

Integration of Thermal Control Electronics and Monitoring Functions in a Multifunctional Structure

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ABSTRACT

In several industrial fields, the integration of functions is a key technology to enhance the efficiency of components in terms of performance to mass/volume/cost ratio. Concerning the space industry, in the last few years the trend in spacecraft design has been towards smaller, light-weight and higher performance satellites with sophisticated payloads and instrumentation. Increasing power density figures are the common feature of such systems, constituting a challenging task for the Thermal Control System. The traditional mechanical and thermal design concepts are evidencing their limits with reference to such an emerging scenario. A promising solution consists in designing structural elements of a spacecraft that can integrate multiple functions: the capability of realizing a high level of integration of the different subsystems (typically structural strength, thermal control, electronics and shielding) into a multifunctional structure (MFS) seems to represent an enabling technology in order to respond to the growing demands of present and future space missions. The MFS concept is based on an efficient use of advanced composite materials and components, on innovative solutions for integrated design, dedicated modeling and simulation tools as well as advanced assembly/manufacturing approaches.

Following past experience in this field, partially financed by the EC FP6 MULFUN project and described in [Gottero 1], a research program on the development of lightweight high-performance multifunctional structures has been established by Thales Alenia Space Italia

(TAS-I) in cooperation with the University of Perugia (Italy). Aim of the study is the integration of thermal control, electrical and diagnostic functions into a unique high-performance structure. A demonstrator named Advanced Breadboard (ABB) was conceived with a high-performance Carbon/Carbon sandwich panel and an integrated electronic board, made with Polyimide flex circuits technology. The electronic board controls a temperature monitoring subsystem. The monitoring subsystem is a Dallas USB/1-Wire bus interface that is able to read a chain of temperature sensors distributed throughout the panel with a single flat cable with two copper strips. A DC/DC converting subsystem feeds three heaters directly integrated on the flex circuit.

The integration of ABB is currently under completion. Recent advances in the research, including drivers and details of the ABB design and results from the integration and testing of a preliminary breadboard, are reported in the paper, with emphasis on thermal aspects.

GENERAL

Nowadays the integration of multiple functions is a key technology in many fields. In spacecraft technology, the current trend is towards compact and highly integrated systems, with strict requirements on all budgets (mass, volume, costs and time of manufacturing) and improved performance. The integration of most functions seems a promising solution to address these issues, based on

advanced materials and components as well as on innovative approaches to the design. The Multifunctional Structures (MFS) technology is a revolutionary development in spacecraft packaging that eliminates chassis, electronic boxes and cabling by integrating the electronics, thermal control, and structure into a single element, leading to new design concepts of electronics packaging, interconnection, and data and power distribution.

This concept of spacecraft architectures was firstly proposed in the US at the end of the 90's. A demonstrator was flown and validated on the Deep Space 1 spacecraft as part of the New Millennium Programme (NMP) [Rawal 2]. Other experiences related to the MFS are Deep Space 2, STRV-1d S/C, ATDS, etc. Also ESA (European Space Agency) committed projects aimed to the study and development of MFS technology within the programs GSTP-3 e GSTP-4 (General Support and Technology Programme). General information on multifunctional structures can be found, for example, in [Joshi 3], [Abusafieh 4], [Obal 5].

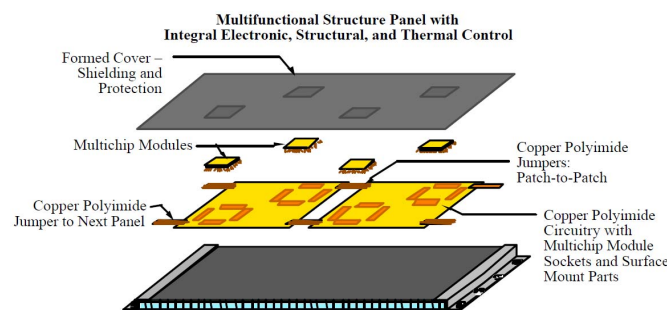


Figure 1: Exploded Assembly View of MFS Panel [Rawal 2]

A typical MFS design (Figure 1, [Rawal 2]) consists of a structural-composite panel that has multi-layer Copper/polyimide (Cu/PI) patches bonded to one side (flexible circuit), heat-transferring devices embedded, and an outer surface acting as a radiator. Electrical interconnects are designed in the Cu/PI layers, circuitry is implemented in MCMs, and flex jumpers serve as electrical interconnects for power distribution and data transmission. The thermal management devices embedded in the MFS may include miniature heat pipes and various types of high-conductivity thermal doublers and straps. Therefore Multifunctional Structures concept is achieved by resorting to:

- the use of materials and components state of the art
- design solutions differing from traditional patterns
- special tools for modeling and simulation
- an innovative approach to production and assembly.

