AN ADVANCED ELECTRICAL POWER SYSTEM FOR CUBESATS
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ABSTRACT

Parallels are being made between the success of the Small Satellite industry and the growing capability of Cubesats. Currently, Cubesats are being used as teaching tools by many Universities and organisations all over the world, but commercial and scientific applications are now being flown on these very small satellite platforms.

Over the last four years, we have used our extensive small satellite power system design experience to develop and refine a CubeSat power system that is highly efficient both electrically and physically. What's more, the system has been fashioned such that it can be purchased off-the-shelf, often on a 1 week delivery. Satellite power system purchases are are made online, via our website, with a credit card for less than the price of a lab power supply.

Being a commercial off-the-shelf power system, the unit by nature needs to be flexible and modular; effectively plug-n-play. In addition, the system has to be simple and avoid unnecessary complexity; this is in contrast to typical university designed CubeSat power systems which, by the nature of the need for innovation, are often overly complex.

This paper will discuss the design and performance of the system and also the approaches that we are taking to allow CubeSat developers to specify and buy their system online.

1. INTRODUCTION

The power subsystem could possibly be the most under-appreciated and forgotten of all of the on-board electrical subsystems. There may be several reasons for this, but the most likely is that most people just don't find the subject interesting enough. There are, of course, exceptions to this generalisation (the author for one), but it is safe to say that no one is currently planning a mission to demonstrate a new power management technique.

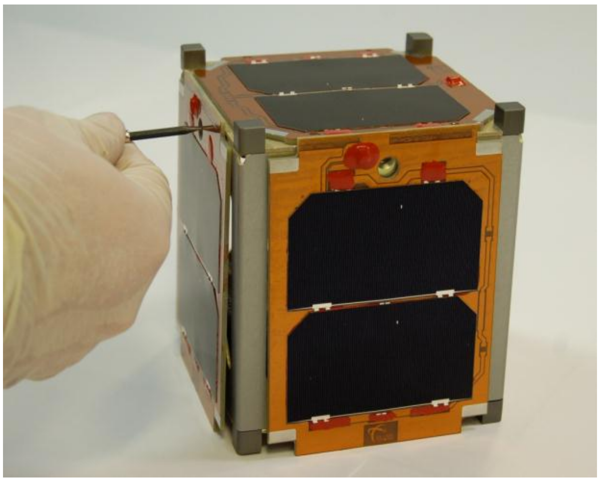

Figure 1 1U Cubesat.

Grabbing the attention of spacecraft engineers are subjects like; more advanced communications systems, on-board data handling, high speed data links, imaging systems, micro-propulsion, attitude control algorithms, sensors and actuators. It is natural that the best people in a small organisation focus on the more exciting aspects of a mission; these subjects will typically be the differentiator of an organisation's space mission from that of the rest of the world.

However, it is also clear that these systems need power, and power that is delivered reliably and efficiently. For most companies and organizations planning their own CubeSat mission, the prospect of producing a reliable, yet affordable power system for their mission is not a trivial problem. Some non-traditional spacecraft manufacturers, such as Universities, are finding out the importance of a well designed power system the hard way. The most common cause of failure on CubeSats to date has been the power system.

As all CubeSats require some sort of power management system, and since this system will differ little from mission to mission, it makes sense to provide an off-the-shelf solution for common buses; such as that used for the CubeSat Kit. By providing such a system, the responsibility of design of the power system within smaller organisations can be removed, allowing the mission design team to focus on the design of the rest of the spacecraft.

Another added bonus of buying an off-the-shelf system is that the power system will have been competently designed by an engineer with more than a fleeting interest in the problem of on-board power. In the case of the power system described in this paper, the developers have extensive experience in power subsystems design and are passionate about providing the optimum systems and electrical design to suit the platform.

The objectives in the design of our CubeSat Power subsystem were as follows:

- Maximise the power available from the solar arrays.
- Provide a high efficiency interface between the solar arrays and the rest of the spacecraft to minimise losses.
- Provide common regulated voltages of 5V and 3.3V.
- Provide a digital interface that can deliver telemetry and telecommand functions for the power system.
- To be independent of user set-up requirements with no need for modification – straight integration with the spacecraft bus.
- To be truly 'plug and play'.

