Evaluating the In-Orbit Performance of Power Management System for the VELOX-PII Satellite

By Jia Min LEW, Htet AUNG, Jing Jun SOON and Kay Soon LOW

Satellite Research Centre, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

(Received August 3rd, 2015)

VELOX-PII is the first Singapore pico-satellite that has been developed in the Satellite Research Centre (SaRC) of Nanyang Technological University. The satellite was launched on 21 Nov 2013. It became the second successful satellite mission in SaRC in addition to an environmental monitoring micro-satellite named X-SAT that has been operating in space since 20 April 2011. The power supply system (PSS) was developed in-house and a virtual-instrument-based prelaunch orbital test system has been developed to measure its performance. The system consists of solar array simulators, electronic loads and a data acquisition system controlled by an in-house developed LabVIEW-based graphical user interface. The prelaunch results show that the PSS hardware design has met the system requirements. Based on the in-orbit data collected, the PSS shows similar performance as the prelaunch test.

Key Words: CubeSat, Pico-Satellite, Power Supply System, Virtual Instrument

Nomenclature

- **E**: solar or battery energy
- **I**: system or subsystem current
- **K**: thermal gradient
- **n**: number of solar cells connected
- **P**: solar or subsystem power
- **T**: temperature of solar panel
- **t**: orbit time
- **V**: solar or battery voltage
- **θ**: incident angle of sunlight to solar panel
- **η**: converter efficiency

Subscripts

- **0**: reference
- **batt**: battery
- **boost**: boost converter
- **buck**: buck converter
- **comm**: communication subsystem
- **isc**: short circuit current
- **im**: maximum power point current
- **OC**: open circuit
- **p**: in parallel
- **s**: in series
- **SC**: short circuit
- **sys**: system
- **tracked**: tracked by MPPT
- **voc**: open circuit voltage
- **vm**: maximum power point voltage

1. Introduction

In space, the primary source of energy is the solar energy. The main role of the power supply system (PSS) is to harvest sunlight power and regulate it to provide energy for the satellite. Recent advancement of electronic technologies has led to the emergence of cube shaped satellite known as CubeSat which has a dimension of 10 cm by 10 cm by 10 cm. It reduces the cost and development time making it ideal for educational purpose or proof of concept on experiments used in future bigger satellites.

There are several commercial-off-the-shelf (COTS) PSS for CubeSat that offer the advantage of reducing development and testing time. Furthermore, the products have space heritage providing higher confidence level to the end user. The main limitation of COTS is its lack of flexibility. For examples, they do not allow additional load channels or in-house developed algorithms to be used.

Figure 1 shows a picture of VELOX-PII, which is the first Singapore’s pico-satellite built by the students. It was launched on 21st November 2013 at 07:10:11 by the Russia’s RS-20B launch vehicle. VELOX-PII carries both in-house developed and COTS components. The fine sun sensor, attitude determination and control system (ADCS) and power supply system including the solar panels were developed by the undergraduate and postgraduate students in Nanyang Technological University. The onboard data handling (OBDH) system, batteries and GPS module are COTS components.
Table 1 lists the key specifications of VELOX-PII. It is a 1U CubeSat with a total mass of 1.33 kg. The VELOX-PII has two in-house built fine sun sensors (30 and 60 degrees field-of-view), a fault tolerant power management system, three magnetic torquers and two inertial measurement units (IMU). In addition, a 2GB SD card installed onboard allows the satellite to log the real time housekeeping data at one-minute interval for a year of operation in the orbit.

