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Advanced Methods for Structural Machining and Solar Cell Bonding Allowing High System Integration and their Demonstration on a Pico-satellite

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ABSTRACT

The constraints on mass and size imposed on pico- and nanosatellites drive spacecraft designers to seek fabrication methods allowing a large degree of integration. From a configuration point of view, as sizes decrease the notion of subsystems vanishes, the structural interfaces become unique and need to be custom-made. This paper describes the integration concept of the SwissCube pico-satellite with special focus on the state-of-the art structural machining process. It also presents a new soldering technique for solar arrays. Both technologies are well suited for pico- to small- satellite applications and introduce flexibility in the design process.

The first part will introduce the configuration of the SwissCube and present the advantages of wire electrical discharge machining (EDM) to manufacture the satellites primary structure. This technique, used for the SwissCube pico-satellite, has allowed the manufacture of a complex lightweight monoblock frame that serves as primary as well as secondary structure. The frame is one of the lightest in the CubeSat community while its rigidity is very high as shown by FEA and vibration tests.

The second part will focus on a new bonding technique for solar arrays. So far the common technique for solar array bonding consisted of attaching solar cells with silicon or epoxy adhesives. In the frame of the SwissCube project, an innovative assembly approach of solar cells has been investigated. It consists of soldering solar cell on a printed circuit board panel with a process of brazing. Environmental tests have been successfully performed to evaluate the reliability of this process. Non destructives tests were also done to evaluate the quality of the solder pads.

INTRODUCTION

To increase the performance of small-satellites technologies are required that drastically reduce the mass and power of components without compromising performance. It becomes therefore imperative to re-invent the way by which functional elements are integrated. This novel class of miniaturized spacecraft forces highly integrated subsystems, where the traditional physical boundaries between subsystems are removed, a design paradigm known as Multifunctional Structure (MFS)[1]. The idea is to integrate thermal as well as electrical functions into conformal load-bearing structures. This level of integration effectively eliminates traditional electronic boards and boxes, large connectors, bulky cables, and thermal base plates, implying major mass, volume and cost savings[2].

This paper presents two advanced concepts in spacecraft manufacturing that increases integration density and reduces mass. These new integration concepts are a state-of-the art structural machining process as well as a new bonding technique for solar arrays. Both have been developed in the framework of the SwissCube satellite mission, a CubeSat built by ”Ecole Polytechnique Fédérale de Lausanne (EPFL)” and several other Swiss academic partners. Although the primary objective of this satellite is to provide a dynamic and realistic learning environment for students, emphasis has been placed on the quality of workmanship. The mission's scientific objective, i.e. take measurements of the Airglow phenomena (see Figure 1), has imposed a design approach for assembly that allows an efficient integration of the platform subsystems and the optical payload within the available 10×10×10 cm^3.

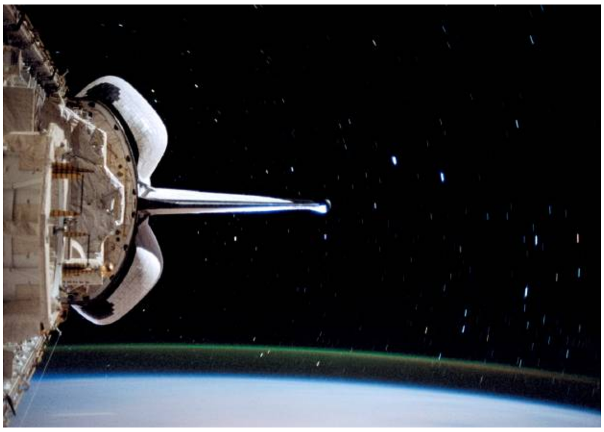

Figure 1 : Airglow phenomena (green line just below the Space Shuttle) [photo NASA].

The first part of the paper will introduce the configuration of the SwissCube, describe the various sub-systems of the satellite and explain the adopted solutions for their integration into the main structure.

The second part will present the advantages of wire electrical discharge machining (EDM) to manufacture the satellites primary structure. At present the most common machining techniques used in the space field are CNC milling and CNC turning, both chip cutting operations. Wire EDM cuts metal by producing a rapid series of repetitive electrical discharges between a very thin wire and the piece of metal being machined. The advantages of this technology are the capability to machine complex and thin shapes where conventional methods would fail due to excess cutting tool pressure. This technique has been used for many parts of SwissCube, especially the satellite structure, a complex lightweight monoblock frame that serves as primary structure and provides part of the secondary structure. With 95 grams, the Swisscube structure is one of the lightest in the CubeSat community. Finite elements analyses and modal tests have been performed to ensure that its rigidity satisfies the requirements.

The third part of the paper describes an innovative bonding approach for solar cells. Currently rigid solar cells assemblies are done by adhesive bonding of solar cells onto satellite panels. For SwissCube a new technique has been developed, which directly solders the solar cells onto FR-4 substrate panels. Various type of solder paste as well as copper footprints on the panels have been investigated. To space qualify this new bonding technique, environmental tests such as random vibrations and thermal shocks, have been performed. No failures or cracks of solar cells have been visually observed. Moreover, two kinds of non-destructive tests, X-ray and ultrasound inspections, have been done to evaluate the quality of the solder pads. Those inspections, performed before and after environmental tests, have not shown any significant degradation of the solar cells or solder joints.

SWISSCUBE CONFIGURATION

SwissCube is a small cube-shaped satellite with 10 cm side length that weighs less than 1 kg. Although it is small, it contains all the critical subsystems and functions present in larger satellites. An exploded view of the SwissCube satellite is shown in Figure 2.

The outer mechanical interfaces and design of SwissCube are defined by the CubeSat Design Specifications[3]. For example the external size of the satellite and the locations of the access port or deployment switches are imposed. The internal layout of the SwissCube is limited by two principal restrictions: the payload and the arrangement of printed circuit boards (PCBs). The ideal configuration is one optimizing both constraints at the same time.

As shown in Figure 2, the satellites primary structure is manufactured from a single block of aluminum. This "monoblock" approach offers the best relationship between mass and rigidity but has the disadvantage of significantly increasing the complexity of the satellite's assembly procedures. Secondary structures are directly attached to the external or internal sides of the monoblock.