2. CUBESAT ELECTRICAL POWER SYSTEM (EPS)

CubeSats come in various shapes and sizes, so it is necessary to have a number of power system solutions to cater for the requirements of each configuration. For this reason, the CubeSat EPS design needed to be highly modular and adaptable;

POWER SYSTEM ARCHITECTURE

The CubeSat EPS developed and described in this paper uses a Maximum Power Point Tracker (MPPT) system with a battery bus. The designers determined this to be the most versatile and efficient toppology, and is ideal for CubeSats. In the CubeSat EPS, the MPPT topology is implementated using a dedicated MPPT for each opposing solar panel pair. This configuration has many advantages:

- It allows the use of different solar cell technologies and string lengths on each panel.
- The Maximum Power Point (MPP) of an individual panel can be tracked over the changing thermal conditions whilst in sunlight. The panels are likely to be at different temperatures and hence have different characteristics, so this is important.
- The system is highly modular and easily adaptable to multiple solar panel configurations.
- It provides a graceful degradation in the system design with the loss of a panel or an MPPT
- The battery typically needs to be charged for the majority of the sunlit period, so additional loss through having a switch-mode power supply (SMPS) in series with the array has little impact on the overall solar efficiency of the power system.
- The direct connection between the battery and the bus provides maximum efficiency during eclipse operation.

Using this configuration it allows the EPS to maximise the power from the arrays at the beginning of the sunlit period, replenishing the charge of the battery in a quicker and more controlled manner. In addition, once the battery is fully charged and there is low power demand on the bus, the unwanted power is left in the solar array by moving off the maximum power point, so no need for hot and heavy analogue shunt electronics. The MPPT is typically a DC-DC converter and therefore can regulate its output to the end of charge voltage of the battery once this level is reached, removing the need for a complicated charge control system.

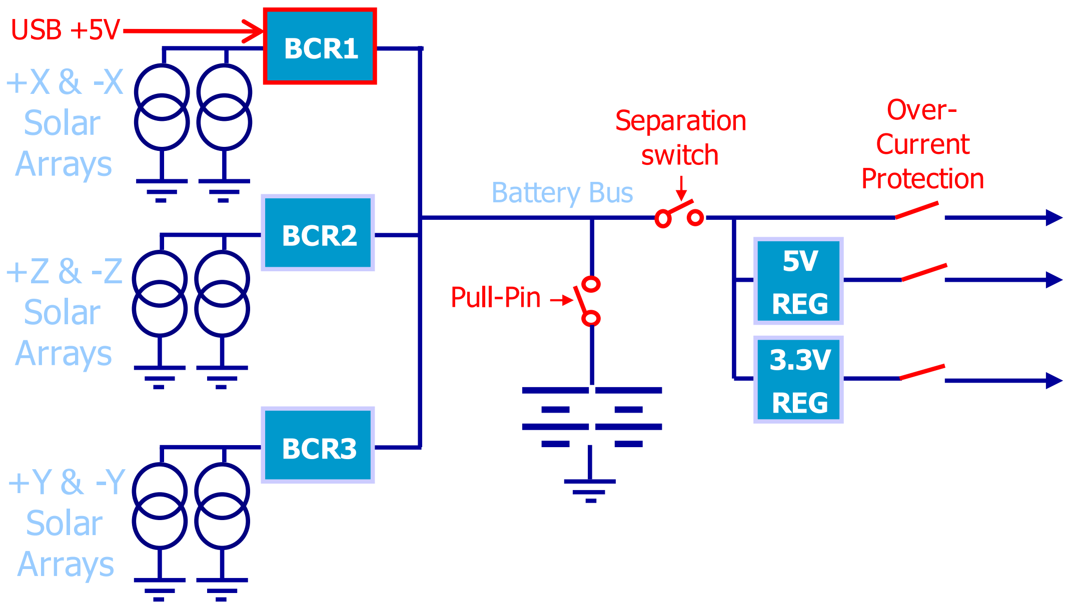

Figure 2 Block Diagram of CubeSat Power System

BATTERY CHARGE REGULATOR

With so little power available on a CubeSat, it is essential that the interface between the solar arrays and the rest of the spacecraft is optimised for both energy transfer efficiency and systems design. As previously described, an MPPT/BCR (BCR stands for Battery Charge Regulator) system ensures that the voltage of the array remains at its optimum value when the power requirement demands, but it is also essential that the BCR itself is efficient.

Peak Power Tracking is implemented in hardware only, using only two op-amps. By using such a low component count we are able to maintain high efficiency even at low power levels. It also means that the design is more reliable since there are fewer components that can fail. Furthermore, thepower electronics of the BCR is designed such that the overall efficiency of the circuit is high at about 90%.

In order to make the maximum use of the system volume and mass, this BCR was designed to operate when connected to two solar panels, each on opposite sides of the spacecraft. This is possible because only one solar panel on the same axis can be in sunlight at any one time. For CubeSats with only body mounted panels, this means that 3 BCRs interface to SIX solar arrays. For missions that have deployable solar arrays, and hence more solar arrays in sunlight at one time, the power system has been designed such that a daughter board can be added containing additional BCRs, expanding solar array interfacing capability.

