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Lightweight Technologies for Exploration Rovers (ROV-E)

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1 Acronyms

AIT	Assembly Integration and Testing
BLDC	Brushless Direct Current Motor
BMS	Battery Management System
CB	Carbon Black
CFRP	Carbon Fibre Reinforced Plastic
CNT	Carbon NanoTube
COMM.	Communication
COTS	Component-of-the-shelf
DoF	Degree of Freedom
DRIVE ACT.	Driving Actuation
ELEC. & SENS.	Electronics & Sensors
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FEA	Finite Element Analysis
FL. LOOPS	Fluid Loops
fPCB	flexible PCB
GFRP	Glass Fibre Reinforced Plastic
GNP	Graphite NanoPlatelets
GUI	Graphical User Interface
HTR	Heaters
I	Intensity
IC	Integrated Circuit
INS. & COAT.	Insulations & Coatings
IPB	Internal Panel Breadboarding
LCM	Liquid Composite Manufacturing
MB	Mother Board
MER	Mars Exploration Rover
MFPS	MultiFunctional Power Structure
MFTS	Multifunctional Thermal Structure
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MWCNT	Multi-Walled Carbon NanoTubes
OBC	On-Board Computer
OS	Operative System
PCB	Printed Circuit Board
PCDE	Power Conditioning and Distribution Electronic
PCDU	Power Conditioning and Distribution Unit

PCM	Phase Change Material
PLM STRU.	Payload Module Structure
PMU	Power Management Unit
PV	Photovoltaic
S&T	Scientific and Technological
SA	Solar Array
SA ASSEM.	Solar Array Assembly
SMD	Surface Mounted Device
STEERING ACT.	Steering Actuation
SVM STRU.	Service Module Structure
SWT	Single Wheel Testbed
T	Temperature
TRL	Technology Readiness Level
UTCP	Ultra Thin Chip Package
V	Voltage
VEH. FRAME	Vehicle Frame
VOC	Volatile Organic Compounds
WEB	Warm Electronics Box

2 Scope

This document corresponds to the final publishable summary report of ROV-E project and includes: an executive summary, a summary description of project context and objectives, a description of the main S&T results, the potential impact (including the socio-economic impact of the project) and the main dissemination activities and exploitation of results/foregrounds.

3 Executive summary

A need for light-weight structures with a performance comparable to current solutions and which satisfies future scientific needs is identified to be important for future planetary surface exploration missions. Improvements are necessary on the reduction of the mass of the systems that constitute the Rover.

Multifunctional structures are technologies, currently under development, envisioned as possible breakthroughs in the recent advances to reduce space systems mass and volume.

The basic concept of these technologies is to joint additional functions to the primary load bearing function of the spacecraft's structure. The benefits of MFS against traditional design can be summarized in:

- to eliminate chassis and cabling, reducing electronic enclosures and harness.
- to maximize functional elements volume ratio (maximum integration)
- weight and volume saving (more than 40% increase of mass fraction and more than 30% increase on volume availability expected)
- to reduce thermal paths from the electronic components to the radiating means
- to enhance robustness and reliability

Versus these advantages, several technical points have to be validated and strictly verified, in order to determine if the usual "qualification levels" expected on space assets will be achieved in terms of structural behaviour, thermal and EMI/EMC behaviour, etc.

Multifunctional structures take advantage of the features of composite materials. These materials are central in aerospace applications due to the weight savings that could result from using low density polymer matrix composites made from high modulus, high strength fibres. The attributes of composites include high specific strength (strength per unit weight) and stiffness, corrosion and fatigue resistance, tailorable conductivities, controlled thermal expansion and the ability to be processed into complex shapes. They are lightweight, allowing for more fuel or payload mass. The physical, mechanical, electrical and thermal properties of composites are highly tailorable, which can also afford them multifunctional behaviour. It has now to be checked if the interesting properties observed in aerospace conditions will be confirmed in space and planetary conditions allowing new perspectives in the use of high performance multifunctional panels.

Starting from a high performance structural panel, the ROV-E studies and activities has aimed to add new capabilities in order to obtain a valuable multifunctional structure. The additional functions that have been explored are: thermal, structural, EMI-EMC shielding, mobility, monitoring, power generation and power storage.

Three prototypes have been developed integrating the technologies studied within the project.

- **Internal panel incorporating health monitoring and electronic functions**: the prototype has been designed and partially manufactured. Due to problems in the manufacturing of the Smart Skin, it has not been possible to integrate and validate the whole prototype in the frame of the project. It is expected to perform the validation in the next 3 or 4 months with TAS-I internal funding.