The payload, a miniaturized telescope of Ø 30 mm × 45 mm, is placed in the center of the +X face of the satellite. The PCB containing the optical sensor is directly attached to the payload assembly. This orientation gives favorable values for inertial properties and allows placing two solar cells on the external panel containing the camera aperture.

The electronic boards inside the satellite are arranged into two PCB stacks placed on each side of the optical payload. These stacks contain the attitude control and determination system (ADCS), the communication subsystem (COM and BEACON), the command and data management system (CDMS) and the electrical power system (EPS). Electrical and data interfaces are routed through a connection and a power distribution board (motherboard) placed perpendicular to the PCB stacks. The electronic boards are separated using

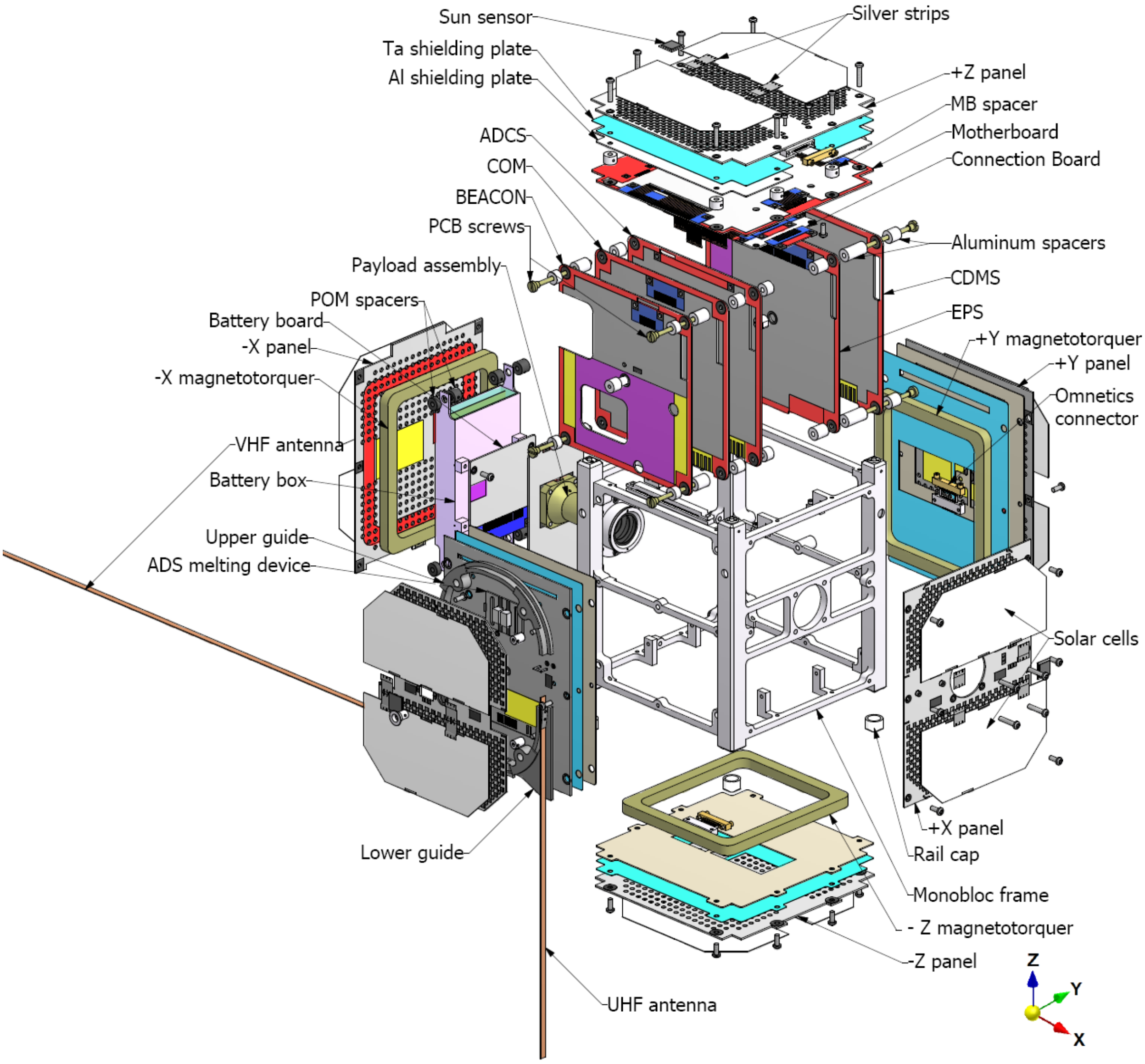

Figure 2 : SwissCube exploded view.

aluminum spacers. Their role is to mechanically connect the different PCBs together as well as to attach the PCB’s stack and battery subassembly to the primary structure. Additionally, the spacers serve as a thermal path between the PCBs and the aluminum frame. Both stacks are fixed on the internal +Y and -Y faces of the satellite, allowing a large amount of free space for the payload subsystem and keeping an increased accessibility to components placed in the centre of the satellite.

The use of a motherboard and connection board simplifies the routing of wires. Whenever possible interface cables are directly soldered to the PCB's to increase reliability. To avoid failure of solder joints the cables are clamped down by means of specially designed mechanical stress reliefs.

Six external multifunctional panels close the cube. They are directly screwed to the satellite's primary structure. These panels are made of PCB substrate and are subassemblies including solar cells, sun sensors, read-out electronics and a radiation shield. An Omnetics space graded miniature electrical connector is used to link the external panel with internal electronic boards. In order to protect internal PCBs from space radiation, shielding plates are located just behind external panels, more precisely on +Z, -Z, +Y and -Y panels. According to Fan and al. [4], our optimal shield consists of multiple layers of different shield materials, a high-Z layer (Tantalum) sandwiched between a low-Z layer (Aluminum).

Three magnetotorquers constitute the active actuators of the SwissCube. They consist of copper coils which interact with the Earth's magnetic field and are glued on the interior faces -X, +Y and -Z sides of the cube. For the attitude determination the sensors are:

- A 3-axis magnetometer to measure the Earth's magnetic field intensity and direction. These magnetometers are located on the ADCS board.
- Three 1-axis MEMS gyroscopes to measure the spinning rate of each axis. The first one is directly mounted on the ADCS board. The two remaining are mounted on a bracket screwed onto the ADCS board.
- 6 novel MEMS Sun sensors to determine the sun vector. They are glued on each external panel and electrically connected by wire bonding.

