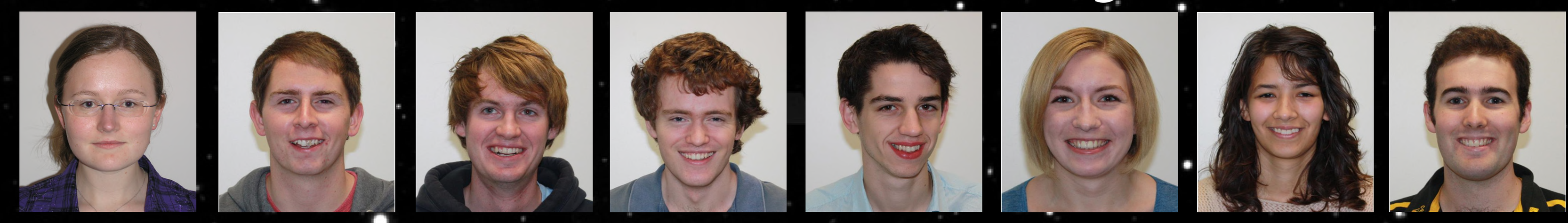
THE UNIVERSITY OF WARWICK

European Student Moon Orbiter
Electrical Power System Team

esmo
www.esmo.co.uk



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1. Introduction

The ESMO project is an ongoing space mission commissioned by the European Space Agency (ESA) and is being undertaken by 23 Universities across Europe. Planned for a 2015 launch, the aims of the satellite are to encourage students into science and technology based careers and gather scientific data from the Moon. The team at Warwick are responsible for the design, build and testing of the Electrical Power System. This consists of the Solar Array, Battery, and the Power Conditioning and Distribution subsystems.

2. Aims & Objectives

1. Development of current designs towards Critical Design Review **(Figure 1)**
   a) Redesign the Solar Arrays following changes by structures team
   b) Redesign the Solar Array Regulation system
   c) Design the load protection systems
   d) Develop a Power Management Unit
   e) Design a Battery Management Unit
2. Validate designs through modelling software and prototyping
   a) Improve and validate current thermal models of the resized battery to determine if a battery heater is required
   b) Update the current battery model to accommodate capacity fade and string failure
   c) Validate previous thermal models of the solar arrays using ESA preferred software ESATAN TMS
   d) Prototype and test the load protection systems
   e) Complete vibrational analysis of new Solar Array design

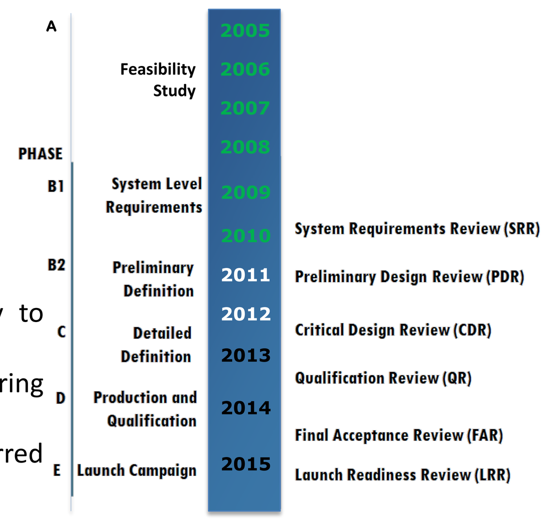

Figure 1 - Approximate schedule for ESMO

3. Solar Arrays

The solar arrays are the only source of power generation for the ESMO satellite, they are constructed from a number of layers - shown in **Figure 2**.

