20 solar cells, whereby two master strings are connected permanently to the batteries while the remaining ten strings are switchable based on the actual load requirements. This solution provides an efficient and simple protection against overcharging of the two Li-Ion battery packs and guarantees minimum operation in case of failures. Each of the two space-graded SAFT MP176065 cell battery packs has a capacity of 5.6 Ah and is arranged in a 7s-1p configuration. In total they will undergo more than 15,000 charge-discharge cycles during the three-year-life. To ensure the battery life accordingly, simulations with respect to the operation plans were conducted which highlighted that the depth of discharge level is kept to less than 20% according to the battery manufacture's requirements.

The power distribution module employs a hybrid scheme in terms of using both an unregulated and a regulated bus. The unregulated bus with $28 \text{ V} \pm 4 \text{ V}$, which is provided by the solar panels (primary source) and / or the batteries (secondary sources), is used to distribute power to the RF systems as well as the IRIS imaging payload and parts of the ADCS. These generate the required voltages through local DC-DC converters. For the remaining systems of X-Sat, regulated power busses with 5 V and 3.3 V are provided. The main advantage of this hybrid approach is that it provides isolation between the RF systems and the digital systems, which reduces problems related to EMI and EMC [6]. Moreover, the concept improves the overall grounding of the satellite and reduces the impact of single event upsets.

3. PAYLOADS

The satellite carries three payloads: the imaging system IRIS (allusion to the Greek god of light) derived from an earlier design for KITSAT-3, the ADAM platform of the University of South Australia on board of FedSat and KAIST-4, and NTU's PPU for high-performance in-flight data processing.

3.1. IRIS

The multispectral camera IRIS is a push-broom scanner with three individual scan lines in the green (520–600 nm), red (630–690 nm) and near infra-red (760–890 nm) wavelength range of the electro-magnetic spectrum. Due to the chosen design of three line scanners manufactured on the same chip, it is expected that the system will exhibit only minor subpixel misalignments between corresponding pixels from different bands.

The optics is a variant of the Mangin telescope design with a primary and a secondary mirror and two correction lenses. The aperture diameter of the telescope is 120 mm and will provide a ground sampling distance of 10 m with a swath width of 50 km based on the nominal flight altitude.

Internally the IRIS is equipped with a redundant signal processing and control module based on a PowerPC architecture, which allows Reed Solomon coding for safe storage in the built-in 1 GB memory module. Access to the image data is through a 50 Mb/s

LVDS link that reads the encoded data from the storage after image acquisition and an 81 Mb/s link that enables real-time access during imaging.

3.2. ADAM

The X-Sat version of the ADAM instrument is adapted from the original FedSat payload. Its objective is two-way low data rate communication with low power remote mobile terminals using UHF [12]. Uplink of data is performed at 313 MHz using TDMA whereas downlink is at 400 MHz based on TDM for simultaneous access of five terminals. Consolidated data acquired from the terminals are downloaded through X-Sat's S-band as CCSDS-conform telemetry packets. The actual mobile terminals can be customised for a variety of applications ranging from land and maritime to aeronautical mobile data communication.

3.3. Parallel Processing Unit

The PPU enables on-board image data selection, classification and compression providing the means to improve the efficiency of earth imaging and data transmission operations [13]. The system comprises two FPGAs (Actel AX500, 100 MHz) which are the backbone for twenty StrongArm (Intel SA-1110), each with 64 MB of local SDRAM (Samsung K42561632D). The choice for this particular processor was determined through its $0.35\,\mu m$ manufacturing process, i.e. the relatively small sensitivity to radiation, and the provided performance energy ratio of 115 MIPS / 200 mW. The FPGAs are connected to two pairs of three Atmel 4 MB serial flash chips, which contain the bootloader, OS kernel and filesystem images used to boot the processing nodes. In summary, the architecture resembles a cluster with a peak performance of 4000 MIPS. The design is based on COTS components and provides a high degree of fault tolerance through its design based on redundancy [10].

4. GROUND SEGMENT

The ground segment of the X-Sat mission comprises the 6.1 m dish for TT&C mission control and operation ground station (S-Band) in NTU and the 13 m solid parabolic reflector dish for image data reception (X-Band) at CRISP with G/T 35dB-K and elevation tracking angle of less than 10°. The latter station is an existing facility whereas the TT&C mission control and operation ground station is a new facility currently under development as part of the X-Sat project. It is based on the Explorer 12000 antenna and controller and the S-band transceiver from Integral Systems, USA. For the CCSDS processor the Enertec 3801-20 modulator / demodulator from Enertec, France, was selected. The major development work covers the integration of vendor-supplied equipment and the design and development of the actual ground system software.

The software architecture uses a distributed object design to implement a multi-tier client-server distributed computing architecture. Enabling technologies include the use of virtual machine frameworks such as .NET and J2SE/J2EE. The distributed computing design provides scalability, inter-operability, reconfigurability as well as rapid recoverability in mission critical applications while the use of an object model promotes the adoption of best practices in software engineering methods throughout the life cycle of the software project [5].

5. CURRENT STATUS

The completely funded project is well on its way with the engineering model and the qualification model awaiting completion in April 2005 and February 2006, respectively. Finally, the piggyback launch using the PSLV-C2 launcher of ISRO from Sriharikota, India, is scheduled for the first quarter of 2007.

6. ACKNOWLEDGEMENT

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