For the RF communication with the Earth two antennas are placed on the -Y face of the satellite. The first for downlink data is a 180 mm long UHF monopole antenna of 437 MHz frequency. The second one for uplink is a 610 mm long VHF monopole antenna using a frequency of 146 MHz. As the antennas are longer than the satellite, they are wrapped around plastic guides and released once the satellite is in orbit by melting a polymer wire. The heat required for melting the wire is created by the current passing through a nichrome wire in contact with the polymer wire. RF cables are directly soldered at the extremities of both antennas. The other extremity of the RF cable has a RF connector, in order to be connected to the communication board.

SwissCube also carries two rechargeable Lithium-Polymer batteries. Under high vacuum, these batteries can undergo a physical expansion. To counteract this effect a milled aluminum box is used to enclosed them. In order to optimize the inertial properties of the satellite the battery box is located at the opposite site of the payload assembly. The box is attached to the structure at the -X side by the same screws and spacers than the PCB stacks. Thermal simulations and tests have identified the need to insulate the batteries from the satellite. An active thermal control of the battery subassembly is present to avoid extremely cold temperatures for both batteries. A heat dissipation system onto a copper foil is located between both batteries.

Four deployment switches, located at the four +Z extremities of the rails, are used to turn off all power of the SwissCube during launch. The kill switches act also as separation springs which give a relative velocity after deployment from P-POD to separate from the other CubeSats.

WIRE ELECTRICAL DISCHARGE MACHINING

Machining concept

One of the most important material removal methods, called conventional machining, is a collection of material-working processes in which power-driven machine tools, such as lathes, milling machines, and drill presses are used with a sharp cutting tool to mechanically cut the material to obtain the desired geometry. The most common manufacturing processes for metallic structures in space industry are machining, chemical milling, sheet-metal forming, casting, forging and extruding[5].

The development of micro mechanical components, the growing needs for applications of advanced, difficult-to-machine materials have made the wire electrical discharge machining (WEDM) an important manufacturing process to meet these demands[6]. In general Electrical Discharge Machining (EDM) is used for hard metals or those that would be impossible to machine with traditional methods. One critical limitation is that EDM only works with materials that are electrically conductive. Since the introduction of the process, EDM has evolved from a simple process to manufacture tools and dies to preferred method to produce micro-scale parts with the highest degree of dimensional accuracy and surface finish quality.

The history of EDM begins in 1943, with the invention of its principle by Russian scientists Boris and Natalya Lazarenko in Moscow[7]. In the 1950's, progress was made on understanding the erosion phenomenon. It is also during this period that industries produced the first EDM machines. Swiss industries were involved very early in this market, and still remain leaders. Agie was founded in 1954, and les Ateliers des Charmilles (near Geneva) produced their first machine in 1955. With the introduction of numerical position control in the late 1960's and early 1970's, the movements of electrodes became much more precise.

The EDM can be separated in two main types, as shown in Figure 3. In die-sinking EDM, the electrode is shaped and will reproduce its negative form into the workpiece. The wear has to be very low, in order to keep the electrode original shape unmodified during the whole machining process. In wire EDM, the electrode is a continuously circulating metallic wire, which cuts the workpiece along a programmed path. Deionized water is used as dielectric, directly injected around the wire. Die-sinking EDM is mainly used to produce injection molds, whereas the main applications of wire-cutting EDM are the production of steel cutting dies and extrusion dies[7].

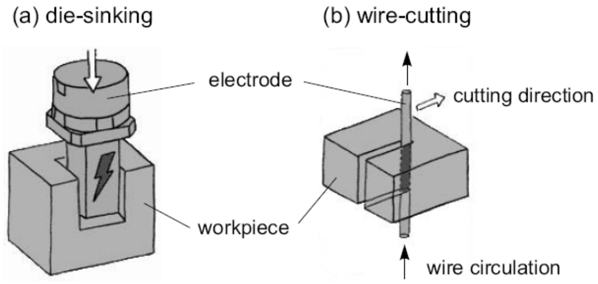

Figure 3 : Two main types of EDM: die-sinking and wire-cutting[7].

The wire electrical discharge machining (WEDM) process can be used to cut plates as thick as 300mm. The wire is held between upper and lower diamond guides. These guides move in the *x–y* plane and on almost all modern machines the upper guide can also move independently in the *x–y* plane, giving the ability to cut complex shapes (for instance a circle on the bottom and square at the top). Consecutive sparks produce a series of micro-craters on the work piece and remove material along the cutting path by melting and vaporization. The particles are washed away by the continuously flushing dielectric fluid. Only a tiny part of material is consumed during the machining. The typical wire diameter is 0.1 [mm], giving a cutting path of 0.12 [mm]. Today, the smallest wire diameter is 20 [μm] and the geometry precision is not far from ± 1 [μm][8].

The quality of the machining, i.e. precision and roughness is directly related to the discharge parameters (current, voltage, discharge duration, polarity...). Sparks with strong current produce deep craters: a high removal rate is obtained but with a high surface roughness. On the other hand, sparks with low current will produce small craters: the surface roughness is low but the removal rate is also low.

To summarize, the main advantages of EDM include machining of:

- complex shapes that would otherwise be difficult to produce with conventional cutting tools
- extremely hard material to very close tolerances
- very small work piece cross-sections where conventional cutting tools may damage the part from excess cutting tool pressure.

On the other hand some of the disadvantages of EDM include:

- The inability to machine non-conductive materials.
- The low machining speed, as compared to the other non-traditional machining processes.
- Thermal stress, which could limit the minimum thickness of the workpiece[6].

Application of the wire EDM for SwissCube

The WEDM is used for the fabrication of three different parts of the SwissCube: the satellite main frame, the battery box and the cable stress reliefs. This chapter will describe the used machining facility and the parts manufacturing process.

A Charmilles Robofil 200 machine has been used to fabricate mechanical parts by WEDM. This facility uses a zinc-copper wire with a diameter of 0.25 [mm]. The electrical characteristics are a current of 32[A] and a voltage of 120 [V]. The electrical discharges duration is around 7 [μs]. The maximal dimensions that can be machined are 220×160×120 mm^3 in X, Y and Z axes.