- The **coverglass** protects the cells from the intense solar radiation.
- The **solar cells** convert the solar radiation into electrical power.
- The **Kapton** electrically isolates the solar cells from the rest of the structure.
- The substrate sandwich of **carbon fibre** and **aluminium honeycomb** provides strength to the panel. This has met **aim (1a).**

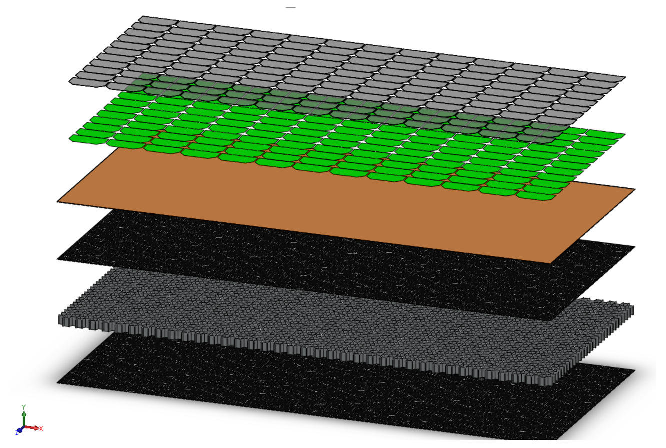

Figure 2 - An exploded view of the solar array

Material	Source
Coverglass	Qioptiq
Solar cells	AzurSpace
Kapton	Prodrive
Carbon Fibre	Prodrive
Aluminium Honeycomb	Prodrive
Carbon Fibre	Prodrive

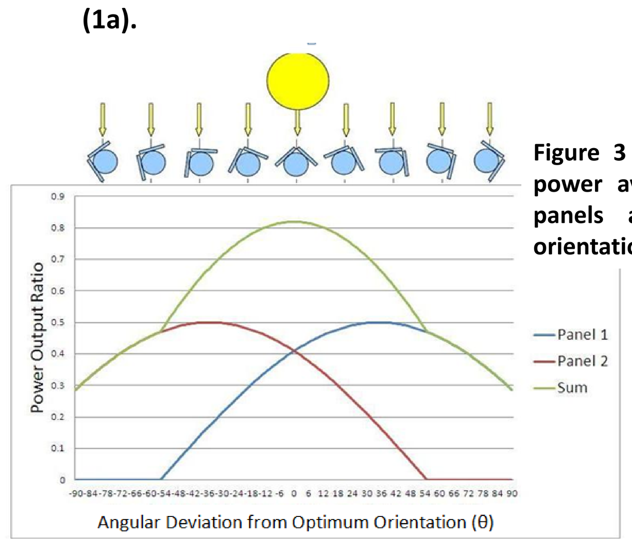

Figure 3 (left) plots the amount of power available from the two solar panels as a function of ESMO's orientation to the Sun.

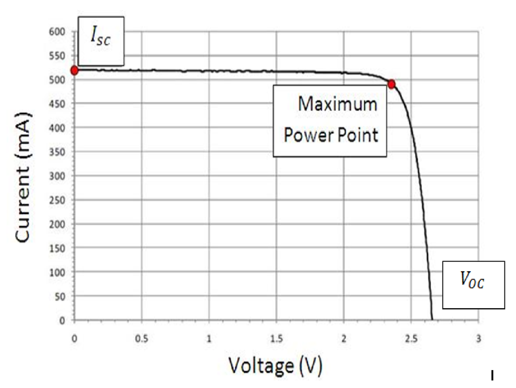

Figure 4 (right) plots the current/voltage characteristics of ESMO's solar cells. With suitable voltage control, the cells can be operated at the maximum power point.

Thermal Analysis

In order to validate the current design the thermal simulation software ESATAN TMS was used to generate a model of the solar arrays as they completed the full lunar orbit. The averaged results of the initial radiative study are shown in °C in **Figure 5**.

This takes into account the radiative effects of the solar flux, lunar albedo and material properties as ESMO passes through periods of full sunlight and eclipse. The thermal modelling methods utilised were based on **NASA** and **ESA** practises.