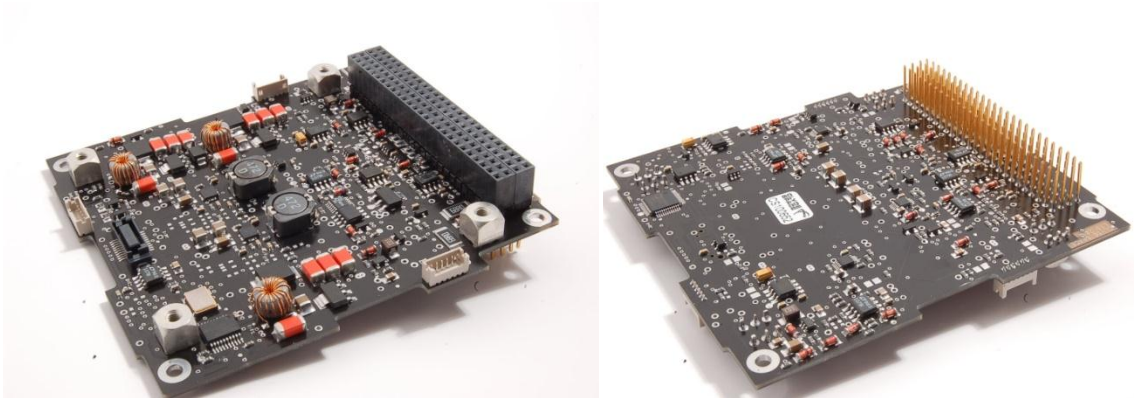

Figure 3 Front and back images of the 1U CubeSat EPS

<u>Power Conditioning Module</u>

The Power Conditioning Module (PCM) consists of two dc-dc converters; one regulating its output to 5V and the other 3.3V. Each converter can provide over 2.5A at an efficiency of 95-98%. Regualting and distributing numerous voltages to the rest of the spacecraft makes the CubeSat EPS a ‘Centralised’ power system; due to the small physical size of CubeSats, this is the most efficient method of suplpying standard regulated voltages.

The PCM provides additional protection features that are essential for protection of the spacecraft from anomalous operational modes. The PCM ‘unloading function’ disables the output of the 5V and 3.3V converters once the battery voltage reaches its minimum acceptable level (i.e. close to zero capacity). This not only stops power consumption on the 5V and 3.3V buses, but also turns OFF the power switch that supplies the battery voltage bus to the rest of the spacecraft. Built-in hysteresis means that all three buses return to operation once the battery voltage has recovered to a reasonable level. This functionality prevents the battery suffering permanent damage due to over-discharge.

<u>Over Current Protection</u>

As previously mentioned, three power buses are provided to the main CubeSat header. It is important to the power system that these lines are protected against over-current in order to ensure that the power system survives a short circuit event down-stream of the power module. The dilemma, however, as an off-the-shelf item that will be used on numerous missions, it is impossible to determine which bus the spacecraft essential systems will be run off (i.e. you don't want to turn off the receiver if you need to command it back on).

The solution was to have a protection circuit that continuously tries to remake the connection to the bus in the event of an over-current condition. Given that all CubeSats are single string with no redundancy, this was deemed to be the best compromise to the problem.

Another added feature of this system is that it is impossible to fully turn-off any of the power buses. Therefore, we have provided a command line that will cycle the power buses; useful when a power reset is required for one of the on-board systems.

Telemetry and Telecommands

The power system has a small microcontroller to provide a serial bus interface using the I2C standard through which system telemetry data can be monitored.

Due to the high number of telemetry channels on the power system, there is a need to interface the signals to the microcontroller via a 32 channel analogue mulitplexer. The telemetry channels on the power system include:

- Solar Array Voltages (one channel per solar array)
- Solar Array Currents (one channel per solar array channel)
- Solar Array Temperature (one channel per solar array)
- Battery Voltage
- Battery Current
- Battery Temperature
- 5V bus, 3.3V bus and Battery bus currents.
- Battery heater status.

The telecommands on the power system are as follows:

- Battery bus over-current protection switch command cycle OFF and ON.