Besides the previously mentioned advantages of a mono-block approach other advantages are a reduction in the tolerance stack-up, an optimal thermal conductivity and the saved mass because no joints are required between the various parts of the frame. On the other hand disadvantages of this design concept are that it cannot be manufactured with conventional processes; accessibility of the subsystems is limited for integration; and design changes imply a complete re-manufacture. In our case the structure was manufactured five times in three years, which turned out to be acceptable. The integration process was thought early on and subsystems were designed to simplify assembly (standardization of the PCBs).

Thanks to the WEDM a complex satellite structure containing a lot of various attach points has been machined in one part. This machining technology gives us the possibility to obtain very thin structural components that would not be possible to machine by traditional process due to excess cutting tool pressure. The following paragraphs describe in more details the design of the frame.

The design of the structure starts with the 4 main rails, given by the CubeSat specifications[3]. They have a section of 9.0×9.0 mm^2. In order to save mass these rails present a passing hole and chamfers. The rails are interconnected with small crossbars which have a section of 4×3mm^2. To these crossbars different mounting points are used for attaching all the components of the SwissCube.

The payload-support is designed as shown in Figure 4. The attachment of the payload is done by 4 M2 screws. The horizontal crossbars of the payload-fixation have the same cross section as the crossbars (4×3 mm^2). As the payload has a length of about 50 mm there is a cantilever effect on the fixation point. Finite elements analyses and modal tests show that the structure is sufficiently rigid at that fixation point (see the paragraph about "Analyses & Tests").

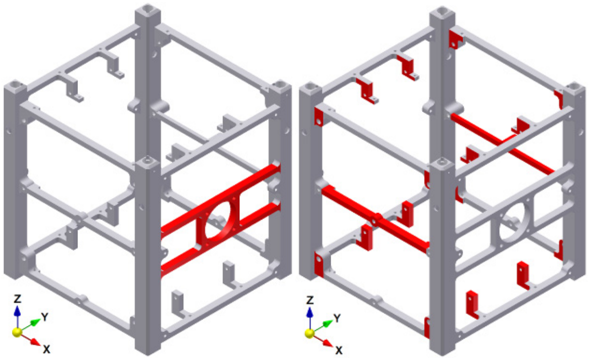

Figure 4 : Mounting points for Payload and PCB-stacks.

In the corners of the -Y and +Y faces some material is kept to provide mounting points for the internal subsystems by the means of the spacers and at the same time to attach the external panels. In the middle of each crossbar in Y direction there are two other attachment points in order to have a counter fixation for the spacers (see in Figure 4 the small "arms" highlighted in red). Such indents on the main frame would be impossible or bulky with conventional machining. Moreover, two additional crossbars are located in the middle of the -Y and +Y faces. They offer the possibility of mechanically connecting the PCBs stacks at their center. This option increases the rigidity and the first vibration mode of the PCBs.

Four attach points are present on the +Z side of the satellite for the fastening of the connection board (see Figure 5). In order to fix the side panels, tapped holes in the various crossbars are foreseen (see Figure 5). The motherboard is also mounted with the aid of taped holes in the crossbars of the +Z-face.

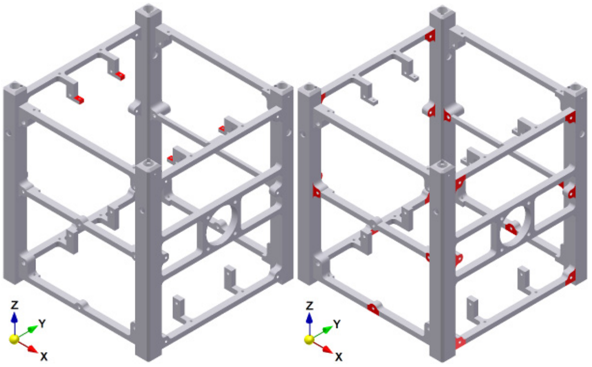

Figure 5 : Mounting points for the connection board and side panels.

The monoblock frame machining can be separated in two steps: the first one consists in milling the six side faces into a cube thanks to the use of a CNC milling machine. The second step is the cutting of the internal volume by WEDM. The part that has to be removed with this process is highlighted in red in Figure 6. Since the WEDM consumes only a small quantity of material, this volume can be recovered for other purpose. After the WEDM, the frame will be finished by traditional machining which means drilling thread, filing of the edges, etc. All these machining steps are executed in two different machine shops at the EPFL.

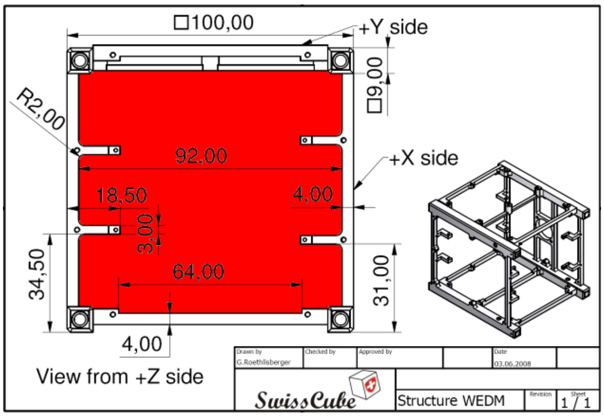

Figure 6 : WEDM of the monobloc frame.

The final mass of the structure is 94.5 g, probably one of the lightest in the CubeSat community. The Engineering Qualification Model (EQM) structure with both surface treatments is shown in Figure 7.

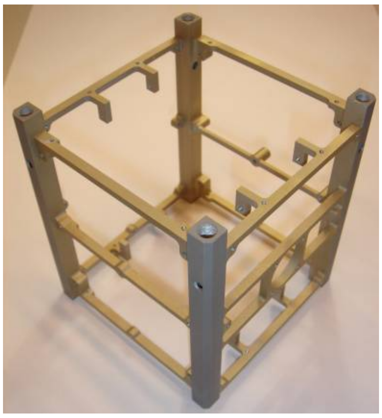

Figure 7 : SwissCube Monobloc Frame (EQM).

The second mechanical part of the SwissCube machined by WEDM is the battery box. A common problem with Lithium-Polymer battery cell is that they may rapidly loose performance and eventually entirely cease function when subjected to a high vacuum. Typically this effect is related to a physical expansion of the battery block. To counteract this effect, we enclose the batteries in a milled aluminum box. The gap between this box and both Lithium-Polymer cells is filled with epoxy resin. This is also a solution to provide mechanical interface between the cell and the satellite structure. With WEDM technology, thin walls of 0.8 [mm] and inner right angles are possible. The inner dimensions of the box are 11.7 x 39 x 66 mm^3, which gives enough space for two batteries. The box is attached to the structure by the PCB-screws and spacers as shown in Figure 2 and Figure 8.