Currently, this shows the solar array model staying within the **-100 to +100°C** range that is required to maintain functionally of all the constituent materials. This is working towards **aim (2c).**

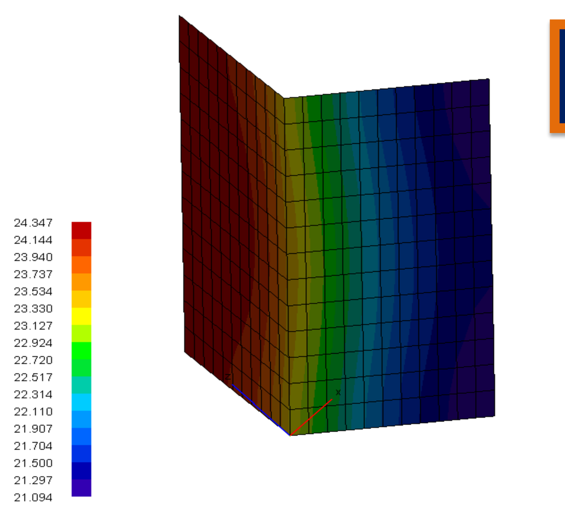

Figure 5 - Averaged results of initial radiative study (21.0-24.3°C)

Vibrational Analysis

To ensure that the solar panel structure survives the high vibrational loading experienced during the mission, the panel structures are modelled and subjected to a random vibrational analysis. However due to its small feature size the honeycomb had to be approximated as an anisotropic material in order to complete this modelling.

The vibration results are shown in **Figure 6**, against the input profile. The input profile is a worst case scenario combining the profiles of all the current launch platforms under consideration. This satisfies **aim (2e).**

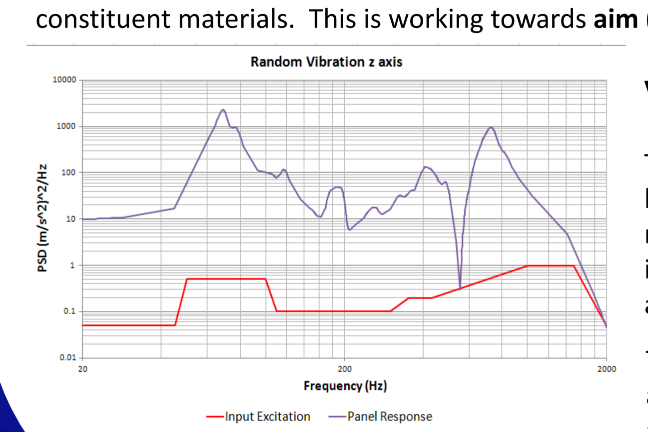

Figure 6 - Worst case vibration response

Part	Source
ESATAN Thermal Modelling Software	ITP Engines
Computer Aided Design/Engineering Software	SolidWorks
Solidworks Training	SolidSolutions

4. Power Conditioning and Distribution Unit

Power Management Unit

The Power Management Unit is the controller for ESMO's power system (**Figure 7**). It must:

- direct power from the Solar Array Regulation, to all of ESMO's sub-systems
- measure solar panel and battery temperature via several thermistors
- calculate the state of charge of the battery
- send this data to ESMO's on-board computer, to be sent on to mission control

1. Hardware
   - Power Management Unit logic will be programmed onto a 'Xilinx Spartan-6 LX45' Field Programmable Gate Array (FPGA) which has been donated by **National Instruments.**
   - FPGAs are preferable to Microcontrollers or Application Specific Integrated Circuits for space applications because of they are reprogrammable, have inherent redundancy and are radiation hardened.
2. Software

The Power Management Unit logic is being developed on the LabView graphical programming software. The code can be directly downloaded onto the FPGA from LabView. This is working towards **aim (1d).**

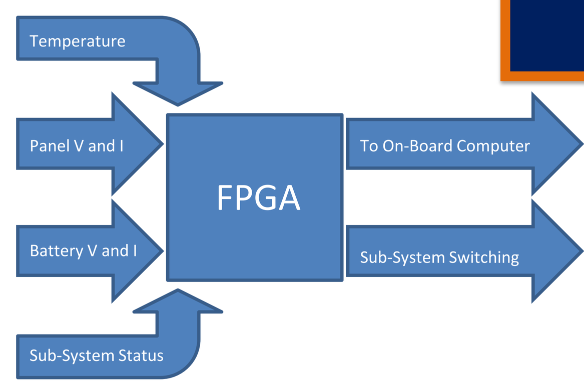

Figure 7 – Block diagram of the PMU functionality

Part	Source
Graphical Programming Software	National Instruments

Solar Array Regulation

This efficiently extracts power from the Solar Arrays in order to charge the battery and to power other satellite subsystems. The system uses a Maximum Power Point Tracking (MPPT) topology. The output of the system is an unregulated power bus, which is connected directly to the battery. The power regulation system consists of:

Buck-Boost Converter: A DC-DC converter which can step up or down the input voltage. The relationship between the input and output voltage is determined by the 'duty cycle's' of the internal switching devices

Control circuitry: The duty cycles are controlled to vary the operating point of the solar arrays. There are two phases in control algorithm, **Battery Charging Phase** and **MPPT Phase** shown in **Figure 8 (left).**

The circuit shown in **Figure 9 (below)** shows the implementation of new design for the control algorithm which fulfills **aim (1b).** Testing of this circuit was completed using a Solar Simulator provided by **Agilent**, results of this are shown in **Figure 10 (right).**

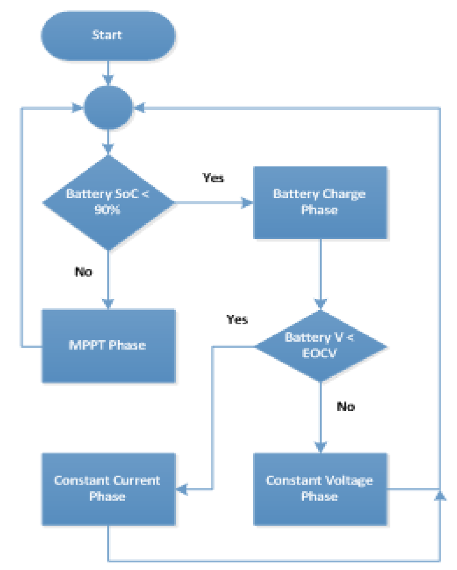

Figure 8 - Top level flowchart for control algorithm

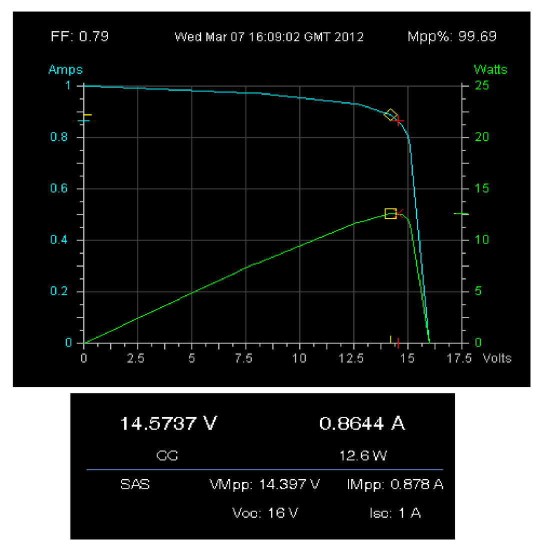

Figure 10 – Measured results showing MPP operation, controlled using solar array regulation prototype

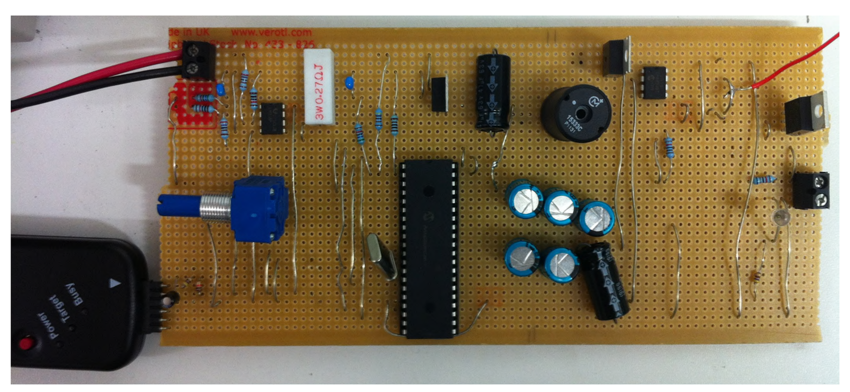

Figure 9 – Solar Array Regulation prototype

Part	Source
Solar Simulator	Agilent Technologies
Components	RS Components

Current Limiters

The power bus supplies power to the satellites subsystems. In order to protect the power system, load protection must be placed between the main bus and the loads. This means that if a subsystem were to fail it would not result in a critical failure of the entire satellite. Simple fused lines are used for the critical subsystems, due to their inherent redundancy. For the non-critical subsystems an alternative is chosen. The requirements are depicted in **Figure 11** this design fulfils **aim (1c)**:

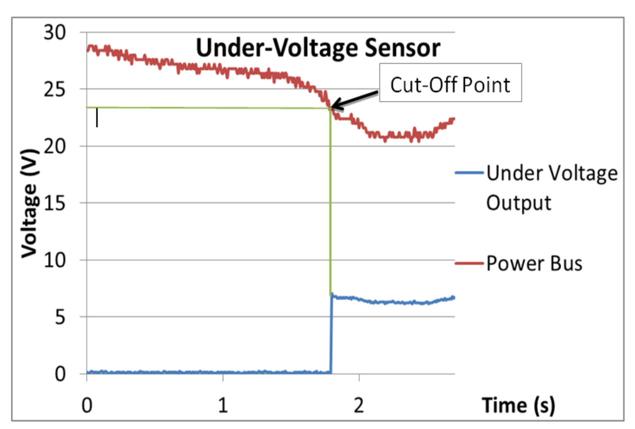

Figure 13- Under Voltage sensor output

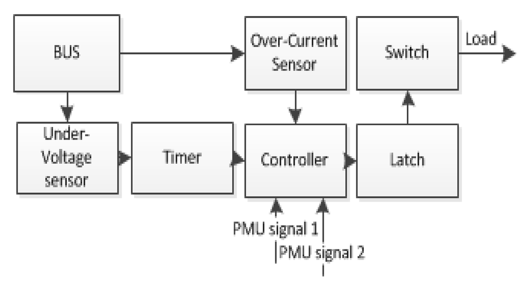

Figure 11- Current Limiter Architecture

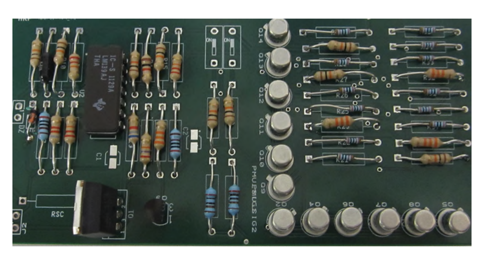

Figure 12 – PCB prototype

The circuit was prototyped and is currently being tested. A PCB circuit, **Figure 12 (above)** was made in order to fully verify the operation of the circuit. The under-voltage sensor output from the PCB is seen in **Figure 13 (right)** which is working towards **aim (2d).**

Part	Source
PCB	Lyncolec
Components	RS Components

5. Battery

The battery provided by **ABSL** are providing eighty Sony 18650HC lithium-ion cells arranged in 8s10p configuration (8 series, 10 parallel)**.** It provides the power for the satellite during eclipse and is recharged using excess power from the solar arrays during periods of sunlight. In order to meet **aim (2b)** a Simulink model has been created to simulate this behaviour.

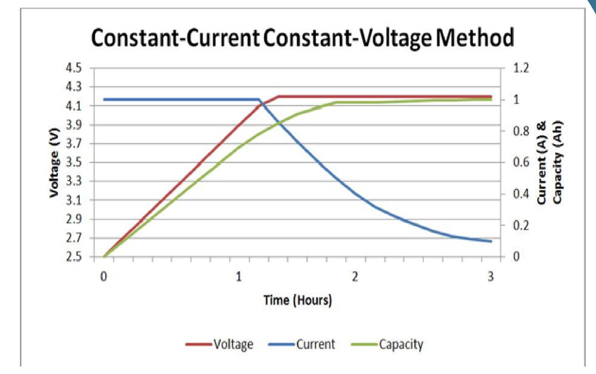

Fig 14 - CC-CV characteristic graph

Battery Management Unit

For the battery to meet **aim (1e)** proper protection and management is vital.