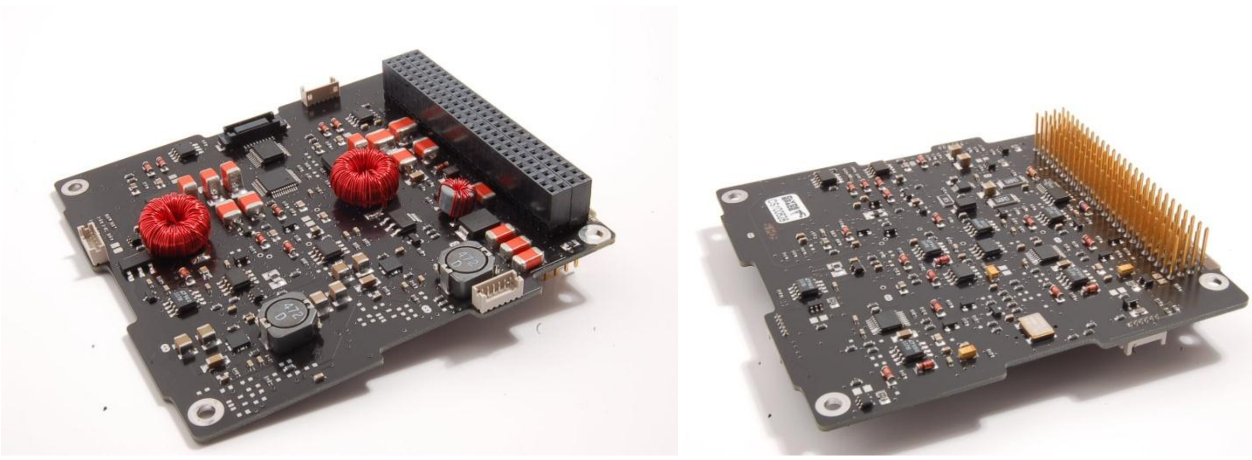

Figure 4 Front and back images of the 1U CubeSat EPS
(Note the larger inductors needed for the higher power 3U Solar Panels).

3. SOLAR PANELS FOR CUBESATS

Of the available solar cell technologies, the GaInP2/GaAs/Ge multi-junction cell is the only real option for CubeSats. Other than having a significantly higher efficiency than other technologies, the most advantageous characteristic of this technology is that the terminal voltage of the cell is over 2V (at least double that of other typical cell technologies). Given the relatively small panel area available on a CubeSat, it is possible to acheive a useable array voltage with only one cell. This enables the use of large area solar cells - the standard cell size of the space industry – providing a cost-effective means of getting decent power levels from CubeSat solar panels.

For 1U CubeSats, a single 100mm x 83mm panel can accommodate two High Efficiency Large Area solar cells. This equates to a power of greater than 2W and a terminal voltage of between 4V and 6V. Most of the major solar cell providers in the USA, Europe and Japan can provide multi-junction cells. We have typically used the Spectrolab UTJ cells for our CubeSat panels, the large area cells having dimensions 39.70mm x 69.11mm. For solar panels with significant cutout areas on the solar panel, we use 20mm x 20mm to enable us to acheive the same panel voltage as a standard 1U solar panel.

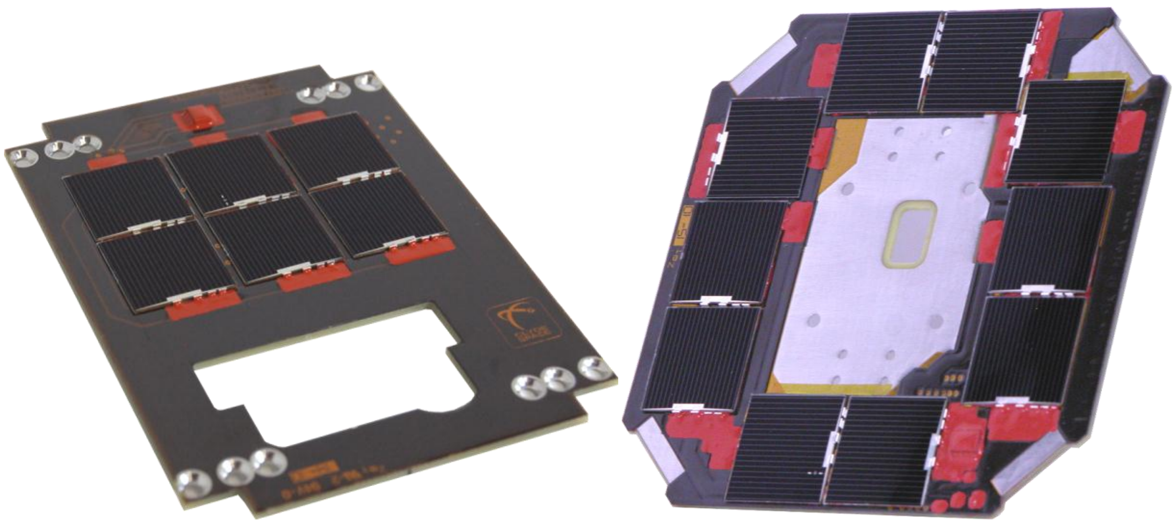

Figure 5 1U CubeSat Solar panels using 20mm x 20mm Spectrolab solar cells.