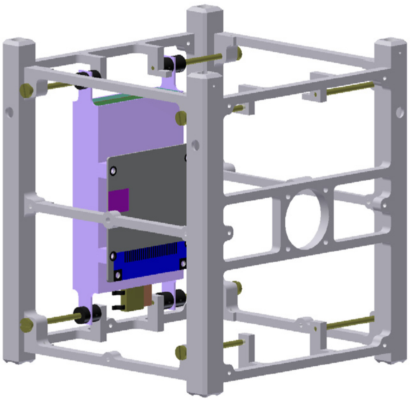

Figure 8 : Attachment of the battery box (in purple).

The first step in producing the battery box consists in milling the exterior of the part using a CNC milling machine. The second step is the cutting of the internal volume by WEDM.

The third mechanical parts of the SwissCube machined by WEDM are the stress reliefs that block the cables and thus mechanically protect the soldered joints against vibration. A 4 mm thick Aluminum plate is prepared and all stress reliefs are cut by WEDM in one time. This machining technology gives us the possibility to have very thin slots, one for each cable. This design permits to mechanically block the cables with a more uniform contact pressure and also to tightly separate the cables before soldering them on the PCB (see Figure 9).

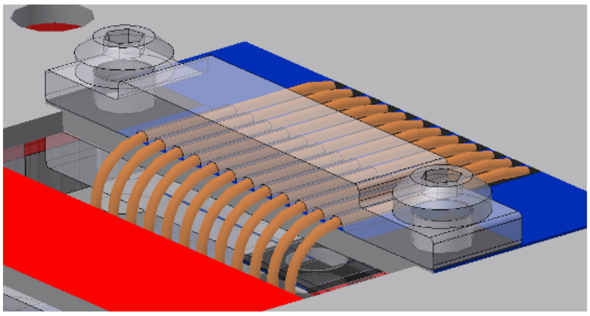

Figure 9 : Cable stress relief (in transparency).

Analyses & Tests

Structural performance benefits from a small frame; natural frequencies increase and bending moments scale very favorably with decreased size. However, the requirement of a light structure makes it desirable to reduce the margins of safety to a minimum. For this purpose reliable information about the loadings as well as an accurate model to predict the behavior of the structure caused by these loads are needed. An accurate model which correlates with the physical tests is an effective tool to predict the behavior of the structure after changing properties of satellite components, or after applying a different loading. Modal tests have been performed in order to obtain experimental values (eigenfrequency, damping), which are used to calibrate the FEA model.

Due to the complexity of the design and the abundance of components inside the CubeSat, the finite elements model is simplified to represent only the basic structural components of the satellite that will be load bearing (see Figure 10). It is still unknown whether the satellite will be launched horizontally or vertically. This circumstance requires three separate FE analyses to be performed; two horizontal cases, acceleration in X or Y direction, and one vertical case, in the Z direction.

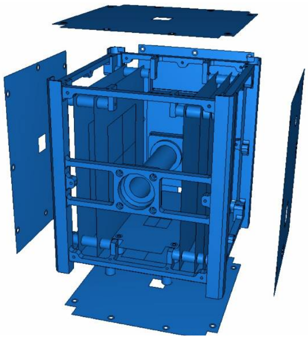

Figure 10 : Simplified version used for FEA.

The worst case static load of 7.5g was identified for SwissCube on the potential Dnepr launcher. Including a factor of safety of 1.25, a worst case acceleration of 10g has been considered for the static analysis. The determined margin of safety for the whole satellite is a factor of 21, the weakest points being the Z-axis rail ends. Since this structure is basically constructed of thin beams, one final check is made to ensure that the reduced-section cross-bars and rails will not fail in buckling. Critical stresses of buckling for the rails and crossbars are equal to 716.4MPa and 137.5MPa respectively. With a maximum stress of 1.3 MPa in the horizontal case for the rails and crossbars and a factor of safety of 1.25, the margins of safety (MOS) are 440 and 83 for the rails and crossbars in the horizontal case. For the vertical case, the maximum stresses are 1MPa and 2.85 MPa for the crossbars and rails respectively, so the MOS are 200 and 109 for the rails and crossbars in the vertical case. Thus the satellite structure has very large margin of safety, i.e. the structural components will not fail in compressive yield for any of the worst case loading conditions.

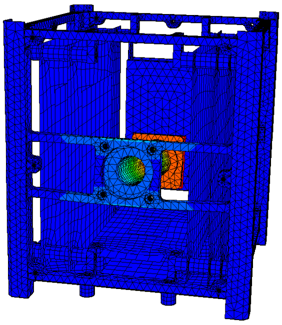

Figure 11 : 8th mode of the satellite assembly.

Modal analysis has been performed with the same simplified model using the Abaqus software. The first eight modes apply to the PCBs (external panels or internal PCBs) around 300 Hz. The first vibration mode of the primary structure (payload support) takes place around 430Hz (see Figure 11), which is far above the launch requirements. The deformations have been arbitrarily enhanced to allow the reader to more easily identify the difference in the shapes of the modes.

Sinusoidal, random vibration and shock tests at qualification level have been performed in August 2007 on a Structural Model composed of some functional parts and other mass-dummy parts. The test levels were 9.9 [G_{rms}] for the random test and 4'500 [g] at 10 [kHz] for the pyroshock test. The model successfully passed these various mechanical tests without problems.

SOLAR CELLS BONDING

State of the art

Most of the small satellites around the world nowadays use solar cell assemblies (SCA's) for the power generation. The process of bonding the solar cells onto the structural panel is a critical manufcturing step. At present, adhesive bonding is done manually and is by far the most commonly used technique to manufacture rigid solar panels for conventional satellites[9, 10].

The adhesive must not only withstand repeated temperature cycles but also the mechanical stress during the launch in order to guarantee a high reliability in the space and launch environments. A long-established way of solving this problem is using a low outgas silicone adhesive like NuSil CV-2568[11] (see Figure 12). Due to its physical properties this silicone adhesive is especially useful to bond solar cells on solar panels[12].