- **Self-powered external panel with storage capabilities**: A prototype integrating space qualified PV cells, battery cells and the electronics that interconnect the PV cells and the batteries has been developed. Initially, the prototype worked properly but a failure occurred in the PV generator during the detailed functional validation. Failure analysis carried out indicates that a hot spot during the interconnection of the PV cells could have caused a latent damage in the generator.

  Initial functional tests allow validating the suitable performance of batteries, PMU and BMS, extracting maximum power from the input and delivering the required power at the output, while maintaining battery integrity

  It was possible to operate the panel in the required temperature envelope of 0 – 30 C.

  The structure and the batteries survived the non-operating temperature range (-55 and 65 C temperature excursions).

  Survive a vibration environment of up to 15 g and 11 grms in the out of plane orientation and 10 g, 9.2 grms for in plane orientations. A failure in the shaker prevented performing higher level vibration testing.

  For all the environmental tests the embedded battery cells have shown to remain unaffected and balanced at 3.8 V.

- **Mobility system prototype**: single-wheel-testbed (SWT) has been designed, manufactured and placed into operation. The main advantages of testing a single unit is that the operational point can be accurately adjusted (e.g. wheel load or slip) and that the performance of the isolated wheel actuator can be evaluated and no parasitic elements or effects influence the measurement. During the project a novel actuator unit for planetary rovers has been developed. The developed actuator is based on a powerful brushless direct current motor (BLCD) in combination with a single Harmonic Drive gear. The overall volume and mass is reduced and the actuator suffers less from reduced efficiency due to extreme low temperatures

Developments carried out in ROV-E project allow reducing the weight and optimizing the performance of elements and rover equipment, being able to include more scientific payload to the same limitation of weight, or reduce the cost of the mission for the same scientific payload. A mass reduction will decrease the fuel required to access the outer space, aspect that is considered determinant in this kind of missions. On the other hand, a maximum functional ratio has been achieved. A step forward in the integration of functions has been performed.

Rough and preliminary estimates indicate important mass and volume savings can be obtained by means of the application of the multifunctional technologies: **36 % mass reduction and around 45 % in volume** (Prototype 2).

4 Summary description of project context and objectives

4.1 Project Concept

Multifunctional structures are more than a new material a design concept. Previous ESA and EC activities initiated some studies and development for re-design space structures mainly for electronic housings and satellite platforms. These studies were focused on the development of structures with integrated electronics manufactured with high thermal conductivity composite materials that provide an improved thermal and mechanical behaviour. ROV-E project has intended to perform a step further in the developments.

The project has considered the multifunctional design concept as a whole and has worked in the development of technologies to be integrated in future rovers. The multifunctional approach has been applied on several Rovers subsystems: mobility, power, storage, monitoring and supporting structure.

Mass is a major issue for interplanetary missions as each additional kilogram influences the cost of the mission and it requires more fuel to be carried (the trajectory is very long). Additionally, the autonomy of rover vehicles is too much dependent on its weight for both propulsion and flexibility on their movements. AURORA programs have identified the possibilities to use **lightweight and integrated** electronics for moon and mars vehicles.

In order to give answer to the identified needs, the ROV-E project has been focused in the use of the **multifunctional technology** applied to **composite** materials.

Conventional spacecraft subsystems are designed and manufactured separately, being integrated only during the final stages of the satellite development. This requires containers for subsystems' hardware, mechanical interfaces, panels, frames, bulky wire harnesses etc. which add considerable mass and volume. As all subsystems are generally secured to the structure, the **multifunctional structure** approach aims at merging these elements into the structure, so that the structure also carries out some of the subsystems typical functions, e.g. electrical energy storage. The main advantages of the fully exploited technology are:

i) removal / reduction of the bolted mechanical interfaces and most of the subsystems' containers

ii) reduction of the satellite structure mass, as the strength of the parts of the subsystem embedded into the structure are exploited, and substitute purely structural parts

iii) reduction of the overall satellite volume, as elements like battery packs or electronic harness can be built into the structure's volume.

There are still issues that need to be addressed to allow a wider utilization of multifunctional structures. However, the development of concurrent engineering approaches, to carry out an integrated design of the spacecraft, together with advances in the subsystems disciplines, will help to promote the further diffusion of multifunctional structures. In Figure 1 a scheme of the traditional design concept versus the MFS technology is depicted.

To give a step further in the application of the multifunctional technology, the approach followed in ROV-E was to integrate not only thermal and structural functions within the carrier structures but also additional ones as EMI-EMC shielding, mobility, monitoring, power generation and power storage. Within the ROV-E project, **developments in the following subsystems have been carried out: mobility, monitoring, internal structure, chassis, power and power storage.**

This re-engineering implies the study of the basic technologies required to improve the performance of each subsystem.