For 3U CubeSats, it is possible to accommodate up to 8 large area cells in series on the 330mm x 83mm side panel, resulting in a voltage of 14V to 24V at the panel. The image below shows a 7 cell 3U CubeSat side panel using Spectrolab 28.3% efficient cells.

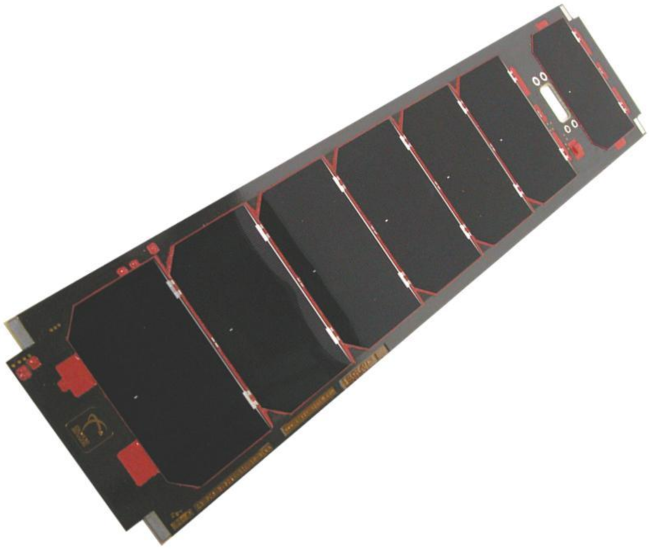

Figure 6 1U Clyde Space 3U CubeSat Solar Array

CubeSat Battery

At Clyde Space we have in-house expertise in the use of commercial Lithium Polymer cells in space, and we have developed a screening programme for the use of our cells on space missions. The cells that we use have dimenions of 59mm x 37mm x 5mm, and are athe perfect size for a slim 2 cell CubeSat battery. Furthermore, 2 lithium ion cells in series provide an ideal voltage of 7V - 8.4V, making it simple to efficiently generate the 5V and 3.3V buses using step-down converters.

For battery capacity requirements, this can tend to be mission specific, but certain general platform information allows the battery capacity requirement to be determined. For instance, the typical Orbit Average Power (OAP) for a 1U CubeSat in a sun synchronous orbit with maximum eclipse should be no more than 1.8W (the panels are 100mm x 83mm, so even with high efficiency cells the maximum power per panel is about 2.1W). Therefore, the maximum battery capacity would be required for 1.8W for 35 mins = 1Whrs. With a DoD of 20%, this equates to a battery capacity of 6Whrs. With Lithium Ion cells it is important to also consider that the capacity fades over the battery life. 30% fade is a reasonable assumption for a 3 year mission in LEO, therefore a battery capacity of 9Whrs at beginning of life (BOL) is preferable.

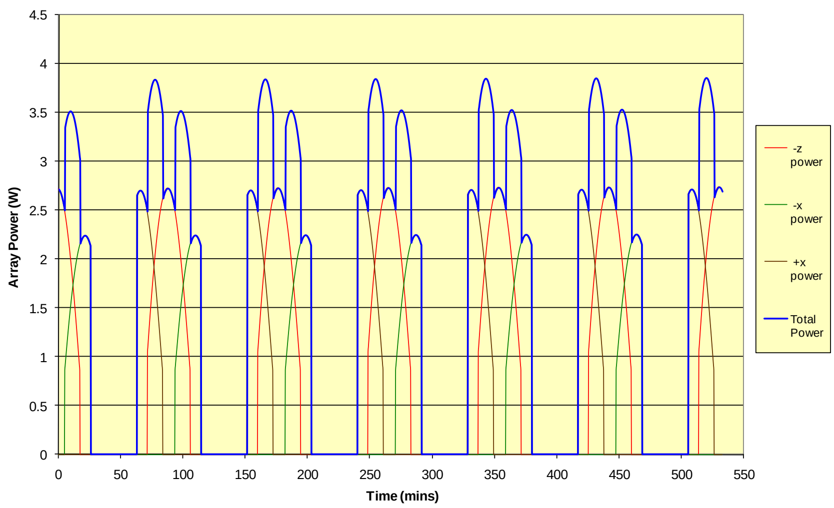

Figure 7 Typical Power Profile of a 1U CubeSat.

Our solution is to have a scalable, integrated two or four cell battery (2s1p or 2s2p) for 1U CubeSats and a separate scalable battery for up to 2s3p per battery unit. Each two cell lithium polymer battery string provides a minimum BOL capacity of 2 x 3.7V x 1.25Ah = 9.25Whrs.