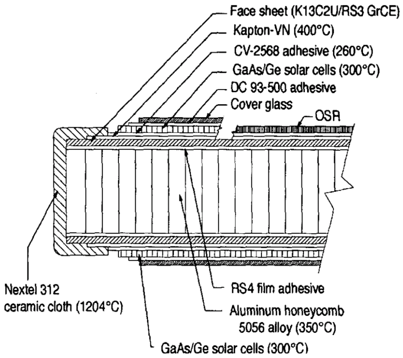

Figure 12 : Solar panel bonding design for a Mercury Orbiter[13]

The process of adhesive bonding can be described as the five following steps:

- Surfaces are cleaned and degreased with a solvent.
- A silicone primer like NuSil SP-120 is applied before dispensing the adhesive on the surfaces in order to improve the adhesion.
- The adhesive is mixed with a catalyst and then applied on the solar panel or on the backside of the solar cells.
- Solar cells are placed on the solar panel which is usually a Kapton covered aluminum substrate (like honeycomb).
- The adhesive is heated, hardened and finally tested.

Similar techniques have been already used to bond solar cells on CubeSats. However, due to cost and fragility of SCA's this manual process of fabrication is always critical and must be performed very carefully. Moreover undesirable effects like non-uniform adhesive deposition, outflow of adhesive or solar cell contaminations can strongly affect the performance and reliability of the solar panel assembly.

Another way of bonding the SCAs on the spacecraft solar panels is soldering (brazing). Some manufacturers of triple junction GaAs solar cells specify the possibility of soldering the SCA's, however there is not a big amount of information available on these techniques.

Design of solar cells bond pads on Swisscube

The first idea was to bond the solar cells on carbon fibre panels with a standard adhesive. This method was tested on the first SwissCube prototype but was discarded due to inacceptable solar cell contamination. In consequence a new design was considered and selected with the goal of facilitating electronics addition and routing on the panels (sun sensors, temperature sensors, connectors, etc.), improving thermal dissipation from the cells to the frame (dissipation layers inside the panels) and making the integration of radiation shielding easier. Thus the carbon fibre panel substrate was replaced with a standard glass fibre (FR-4) panel in order to design a PCB for each face of SwissCube. Soldering was then a new way for the solar cells attachment design. This new way of bonding has the advantage to be partly automated (screen-printing of the solder paste). Therefore the risk of contamination and non-uniform deposition is noticeably reduced. Analyses were performed in order to define the best solder paste for this application and various footprints were also tested.

As shown by the thermal analysis, the maximal temperature of the SwissCube solar panels during the mission will be approximately +70°C. This maximal temperature allows selecting a low melting temperature solder in order to reduce the mechanical constraints on the solar cell, on the solder joint and also on the PCB footprint. Low melting temperature solder pastes are available on the market but due to the presence of indium most of them are very expensive. Moreover indium is not recommended when gold is used for the surface finish of the PCB (it is the case on the SwissCube panels) for two major reasons. First, gold and indium form an amalgam that is very brittle and somewhat porous[14, 15]. Secondly the indium solder requires a very active flux. Since the flux cannot be completely removed, any moisture that penetrates into the pads later can spread the acid contained in the flux and deteriorate the joint.

Thus, it was decided to use a solder paste without Indium. The choice was a solder with Bismuth: Sn18Pb32Bi50 (eutectic alloy) with a melting temperature of 98 °C. This paste is easy to use and has also the advantage to be cheap.

Two main parameters were taken in account for the footprint design:

- the total mass of solder (depends on the size of the footprint)
- the solder flux evacuation (depends on the shape of the footprint).

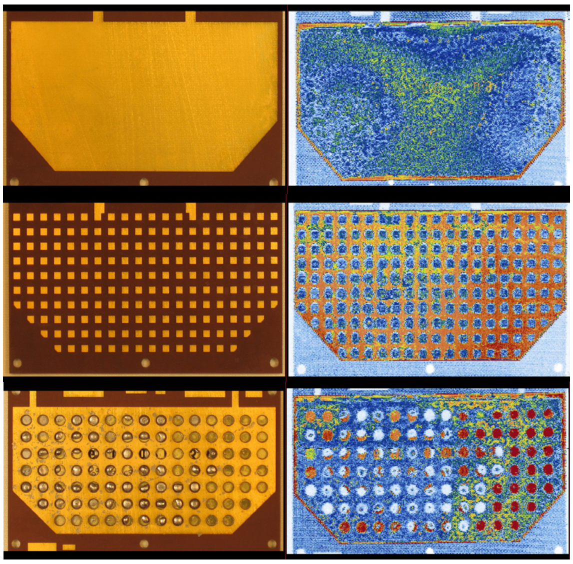

Figure 13 : Three different footprints with the ultrasound inspection of the soldering joints.

As shown on Figure 14, three different footprints were tested before choosing the appropriate compromise. The first is a full surface of copper with the same dimensions as the solar cell. The second design is a network of small squared pads and the third is a network of through-holes on a full surface of copper. Working with various footprints was very helpful to understand the behaviour of the solder and the flux and also to select the final design. The appropriate compromise is a design with a network of copper pads. A network of through-holes in the PCB was added (as show in Figure 14) in order to facilitate the flux evacuation and also to lighten the panels. This design has given very good results after thermal and vibration tests.

Assembly Procedure

The bonding of solar cells on the PCB is divided into four main steps. The first one consists of applying the solder paste by means of a screen printing process. In the second one, solar cells are placed on the PCB. Then, the PCB is baked in order to bond the solar cells, and last, the whole assembly is cleaned to eliminate all trace of residual flux. These four different steps are described in the following paragraphs.

Screen-Printing

A process of screen-printing is employed to cover the footprint of the PCB with a solder paste. The screen printing (or "serigraphy") consists of applying a substance (generally ink but in our case, a solder paste) on a support using a screen with a mesh. Some areas of the screen are blocked off with a non-permeable material to form a stencil, which is a negative of the image to be printed. The open spaces are where the solder paste will appear[16]. After having placed the grid on the machine of serigraphy, the PCB panel is fixed on a moving table with adhesive tape. Next, the PCB is placed under the grid, a scraper spreads the paste, which goes through the grid only in the desired places (see Figure 14).