Table 1. VELOX-PII technical specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>100 mm x 100 mm x 113.5 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>1330 grams</td>
</tr>
<tr>
<td>Orbit</td>
<td>Sun-synchronous, 650 km altitude</td>
</tr>
<tr>
<td>ADCS</td>
<td>1 GPS receiver, 2 IMUs, 1 dual-FOV sun sensor, 5 coarse sun sensors, and 3 magnetic torquers</td>
</tr>
<tr>
<td>OBDH</td>
<td>100 MHz 8051 MCU, 2 GB SD card, UART and I2C data interfaces</td>
</tr>
<tr>
<td>Uplink</td>
<td>1200 bps AFSK 437.305 MHz</td>
</tr>
<tr>
<td>Downlink</td>
<td>1200 bps BPSK 145.98 MHz, 6-20 dots/second AX-25 Beacon</td>
</tr>
<tr>
<td>PSS</td>
<td>5 GaAs panels for 2.4 W peak, 2600 mAh Li-ion battery</td>
</tr>
<tr>
<td>Thermal control</td>
<td>Battery heaters</td>
</tr>
</tbody>
</table>

For VELOX-PII, the PSS was built in-house to meet the mission requirements. Since the mission success is dependent on the reliability of the PSS, a comprehensive test system was setup to qualify it.

In this paper, the details of the prelaunch test setup are discussed. The system uses LabVIEW as the main software to control the test instruments. It is able to emulate the actual photovoltaic (PV) array output to the PSS based on the temperature and solar irradiance calculated from the mission scenario. Moreover, the electronic loads used in the system provide dynamic loading to simulate the loading of actual subsystems at different time in the orbit. A data acquisition system is used to record all the required voltage and current measurements for data analysis. The efficiencies of different modules in the PSS are calculated to evaluate its performance.

During the prelaunch test campaign, the maximum power point tracker (MPPT) based on the modified Perturb and Observe algorithm was validated. In addition, a fixed operating mode for the MPPT was also tested to study the energy balance in the event when fault occurs. Besides that, the dc–dc conversion efficiency was calculated to study the performance of the PSS.

The actual in-orbit data of VELOX-PII had been downloaded and compared with the prelaunch test data conducted in the laboratory. Besides validating the data, the performance of the PSS is also used to determine if there is any early sign of degradation.

The outline of this paper is as follows: Section 2 presents the design of VELOX-PII power supply system. Section 3 discusses on the prelaunch orbital testing system. The prelaunch result and actual orbit data will be compared and discussed in Section 4. Finally, Section 5 concludes the findings.

2. VELOX-PII Power Supply System

The block diagram of the PSS in VELOX-PII and its experimental setup are presented in Fig. 2. As shown in the figure, the PSS consists of two modules namely the battery management module, and power conditioning and distribution module.

In the laboratory, the battery management module receives the solar energy from 3 solar array simulators. The peak powers from the solar array simulators are tracked by the three boost converters of battery management module. The extracted solar power is then used to charge the Li-ion batteries and supply the step down power converter. To protect the batteries, an inrush current protection circuit is incorporated. In addition, the overcharging protection system ensures that the charging circuit is disabled when the batteries are fully charged. The battery management module also monitors the temperatures of the batteries. When the temperature of the battery is below 0°C, the battery heaters will be turned on.

For the power conditioning and distribution module, it uses DC/DC buck converters to step down the unregulated battery voltage to 3.3V and 5V. The 3.3V bus is for the MCU and EEPROM of PSS. The 5V bus is distributed to various subsystems or payloads via distribution switches.
3. Prelaunch Orbital Test System

Before the launch of VELOX-PII, extensive prelaunch orbital test had been conducted on the PSS to validate its performance. This was done using the actual orbital dynamics for each mission scenario so that information such as incident angle of the PV panel to the sun can be obtained. These values were then used to calculate the PV array profile and subsystems loading.

3.1. Test setup

The test setup is shown in Fig. 2. It consists of three solar array simulators (SASs), a four channel electronic load and a data acquisition (DAQ) system to log the voltage and current measurements in every second.

The SASs are used to emulate the actual PV panels output based on their open circuit voltage, short circuit current, maximum power point voltage and maximum power point current.

Similarly, the power consumption of the four different subsystems can be simulated using the four channel electronic load. Based on the mission profile and the corresponding loading at different orbit time, the electronic load can be programmed to simulate the system loading.