1. Charging is implemented using a constant-current constant-voltage (CC-CV) method (**Figure 14**), ensuring the battery remains within its safe electrical limits, 20V -33.6V**.**
2. The maximum battery capacity is 15Ah. However, capacity inevitably fades over time (**Figure 15**). In order to minimise this, battery charge and discharge regulation is required:
   - Charge/Discharge currents less than 15A (i.e. < 1C) reduce capacity fade.
   - The charge/discharge currents should be similar so as to further reduce capacity fade.

Protection is provided using fused lines and current limiters to prevent too much current being sourced/supplied from/to the battery (i.e. < 15A for charge/discharge).

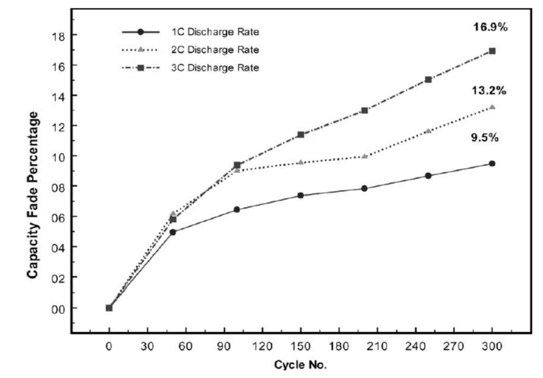

Figure 15 - Capacity fade study of lithium-ion batteries cycled at high discharge rates. Ning, et al. Columbia : Elsevier, Journal of Power Sources, 2002/3, Vol. 117

Thermal Analysis

To ensure the battery is operating within its thermal limits (-30°C to 60°C) throughout the mission, a number of thermal studies were carried out using **SolidWorks** to satisfy **aim (2a).**

A simplified CAD model was generated and radiative and conductive thermal loads were placed on it, using material properties provided by ABSL. The battery interface temperature range of 5 – 30 °C was applied at the connection points.

Initial steady-state studies **(Figure 16)** assumed a constant heat power generated by the cells during the mission, subsequent transient studies used dynamic heat power profiles. This enabled the team to observe the minimum and maximum temperatures generated to compare with the thermal requirements for the battery . The analysis will ultimately determine whether or not a heater will be required to keep the battery within its operating limits.

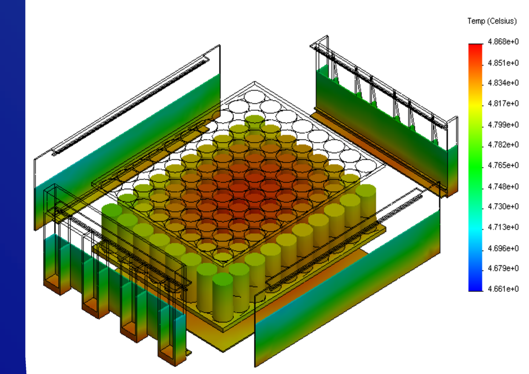

Figure 16 - Output from the thermal model showing temperature variation through the battery (4.66-4.87°C)

Part	Source
Battery	ABSL
Battery Electrical Analysis Software Tool	ABSL
Computer Aided Design/Engineering Software	SolidWorks

6. Conclusions & Further Work

1. Development of current designs towards critical design review
   a) Solar Arrays redesigned subject to modelling results and approval.
   b) Solar Array Regulation architecture re-designed, hardware finalised pending further control algorithm testing.
   c) Load protection system developed and verified.
   d) Architecture design of Power Management Unit completed. FPGA prototyping in progress .
   e) Battery Management Unit has been fully specified, individual elements designed pending verification.
2. Begin validation of designs through modelling software and prototyping
   a) Mechanical and electrical modelling has concluded that a battery heater will not be required.
   b) The battery model has been redesigned. Testing will be carried out to determine battery suitability.
   c) ESATAN thermal model completed for Solar Arrays in Lunar orbit, other phases of mission and full satellite model in progress.
   d) Load protection system prototyped, testing of the PCB manufactured by **Lyncolec** in progress.
   e) Vibrational analysis completed