4.2 Objectives

The main objective of ROV-E project is the development of the technologies required to obtain **lightweight–fully integrated equipment and subassemblies for exploration rovers** based on multifunctional structures.

The aim is to give a step forward in the multifunctional technology, integrating not only structural and thermal functions in the prototypes but also other functions as electrical, health monitoring, EMI-EMC shielding, power, storage and mobility functions for rover driving and steering.

ROV-E aims:

- To improve the technologies to be applied to the multifunctional structures.
- To investigate new functionalities to be incorporated in the MFS.
- To validate the use of these new technologies on a rover representative environment.

Direct benefits include:

- Mass and volume savings allowing more scientific payload to the same limitation of weight
- A mass reduction will decrease the fuel required to access the outer space, aspect that is considered determinant in this kind of missions
- Integration and miniaturisation
- Reduce the cost of the mission for the same scientific payload (due to the mass reduction)
- Perform a step forward in the development of the multifunctional structures.
- The developments carried out in this project are directly applicable not only to exploration vehicles but also **to spacecrafts and even to other sectors as aeronautics where mass and volume play a key role**.

4.3 ROV-E project strategy

The project has been divided into the following phases:

Phase 1: Definition of future scenarios for European space transportation and exploration and ensuing possible missions objectives. The reference scenario was built; applications where the MFS could be applied as well as the required technologies were identified. A MFS based rover design concept was defined.

Phase 2: This phase corresponded to the core of the project and has been devoted to the development or improvement of the technologies to be integrated in the multifunctional structures.

Phase 3: In this phase prototypes integrating the technologies developed in phase 2 have been manufactured and validated in order to assess the benefits of the multifunctional technology. The following prototypes have been developed:

1. Rover internal panel incorporating health monitoring and electronic functions: A rover internal panel has been developed where a smart layer containing health monitoring, heaters and cabling had to be integrated in a composite support structure as a last step. Due to delays in the procurement of the Smart Skin, this prototype could not be finally integrated and validated in the frame of this project.

2. Self powered external storage panel. An external panel integrating solar cells in the external skin, using a battery as core of the structure and including the power management system, to control the exchange of electric energy between these two elements and the other subsystems has been developed. Problems in the test campaign have hinder to perform the validation as foreseen. However, preliminary rought estimations indicate the integration of the battery in the structure could result in considerable mass and volume savings, and therefore increase the overall efficiency of the system.

3. Mobility system prototype to show the performance of the concept and simulation tool developed through validation tests.

In parallel in WP8, a technology assessment, exploitation and dissemination strategies have been defined and carried out.

5 Description of work performed and main results achieved

5.1 WP2 "Future rover system review, mission analysis and configuration"

A survey of past robotic missions was performed and issued a report compiling these aspects. The data collected with the survey was summarized in a collection of charts, to extract meaningful information and establish ballpark reference figures for the requirements to be settled for ROV-E.

Mars has been chosen as the target body for the ROV-E fictitious reference rover.

The requirements have been set mainly by TAS-I, leveraging past experience on Exomars and studying other past and present missions to Mars. ROV-E Project had the goal to develop and demonstrate key technologies in support of future European exploration missions. Therefore the requirements fixed by TAS-I were not intended for the production of a whole system and were instead considered only as a guide, provided to Partners so that they could evolve their technologies in a coherent framework.

For example, the requirements document has been used by TAS-I as a canvas to draw more specific requirements for the smart skin product (flexible multifunctional printed circuit board) and the IPB demonstrator (panel with thermo-mechanical substrate panel and a smart skin module).

5.2 WP3: Material properties enhancement

T3.1. Improvement of the through thickness thermal conductivity

The activity has been focused on the development and manufacture of a high-performance composite material with significantly enhanced thermal conductivity compared with that of conventional composite materials.

The matrix material that was selected for this project was Cytec's LTM®123, a high-performance cyanate ester resin with low levels of volatiles post processing and a high in-service performance temperature. Reinforcement for the project work was Mitsui's YS-80A fibres, high modulus carbon fibres produced from a mesophase pitch precursor; the prepreg was a unidirectional tape 300 mm wide and the target fibre content was 60%.

Different fillers were investigated to enhance the thermal conductivity, in particular multi-walled carbon nanotubes (MWCNTs), carbon black (CB) and Graphene.