The overall test setup is developed based on a virtual instrumentation (VI) concept. By using LabVIEW, the SASs, electronic loads and DAQ are controlled using the general purpose interface bus (GPIB).

Figure 3 shows the PSS with the test adapter connected to the test system. With the recorded data, the performance of the PSS such as tracked solar energy, boost converter efficiency, buck converter efficiency and power budget/energy balance can be evaluated.

3.2. Simulation scenarios and parameters

To generate the simulation parameters, a series of simulations had been conducted. Figure 4 shows the simulation flow to obtain the required parameters used in the test system.

The first step is to conduct the satellite attitude simulation based on various rotation rates. For the simulation, the sun model and the actual satellite’s two-line element (TLE) are used. Moreover, the sun incident angle towards each PV panel under different rotation rates of the satellite is calculated and used later to obtain the temperature of the PV panels. This is done by using the finite element model of the satellite in SolidWorks. The solar absorptivity and infrared emissivity of actual PV panels are used in the simulation.

The temperatures of the five PV panels are shown in Fig. 5. For VELOX-PII, the solar panels are mounted on every side of the satellite except -Y direction due to the placement of the GPS antenna.

![Figure 5: Prelaunch PV panels’ temperatures based on 2 degrees per second rotation rate.](image)

Based on the thermal simulation result in Fig. 5, it is observed that the temperatures of the five PV panels are similar except panels 1 and 2 displaying some fluctuations. The maximum temperature during sunlight is 31.16 °C and minimum temperature during eclipse is -24.32 °C.

Using the incident angle and simulated temperature in Fig. 5, the open circuit voltage ($V_{OC}$), short circuit current ($I_{SC}$), maximum power point current ($I_{mp}$), and maximum power point voltage ($V_{mp}$) are calculated using the following equations: 15-17

$$ V_{OC}(\theta, T) = V_{OC}(0, T_0) + K_{OC}(T - T_0) \times n_p $$

$$ I_{SC}(\theta, T) = I_{SC}(0, T_0) + K_{SC}(T - T_0) \times \cos \theta \times n_p $$

$$ V_{mp}(\theta, T) = V_{mp}(0, T_0) + K_{mp}(T - T_0) \times n_p $$

$$ I_{mp}(\theta, T) = I_{mp}(0, T_0) + K_{mp}(T - T_0) \times \cos \theta \times n_p $$

From Eqs. (1) – (4), the power obtained from the PV panels...
at 2, 4 and 6 degrees per second rotation rate is shown in Fig. 6. From Fig. 6, it is observed that the change of power is greater for the 6 degrees per second rotation rate as compared to the 2 degrees per second rotation rate.

From Fig. 6, it is observed that the change of power is greater for the 6 degrees per second rotation rate as compared to the 2 degrees per second rotation rate.

Using Eq. (5), the energies harvested are 2.62Wh, 2.43Wh, and 2.72Wh for 2, 4 and 6 degrees per second rotation rate respectively. Thus, the rotation rate does not have big impact on the energy harvested. However, a rapid change in power might affect the MPPT performance. To guarantee better MPPT performance and satellite control stability, the attitude control system (ACS) is designed to maintain the satellite rotation to be less than 2 degrees per second.

Due to the rotation of the satellite, the PV panels have smaller temperature difference during the sunlight and eclipse as they are not always facing the sun.

To avoid unbalance light intensity on the PV panels, the five solar panels are connected to three MPPT on the PSS. The +X and –X PV panels are connected in parallel to channel 1, +Z and –Z PV panels are connected in parallel to channel 3 and lastly the +Y PV panel is connected to channel 2. Figure 7 shows the output PV power from the three SASs. The eclipse period is from \( t = 0 \) to \( t = 11 \) minutes and \( t = 68 \) to \( t = 91 \) minutes. From the results, it is observed that there are fluctuations in the three channels due to the satellite rotation.