Due to the form factor of the lithium polymer cells themselves, we have been able to use only PCB material to support the cells mechanically. This has enabled the integration of several other functions with the battery, including; a thermostatically controlled heater (with over-ride capability), cell balancing circuit, over current protection, current telemetry, current direction telemetry, plus battery voltage monitoring. A picture of our 2 cell CubeSat battery is shown in Figure 8.

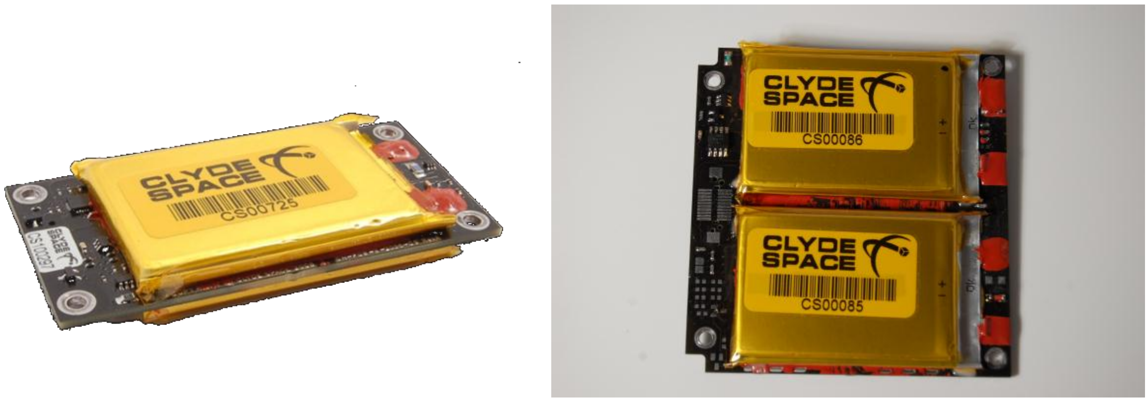

Figure 8 Clyde Space 2s1p CubeSat Battery daughter board and remote battery board.

Figure 9 3U CubeSat battery with cell retainer board.

4. INTERFACES

The main power system interfaces are designed to be compatible with the standard Pumpkin, Inc. CubeSat Kit bus via the stack Samtec ESQ connector. The power system specific connections through the bus connector are as follows:

- Separation/activation switch. Using the NC and C pins of the plunger switch on the launcher interface facet, the spacecraft is held OFF during launch, coming ON only once the spacecraft have separated from the launch vehicle.
- The Remove Before Flight (RBF) switch is used to disconnect the battery negative from ground, hence isolating the battery. This is particularly important when putting the

spacecraft into storage as it enables the battery to be stored in a disconnected, discharged state.

- Battery bus, 5V, 3.3V and ground connections are provided over the main bus.
- With the spacecraft connected only by the USB port, the power system provides the capability to charge the battery using USB power. The maximum charge current over this connection is 0.2 A.

Other connections and properties are as follows:

- The solar arrays connect directly to the power board via dedicated connectors located on the board perimeter.
- The spacecraft ground is connected to the spacecraft structure on the power board to ensure that no currents flow through the structure and for EMC issue prevention. This connection would be made only on one power board where multiple boards are used.

5. POWER SYSTEM PACKAGING

The entire power system electronics and battery are accommodated within the footprint of the standard PC/104 card. The battery is a daughter board to the power system electronics. The main power connections between the battery and the mother board are made through PCB mount busbar studs; these also provide the mechanical means of mounting the battery. Telemetry and control connections are made from the battery via a surface mount stacking connector. Up to TWO battery daughter boards can be mounted on a 1U power system board.

A Power System board on its own has a maximum system height of 18mm. With one battery board this increases to 24mm and with two battery boards it is 30mm. The power system is designed to be extremely mass and volume efficient; these characteristics are critical for CubeSat missions.

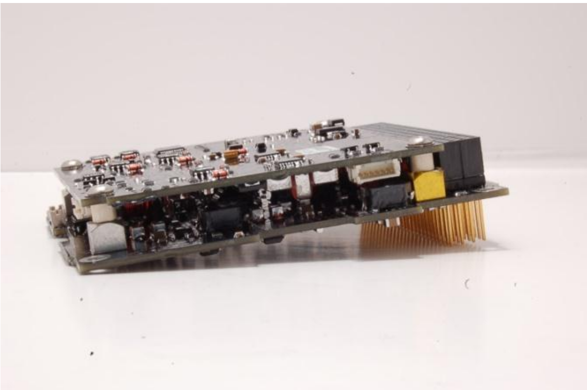

Figure 10 3U Power System for CubeSats with Deployed Solar Panels

The 3U Power Module is slightly different in design in that it is required to interface to 4 solar arrays that can reach up to 9W in power delivery. Therefore, TWO of the 3W BCRs from the 1U system have been replaced with 9W versions; this time using a BUCK topology. Due to the larger power stage, it was not possible to include the battery mounting hardware onto the power system.