The evolution of the presented concept can imply further incorporation of more specific functions: among them, particularly interesting are the diagnostic and control functions, with the final goal of implementing integrated health monitoring/ management capabilities.

The present work is the result of a cooperation between the University of Perugia (Italy) and the Business Unit Space Infrastructures and Transportation of Thales Alenia Space (Turin, Italy) in order to investigate issues of development and modeling of MultiFunctional Structures (MFS). Aim of the research is the integration of thermal, structural, electronic and diagnostics functions into a single structure. In particular, the following activities were performed in the frame of the current cooperation:

- research and characterization of advanced materials and components
- electronic design of a power and temperature monitoring system
- thermo-mechanical design of an high-performance support structure
- production, assembly and test of a breadboard integrating these systems

The proposed breadboard, named ABB (Advanced BreadBoard) has the objectives of demonstrating the possibility to get higher thermal performance with respect to the results described in [Gottero 1] and integrating monitoring functions.

Recent advances in the research, including drivers and details of the ABB design, and results from the integration and testing of a preliminary test bench are reported in the paper, with emphasis on thermal aspects.

HERITAGE AND MOTIVATIONS

In [Gottero 1] past research activities in the frame of the MULFUN project were described. The investigated MFS concept consisted in a structural element integrating surface-mounted distributed electronics (flat motherboards and MCM technology) and thermal control functions. A demonstrator breadboard, named BB2 (see Figure 2 and Figure 3), was designed as a sandwich construction with Aluminium honeycomb and high-modulus high-conductivity Carbon Fiber Reinforced Plastic (CFRP) skins. Commercial Cu-H₂O mini heat pipes were embedded into the panel (8 mm × 450 mm, D section, bonded to the inner surface of the upper skin).

The Thermal Control System (TCS) used to rely on proper combination of material properties and embedded thermal hardware to collect the power dissipated by surface-mounted electronics and spreading the collected heat through the panel to avoid hot spots. The outer face of the panel acted as a radiator. Proper non-isotropic material lay-up was adopted to solve issues related to the CTE mismatch between the carbon skins and the metallic pipes.

The thermal conductivity of the CFRP material was tested at the University of Perugia, obtaining an high thermal conductivity of the laminate: 520 W/(m K) on the fiber direction at 0 °C.

An extensive test campaign and subsequent internally-funded experimental investigations (not reported in the cited paper) demonstrated the compliance of the developed MFS concept and design to the research goals and requirements and the performance of the system. The obtained data were also used to correlate the breadboard thermal mathematical model (TMM), in view of the analytical trade-offs described in the following.

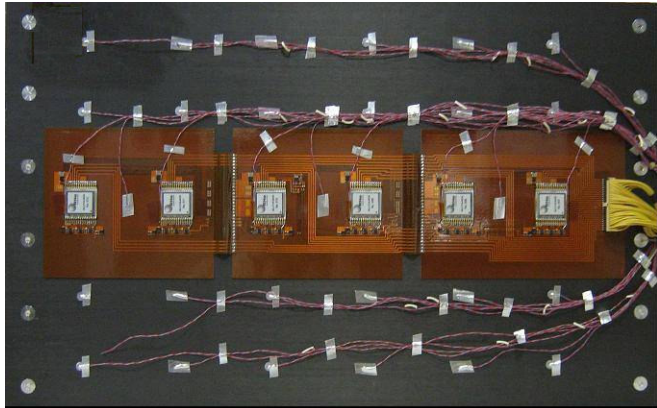


Figure 2: MULFUN BB2 panel instrumented for thermal vacuum test

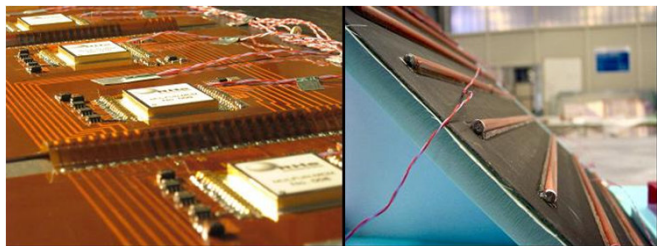


Figure 3: MULFUN BB2, details (surface-mounted electronics and integration of embedded pipes)