VELOX-PII has several operating scenarios. Throughout an orbit, different subsystems and payloads may operate at different loadings depending on the operating scenarios. Table 2 lists the power consumption of every subsystems.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS</td>
<td>IMU</td>
<td>0.35 W</td>
</tr>
<tr>
<td>ACS</td>
<td>MCU</td>
<td>0.20 W</td>
</tr>
<tr>
<td></td>
<td>Torquer</td>
<td>1.00 W</td>
</tr>
<tr>
<td>OBDH</td>
<td>MCU</td>
<td>0.50 W</td>
</tr>
<tr>
<td></td>
<td>Beacon</td>
<td>0.16 W</td>
</tr>
<tr>
<td>COMMS</td>
<td>Transmitter</td>
<td>1.90 W</td>
</tr>
<tr>
<td></td>
<td>Receiver</td>
<td>0.20 W</td>
</tr>
</tbody>
</table>

In this study, the frequent operating mode namely the normal operation mode (NOP) is used to evaluate the performance of the PSS. The worst case scenario is assumed for all subsystem in this study. Figure 8 shows the dynamic load profile during NOP.

In Fig. 8, it is observed that the attitude determination system (ADS) is required to turn on throughout the orbit. The main component of ADS is the inertia measurement unit (IMU) that is required to determine the satellite orientation and rotation speed. The ACS uses the proportional and derivative (PD) algorithm for the satellite stabilization.

For the communication system (COMMS), it is necessary to turn on the receiver throughout the orbit to receive commands from ground station. Besides that, it also sends the beacon signal throughout the orbit. From \( t = 35 \) minutes to \( t = 45 \) minutes, the power consumption of the COMMS increased from 0.36W to 2.26W as the VELOX-PII was transmitting data to the ground station during ground pass. For the on board and data handling (OBDH) system that is responsible for the satellite real time management, it was turned on.
throughout the orbit with a constant power consumption of 0.5W. The dynamic loading of VELOX-PII in Fig. 8 is simulated by programming the electronic load in the test setup.

3.3. Maximum power point tracker performance

In this section, the performance of the MPPT under normal condition (P&O algorithm) and under faulty condition (fixed operating point) is studied.

Figure 9 shows the total power tracked using P&O and fixed operating point. From the result, the MPPT with P&O yields an efficiency of 86.29%. On the other hand, the fixed operating point mode has an efficiency of 44.27%. This shows that under fault scenario, PSS will suffer a 42% degradation.

From this analysis, it can be concluded that the satellite has sufficient power to perform the mission under normal condition. When there is a fault of the PSS microcontroller, the harvested power is reduced but is still sufficient to operate the satellite at minimum performance. This allows the communication with the ground station to resolve the problem.

4. In-Orbit Data Comparisons

The test setup in Fig. 3 with the solar array profile in Fig. 7 and NOP load profile in Fig. 8 have been used to evaluate the tracked solar energy, boost converter efficiency, buck converter efficiency and power budget/energy balance for one complete orbit of 91 minutes.

For the whole orbit data (WOD) which contains the satellite telemetry information log at an interval of 1 minute, it was collected in every ground pass. The downloaded WOD is then used to validate the simulated inputs used in the prelaunch experiments. By comparing the prelaunch experimental and WOD results, the degradation of the PSS can be analyzed.

4.1. Solar panel temperature and tracked power

Figure 10 shows the WOD temperature readings of the 5 solar panels. From the result, it can be observed that the temperatures of the solar panels decreased to –18ºC in the first 12 minutes as the satellite was in eclipse. Subsequently, the temperatures increased as the satellite entered into the sunlight mode. At t = 75 minutes, the temperatures decreased as the satellite entered into eclipse again. In comparison with the simulated solar panel temperature in Fig. 5, all solar panels temperature decreased similarly in eclipse period. During sunlight period, the WOD temperature variation was much larger and faster than the simulated temperature. This is due to the difference in rotation rate and angle between the laboratory experiment and actual satellite operation. In the orbit, the actual rotation rate of VELOX-PII is not always at 2 degrees per second for the three axes.