More recently, our introduction of the CubeSat deployed EPS units means that up to 12 3U Solar panels can be interfaced to the EPS. For this, there are SIX 10W BCRs, each interfacing to TWO solar panels. In addition, we have added a 2.5V regulated voltage to the 5V and 3.3V lines, providing yet more functionality and capability.

6. ONLINE SHOP

Given the nature of the systems described in the previous section, it becomes clear that this is indeed a very different approach to spacecraft systems design and production, not just from a technical perspective, but also from a commercial perspective. Since introducing these products to the CubeSat market in August 2007, there has been an increasing pressure from customers to buy the products with a credit card. Therefore, at Clyde Space we investigated the options available to us in terms of credit card sales:

- The standard option was to have a credit card terminal at Clyde Space and process payments over the phone, but this method is actually only cost effective if you are making multiple transactions per day; CubeSats aren't quite at those kinds of volumes yet.

- The second option was to use internet sales. This can also be expensive, especially when considering the percentage of the sale that 'Paypal' and 'WorldPay' will take for each transaction. When a customer is making a payment of over $1000, these percentages become significant. There is also the issue of the customer being directed off the main website onto a payment website, which is not ideal.

In the end we found a method of having an ecommerce element integrated with our website and not having to pay a premium to the banks for each transaction.

Now that we had decided on the route we would take to enable credit card sales, it was then apparent that the ability to have our products sold online on our website, combined with the technology available for online sales, could open up a whole new approach to the specification and selection of spacecraft systems.

Related Products

Immediately, with online sales, it is possible to list related products on a webpage when a main product of interest is selected. This is not only important as a sales tool, but it is also important for the customer as they will have more information at their finger tips to help them select the systems, accessories and test equipment that they require to make their mission run as smoothly as possible.

For instance, with the 1U CubeSat EPS, most customers will buy ONE or more flight battery, but some also buy a workhorse battery to ensure that the flight battery is in optimum condition for the mission. Customers also require other items such as the solar panel to EPS harness, solar panels, solar panel clips, magnetorquers integrated with solar panels…the list goes on. It is possible to communicate these additional items in text on a datasheet or proposal, but it is much easier to add the additional items to an online shopping basket and buy all of the required items in one transaction.

Product Specifications

At Clyde Space we have reasonably detailed product datasheets, but due to the nature of the products that we have for CubeSats, it is not practical to have a datasheet per variation of CubeSat item. It is also not practical to have datasheets for small items such as harnesses, clips, extra connectors, etc. The nature of ecommerce, however, forces the vendor to detail each item so that the customer knows exactly what they are placing in their basket. This means that there is more information available at the customer's finger tips to enable an informed buy decision to be made.

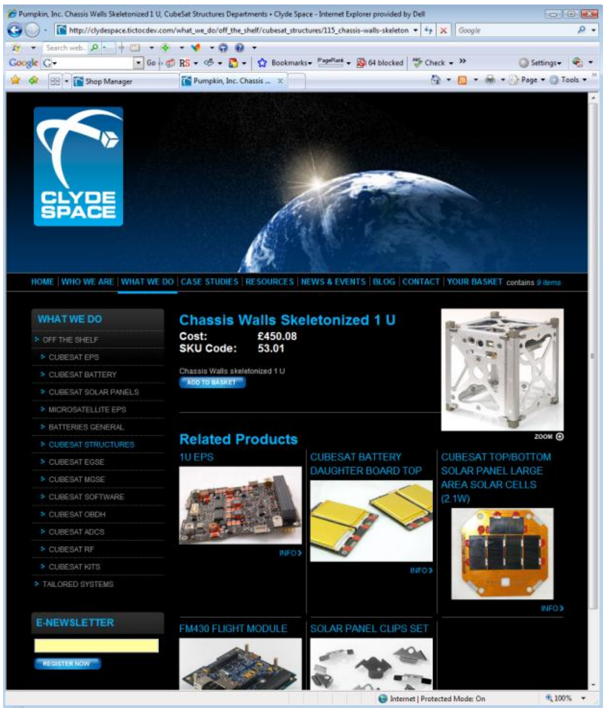

Figure 11 Example of how ‘related products’ helps to guide customers to other required items.