THERMAL TRADEOFFS - Based on the experimental data from MULFUN and other internally developed breadboards and on the related TMM (Thermal Mathematical Models) correlation, the trade-off campaign described in [Gottero 1] was refined to retrieve maximum possible information from the breadboarding activity and to provide inputs to the subsequent research steps.

The analyses were based on TMMs representing the reference configuration (BB2), performed varying the design variables (i.e. skin material and layup, heat pipes type and layout, core material) and the relevant parameters (power dissipation, power density, heat rejection capability, mass, complexity). As already said, the thermal conductivity of the skins was obtained by experimental characterization of the CFRP laminate.

Figure 4 reminds the reference breadboard configuration: the panel layout shows six MCMs on the flat motherboards (in brown) and fourteen heat pipes (dotted lines) embedded into the sandwich.

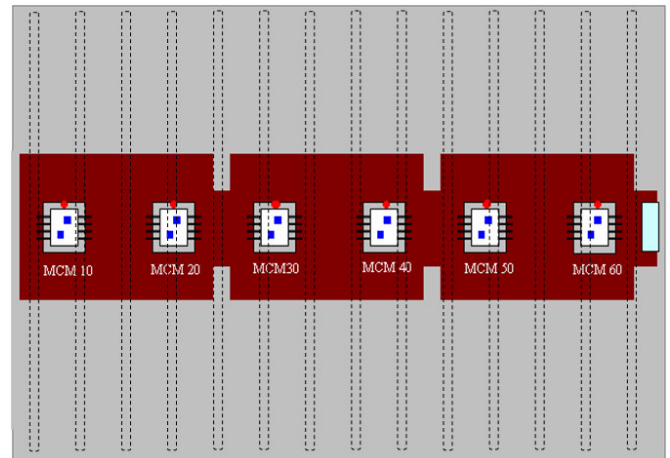


Figure 4: Breadboard reference layout

The trade-off campaign was aimed at quantifying the impact of the various involved parameters and comparing different (traditional and MFS-oriented) design solutions. The design variables were: skin material (aluminum vs. high-conductivity CFRP vs. Carbon-Carbon) and layup (isotropic vs. non-isotropic), heat pipes type (AGHP vs. mesh mini heat pipes) and layout, core material (aluminum vs. Carbon-Carbon). Concerning AGHP, use of aluminum-ammonia devices with 14mm diameter and 20mm fins has been assumed for comparison. The different configurations have been evaluated in terms of thermal performance, mass and design/integration complexity.

Among the trade-off results, one is worth to be discussed here, due to its relevance in the definition of the research evolution described in this paper.

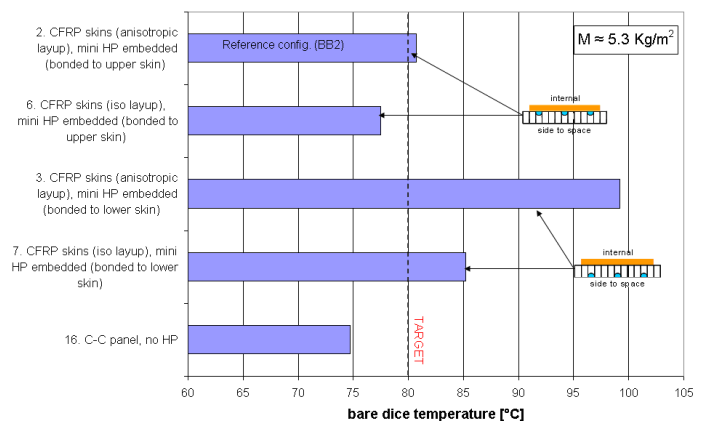


Figure 5: BB2 performance trade-off

In Figure 5 different configurations with the same mass of the reference breadboard are compared in terms of thermal performance (bare dice temperature) at maximum power dissipation. Higher performance w.r.t