For the whole orbit data (WOD) which contains the satellite telemetry information log at an interval of 1 minute, it was collected in every ground pass. The downloaded WOD is then used to validate the simulated inputs used in the prelaunch experiments. By comparing the prelaunch experimental and WOD results, the degradation of the PSS can be analyzed.

4.2. Efficiency of boost and buck converters

The PSS of VELOX-PII consists of boost and buck converters for voltage regulation. The boost converter
efficiency ($\eta_{\text{boost}}$) and the buck converter efficiency ($\eta_{\text{buck}}$) can be evaluated as follows:

$$\eta_{\text{boost}} = \frac{V_{\text{bat}} \times (I_{\text{bat}} + I_{\text{sys}})}{P_{\text{tracked}}} \times 100\% \quad (7)$$

$$\eta_{\text{buck}} = \frac{P_{\text{boost}} + P_{\text{ ACS}}}{V_{\text{bat}} \times (I_{\text{sys}} - I_{\text{comm}})} \times 100\% \quad (8)$$

Using Eqs. (7) and (8), the efficiency for the boost and buck converters are calculated. The results are shown in Fig. 12 for both the prelaunch experiment and the WOD.

Fig. 12. Boost and buck converter efficiencies obtained for prelaunch experiment and WOD.

Unlike the buck converter, the boost converter only operates during the sunlight. From the prelaunch experimental results, the calculated average boost converter efficiency for one orbit is 81%. For the buck converter, the average efficiency is 85%. From the WOD, the boost converter efficiency is found to be 85%, which is close to the prelaunch test result of 81%.

For the buck converter, its efficiency is observed to be 89% from the WOD and is also close to the prelaunch test result of 85%. Overall, it can be concluded that the PSS conversion stage is performing as expected in space.

4.3. Energy balance per orbit

With the calculated solar input energy per orbit and the recorded battery current and voltage, the energy balance per orbit is calculated. The battery current under NOP load profile for the prelaunch test result and WOD is plotted in Fig. 13.

During the eclipse, the battery current was negative showing that it was discharging to supply power to the satellite. Once the satellite entered into the sunlight period, the battery was charged by the solar panels indicated by the positive battery current. The battery energy $E_{\text{bat}}$ under one orbit can be calculated by

$$E_{\text{bat}} = \int I_{\text{bat}} \times V_{\text{bat}} \, dt \quad (9)$$

Under the NOP scenario of Fig. 8, the energy balance of the prelaunch test is calculated using

$$E_{\text{balance}} = E_{\text{Solar}} + E_{\text{bat}} \quad (10)$$

Using Eqs. (9) and (10) together with Figs 7 and 13, the calculated energy balance is 0.051Wh indicating the energy gain is positive.

Fig. 13. Prelaunch test result and WOD battery current.

Using the WOD, the $E_{\text{balance}}$ can be calculated using Eq. (10) from Figs 11 and 13. The calculated energy balance is 0.094Wh indicating that VELOX-PII has a positive energy gain in each orbit.

4.4. Comparison of prelaunch and WOD data

The performance of the power supply system for prelaunch experiment and WOD are summarized in Table 3. From the results, the difference in total track power, the buck converter efficiency and boost converter efficiency is about 4%. The error is small as the change in temperature of the solar panels results in 40mW difference for 22°C variation in temperature. This does not affect the input power greatly.

The efficiencies of the buck and boost converters are similar for prelaunch and WOD showing that the PSS is fully functional and there is no sign of degradation after 200 orbits.

5. Conclusion

A virtual instrument based measurement system for a satellite power supply system has been presented. The prelaunch experimental results have been verified with the actual mission data downloaded from VELOX-PII satellite. Comparing the solar panel temperature readings, the in orbit temperature profile is slightly different from the simulation due to differences in the satellite attitude and rotation rate. The solar array power readings show that the MPPT of the PSS is performing well as the difference of total tracked power is 4%. For the efficiencies of boost and buck converters, the differences are 4% between the prelaunch experiment and in-orbit data. The result indicates that there is no sign of degradation after the launch and early operation.
References