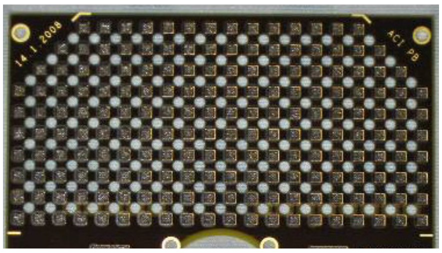

Figure 14 : Panel after screen printing

Positioning of the Solar Cells

When the solder paste is correctly applied on the footprint, solar cells can be placed on it. Due to the size of solar cells in comparison with the PCB and the free space with other components, this operation needs to be done very carefully. As it can be seen in the previous picture, little marks are made on the top of the PCB to mark the position of the solar cells. In our design, we use a network of little holes through the PCB to evacuate the flux during the bake out. These holes can also be used to precisely place the cells. A little piece with small pins on the top is placed under the PCB, with the pins in the hole through the PCB. The cells are laid down on these pins and this method allows a precise positioning of the cells without touching the solder paste (see Figure 15).

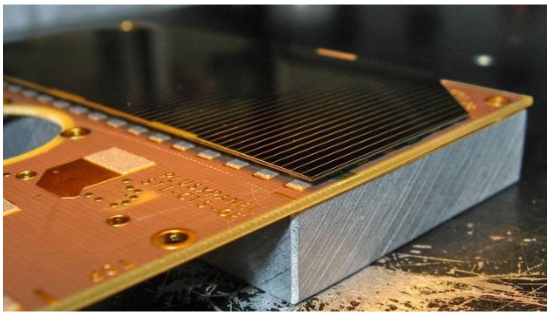

Figure 15 : Solar cell above the solder paste.

Finally the PCB is brought up carefully and the solar cells are in contact with the solder paste. A small pressure needs to be applied on the top of the cells to have a good contact with the paste and to avoid accidental displacements.

Soldering of Solar Cells

The third step is the curing of the solder paste. The solder paste has a low temperature of fusion (98 °C) and it is easy to reach it only with a heating plate. But to limit the thermal constraints and to avoid residual flux and air bubbles in the solder, an oven with a good temperature control and the possibility to establish a vacuum is used. The panel is placed in the oven and attached with Kapton tape. The cells can also be attached with tape. The goal of this attachment is to avoid displacement during the vacuum (cells "float" on the liquid solder paste, and the air flux can make them move). The temperature in the oven follows a predefined profile. It imposes a first step at 60°C during the heating to have a homogenous temperature in all the PCB's. Then a second temperature step at 125°C is applied to be sure that all areas of the PCB and solar cells reach the temperature of fusion. After 2 minutes, when the temperature is stabilized, vacuum is made (1 ~ 10^{-1} mbar) in order to evacuate the flux and air which can stay in the welding. Next, the chamber is cooled by a flux of Nitrogen. The holes in the PCB allow evacuating the flux at the bottom of the PCB and the cells are relatively clean after the baking. As some flux can stay between the PCB and cells, it is necessary to clean them.

Cleaning

The solder paste which is used has a flux called "no clean" because the baking makes it inert and in electrical application, it is not necessary to clean it. Due to the vacuum environment, it is necessary to remove the flux to avoid outgassing and to limit the contamination of the solar cells. As ESA standards[17] forbid to clean electronic components in ultrasonic bath, the panel is just immersed in an isopropyl alcohol solution during several hours to dissolve residual flux as much as possible. To have a better efficiency, a magnetic stirrer can be used to create a flow of alcohol. Finally the panel is dried with compressed air and if some residual flux is still present (trace of flux are easily recognizable on the PCB, as it can be seen on down left of Figure 16) this cleaning process starts again. The step of cleaning must be done very carefully due to the fragility of solar cells.

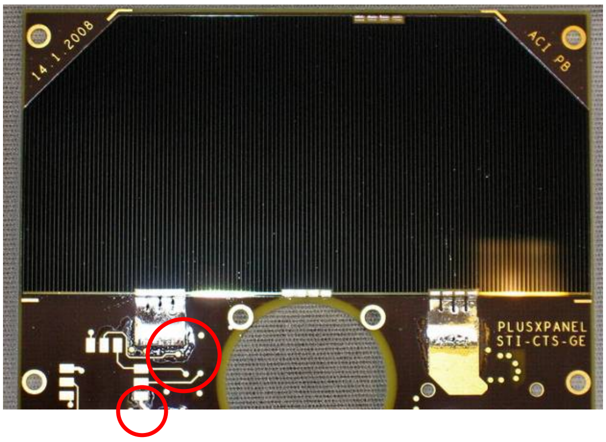

Figure 16 : Functional solar cell bonded on a PCB with residual flux in the red circles

Tests Description

To validate this advanced technology of solar cell bonding, different tests have been performed. For the vibrations and mechanical shocks, the external panels need to survive the same environment as the whole satellite. After the launch, mechanical constraints on the satellite are limited to thermal expansion and thermal shock. Environmental tests have simulated these constraints as closely as possible. Moreover non destructive tests have been performed before and after the environmental tests to evaluate the state of the welding. The different tests are described in the two following paragraphs.

Environmental Tests

Random vibration tests have been performed to verify the rigidity of the satellite, and thus also the external panels. This test was done on the previous design of the panels (the one with square plots and without holes). The qualification test level was 17.4 G_{rms} with duration of two minutes. Due to the unknown position of the satellite during the launch, this test has been performed in the all three directions. An additional test has been performed at the highest possible level (up to test facility limit) for one axis. The whole random vibration level has been increased by 3dB and the duration has been doubled. The overall G_{rms} was 21.3. The test was performed for 4 minutes. Tests were passed successfully, no damages have been observed.

The last test consisted of thermal shocks with a temperature range between -65 °C and 80 °C. The goal of this test was to determine if the solder of the solar cells could support the constraints due to the difference of thermal expansion between the PCB and the solar cell. Previous designs passed successfully this test and made more than 900 cycles (half of the mission). The actual design has been also tested and made 800 thermal shocks between both extreme temperatures.

From a mechanical point of view, these different tests were a success, no failures or cracks of solar cells have been visually observed. To know the state of the welding on the bottom of the cell, non destructive tests were performed.