This level of detail in the online product description enables the customer to place an order at any time of the day from any place in the world with internet access. Given the international nature of the space industry, this is a very powerful capability as it means that at a minimum, a day can be saved in the order placement, this could be critical for projects with tight schedules.

Frequently Asked Questions

No matter how fast the response time from a company to a customer enquiry, there is nothing quite like having the information at your finger tips. We are often asked questions about our designs that we have not yet considered as something that would be on the minds of our customers. We try hard to ensure that as much information as possible is included in our User Manual, but it is sometimes not practical to include everything. In addition, many of our customers are undergraduate students, and they perhaps don’t have the engineering experience that a professional engineer takes for granted.

Another useful resource for us and our customers is the Frequently Asked Questions (FAQ) page. This enables us to list the commonly asked questions about the system (and anticipate a few others) and have them listed on the website for immediate access for the customer. The FAQs can even direct the customer to other sites that have software or interfacing components that can be used to address whatever issue has been encountered. Again, this is a very powerful tool to have and is ideal for the CubeSat community.

Shipping

As with most online stores, it is also possible to have information on the shipping costs immediately when making the purchase.

Future benefits of ecommerce

Clyde Space is continuing to grow its microspacecraft and CubeSat product line through the development of new in-house systems and also through the licensing of existing subsystems from other organisations. The ultimate goal of Clyde Space in this respect is to have a full mission suite of subsystems available to buy on-line off-the-shelf. There are two main objectives in this goal:

1. To encourage CubeSat projects to use the Clyde Space website to buy the subsystems they require and also as a resource for their mission planning and design.

2. To make it possible for a complete Spacecraft to be created and then purchased online using a credit card.

Objective number '2' is key as it will involve the use of web-integrated mission design tools that will down select the appropriate subsystems for the mission. An analogy for this capability is like buying a Dell computer online, where it is possible to customise the system to individual requirements.

We see this capability being available on the Clyde Space website in two steps. These steps are covered in the following two sub sections:

7. Power Budget Analysis and Power System Sizing

The core capability of Clyde Space is in power systems. Our expertise in power systems is not just in the design and manufacture of the components, but also in the sizing and specification of the system for a given mission profile. Therefore, we are planning to introduce an online mission design tool that will enable users to select the solar arrays, battery and power system for their mission.
The tool will provide the ability to view Beginning of Life (BOL) and End of Life (EOL) performance data. All users will be able to register on the website and save their mission design information online.

The mission design software will have a function where the hardware selected for the mission can automatically be added to the online basket ready for purchase. Again, the basket can be saved for purchase at a later date.

CubeSat Design Tool

The next step, however, is more ambitious and will involve an online mission design tool. This element of the online design tool will be developed to coincide with the availability of complete subsystem suites and support systems from the online shop. This tool will include the power budget analysis feature already described, but will include other parameters such as pointing accuracy, on-board data rates, data storage, processing capability, uplink and downlink speeds, groundstation locations, etc.

Figure 12 Online shopping basket with CubeSat subsystems being purchased.

From the information inputted buy the user it will then be possible to build up a picture of the mission requirements and how they relate to the available subsystems. It is likely that this will be an iterative process and refinements will need to be made by the user throughout the process to, for example, optimise the link budget, etc.

Ultimately, there will be the ability to build up the necessary subsystems, add them to the online basket and buy the complete system when ready.

Another benefit of this would be the fact that all of the systems would be already tried and tested compatible with each other. This will reduce the amount of time spent by the customer in spacecraft testing and interface development, further reducing the time to launch of the mission.

8. CONCLUSIONS

Designing and producing power systems, batteries and solar arrays for CubeSats is a very satisfying activity. It is a very different approach to spacecraft and, as such, the customer base for CubeSat systems is often very varied. It makes for interesting work, also in the challenges adapting our processes to ensure that the cost of our systems are low enough for our customers to afford and still maintain margins sufficient to enable us to continue as a viable business.

From a technical perspective, the main challenges were to design a system that could meet the demands of a wide variety of mission profiles, to fit the electronics and battery within a very tightly constrained volume and to design the system to cost and for on-orbit reliability. We are satisfied that we have met our objectives. At the time of writing this paper, Clyde Space has sold over 120 CubeSat Electrical Power Systems to organisations all over the world.

The Clyde Space team are enjoying the challenge of producing cutting edge, innovative hardware and business solutions for next generation CubeSats and other miniature spacecraft and are proud to be a key contributor to be CubeSat phenomenon.

9. REFERENCES

[1] *Clyde Space Website: www.clyde-space.com*.
[2] Andrew E. Kalmann, Pumpkin, Inc, *Recent Advances in the CubeSat Kit Family of Picosatellites*, 19th Annual AIAA/USU Conference on Small Satellites, August 2005.