Non Destructive Tests

After visual inspection, two types of non destructive tests were performed with two different types of measurements to increase confidence in the results. First, observations by X-ray were made. This technique functions by transmission of high energy photons through all the material of the face. The second test was made by ultrasond which operates by reflection of waves. The main goal of these two tests is to determine possible defects in the bonding which can not be seen to with naked eyes, like cracks in the solder between the cells and the PCB.

To observe the quality of a solder bump (e.g. correct quantity of solder paste, homogenous application), the X-ray method seems to be more efficient due to its high resolution and because it works by transmission. So, the image is a projection of the entire layers which are crossed by the X-ray: solar cell, solder and PCB with all copper layers. All these materials transmit the X-ray with different coefficients. By adjustment of the contrast level it is possible to look at one layer in particular. On the other hand, defects such as delamination and planar cracks are difficult to detect using radiography (because it's a projection)

Ultrasonic tests "inject" waves in the material and the reflections are recorded. By adjustment of the focal point and the amplitude of the received signal, the different layers of the material can be observed. External panels with solar cells are immerged in water (good conductor of waves) and a probe sends ultrasound at 25 MHz trough the panel. The focal length for this probe is 10 mm, so the focus point is placed approximately at the level of the solar cell (determined by observation of the echo on an oscilloscope). Then, the panel is scanned by moving of the probe in the direction X and Y, and the echo treated and recorded by an oscilloscope/computer. The observation with ultrasounds has less resolution than X-rays and some small defects are less visible, but cracks and delaminations are normally better visible due to the air layer which appears and causes a stronger reflection of the ultrasounds. This method is often used to control the soldering in many industries including aerospace.

These two different types of observations (one by transmission and the other by reflection) are complementary. X-ray test allows seeing the quality of the soldering, in particular its uniformity in the surface. But it does not give information in the direction perpendicular to the surface. On the other hand, ultrasonic test allows to see defects in the perpendicular direction due to the difference of reflection if cracks appear but with a lower resolution. These two tests have been performed before and after environmental tests and their results will be discussed in the next paragraph.

Analyses and Results

To have a base of comparison for the test, three defects were voluntary introduced before the bonding of solar cells. The first consisted to reduce significantly the quantity of solder paste on one block of the footprint. The second consisted to cover one half of a block with solder mask and the third to cover an entire block with solder mask. For the two last defects, the blocks were fully recovered by solder paste. The rest of the bonding was made normally. The difference between this artificial defects and normal pads was compared during non-invasive inspection.

X-ray allows seeing the form of the soldering with a good accuracy as in Figure 17. A good soldering is regular and covers all the surface of the footprint (like for the most of the blocks). In comparison with the default 1, it can be seen that some blocks (on upper right corner on the picture) did not have enough solder paste or the contact between the cells and the paste was not enough to ensure a good welding. This problem appears regularly on the boundary of the cells.

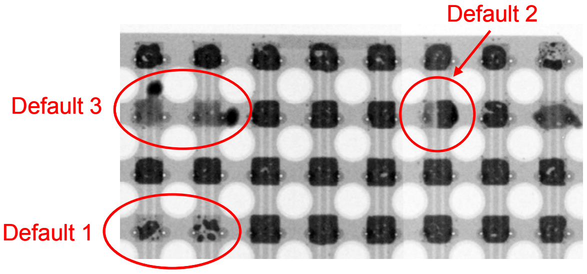

Figure 17 : X-ray inspection with the three defaults.

The observation with ultrasounds has a less good resolution than the X-ray as it can be seen in Figure 18. Some defects are less visible such as defects of solder paste. Furthermore, it can be seen that the defect 2 appears like a correct joint; however, the solder covers only half of the footprint. This problem arises probably from the presence of water between the PCB and the cells. The welding and the footprint, both in metal, have probably the same power of reflection, and water transmits very well ultrasonic between the cells and the PCB, so the recording shows the same echo.

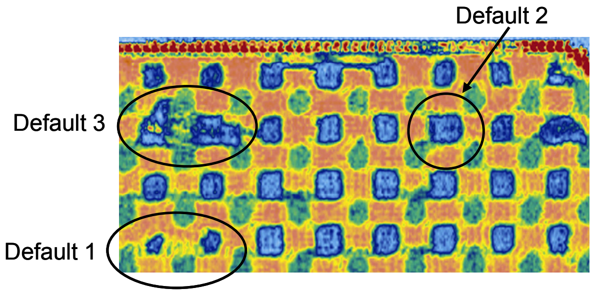

Figure 18 : Ultrasound inspection.

After our test campaign, notably a big number of thermal shocks corresponding to half of the lifetime of SwissCube, solar cells are still attached to their panels and no noticeable degradations appear during the non-destructive tests or by observation to the naked eyes. So this method of bonding is very promising, but some other tests are still necessary to confirm our observations. Different possibility are imaginable notably use a liquid which penetrates the joints and increases contrast in the cracks with X-Ray or computer tomography to have a volumetric (3D) representation of the panel. But these techniques are also very expensive and the facilities are relatively rare. For ultrasonic, use a hydrogel at the surface of the cells can avoid to have water between cells and PCB.

CONCLUSIONS

First, this paper briefly describes the SwissCube pico-satellite and its main characteristics. It goes on by exploring the use of wire EDM for manufacturing of advanced mechanical pieces for spacecraft. Wire EDM is a process of choice for the fabrication of complex mechanical parts. For SwissCube, a very compact monobloc frame has been machined with this process. As new and more exotic materials are developed, and more complex shapes are required, conventional machining operations will continue to reach their limits and the increased use of wire EDM in manufacturing will continue to grow at an accelerated rate.

Second this paper presents a new technique for bonding solar cells and the use of a PCB as an external face that allow to have multifunction panel where all the electronics can be implemented and the solar cells attached with a good reliability. This method shows that the soldering technique provides good strength and survives the harsh launch environment. Further testing are necessary to ensure that the bonding method resists to thermal cycling and fatigue. The performed tests allowed simulating around 60 days in low Earth orbit. However most missions last longer. Nevertheless this new bonding method is very promising for small-satellites short missions.

For the next generation of spacecrafts, advanced structural concepts will be combined with multifunctional micro systems modules to increase volumetric efficiency. The maximum benefits of this approach can only be attained by considering the spacecraft to be a multifunctional structure early in the conceptual design and at the same time optimizing the design across all disciplines. Although advanced structural concepts are highly efficient, changes often entail a complete redesign of the entire system.

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