Starting from the resin master batches, fully-formulated resins with a variety of graphene fill levels have been obtained; these resins have then been studied to assess their curing kinetics and viscosity profiles in order to be able to design a suitable processing cycle which will yield prepreg and laminates of acceptable quality. The best filler was identified to be graphene and an optimum filling level was identified. The quantity of grahene finally selected to dope the resin was 11%wt.

Activities focused in the optimization of the dispersion and deposition processes, manufacturing of the prepreg, manufacturing of the laminates and characterization have also been developed.

A production route was identified for the nano-filled material with the maximum realistically achievable thermal conductivity whilst maintaining the ability to produce prepreg and laminate using available equipment of a prepreg production line and an autoclave for laminate manufacture.

The thermal conductivity was greatly enhanced with minimal impact on the mechanical properties whilst the resin was still sufficiently fluid to be able to convert into a coherent and even thickness resin film, an important stage in the production of high-quality prepreg material.

From the results obtained in ROV-E project, in can be concluded that:

- Improvements in thermal conductivity have been obtained doping the resin with graphene, especially in **through the thickness direction** (around 100 %).
- Based on the C-THERM measurement method, the in plane thermal conductivity is increased around 23%.
- The mechanical properties of the laminate LTM123/Graphene/YS80 are lower than the laminate LTM123/YS80, but this decrease only in one case exceeds the 10% (ILSS test). This difference is attributed to the presence of the graphene in the resin.

T3.2. Development of dismounting adhesives for electronics repair

The aim of this research was to develop an adhesive that could be used to successfully mount and dismount electronic components for integration and repair. The drive for this research came from the need to reduce maintenance and repair costs that could become substantial for highly integrated multifunctional structures.

Taking into account that hydrogen bonds and intermolecular forces are main forces which join adherents, the strategy followed in this study was based on a method which extends intermolecular distance for cutting the joints. Thermally expandable microspheres were distributed into an adhesive, because when an external source (heat) is applied, these microspheres expand. Then, the intermolecular distance extends by the expansive force, bond strength is reduced and thus, the joints, can be separated.

These thermally expandable microspheres were polymeric particles, in which a blowing agent was encapsulated by a polymeric shell. Upon heating the blowing agent vaporizes which increases microspheres internal pressure. When the temperature reaches above the glass transition temperature of the polymeric shell, an expansion occurs (Tstart). In theory, the increase in volume of the particles is retained when cooled, due to the plastic deformation of the polymer (Figure 2).

The thermally expandable microspheres were synthesized by suspension polymerization using radical polymerization, with an in situ encapsulation of the blowing agent as the polymerization proceeds. This **polymerization process was a waterborne one**, thus once all the monomers become polymer **no VOCs** (volatile organic compounds) are produced. On the other hand, blowing agents are **toxic materials**, thus in order to ensure no danger is caused, capsules shall **not leak**. Therefore, a test was performed in order to check that microspheres present no leakage. This test was extended for 6 weeks and leakage was not observed.

An additional trial was performed **exposing the microspheres to vacuum** during 10 hours. No influence was observed. In addition, after applying vacuum, microspheres were heated up and their expansion ability was confirmed.

Once the microspheres were synthesized and their expansion ability was assessed by optical microscopy (125ºC 10 min and 150ºC 10min), they were incorporated manually into a thermal conductive adhesive.

Several trials have been performed using different adhesives and silicones, using different blowing agents and different polymeric shells. None of the trials performed as expected. The combination of the selected adhesive (controlled by applications requirements) and the developed microspheres did not lead to the development of an adhesive with debonding capacity.

The activity of the **dismounting Adhesives was disregarded for further development within ROV-E**.

T3.3. Composite EMI/EMC behaviour enhancement

Calculating theoretical evaluation and analysis of the published data showed that the carbon-fiber plastic EMI shielding effectiveness increasing may be achieved by the introduction of magnetic and conductive fillers into the structural carbon-fiber plastic.
The following conductive fillers are applied:

- thin-layer metal foil;
- metal coating of the fibers or plastic;
- dispersed conductive metal fillers;
- nanostructured carbon-based particles.

Shielding efficiency measuring (K_{perm}) was held for transparency in a screened room (free space method) at the frequency 2,5 GHz. Samples, which size was 90x90mm^2, were placed in screened envelope of grid with cell of 50 micrometers and hole of 50mm diameter. General view of the sample with the transmitting and receiving antennas is shown in Figure 3. The equipment used was a Generator G3-22 (1,8-3.0 GHz), P6-16 transmitting antenna, P6-23A receiving antenna, U2-8 measuring-selective amplifier.

Metallic foils application

Copper and aluminum foil is applied between two layers of prepreg. The obtained samples consisted of two layers of fabric and had a thickness of 1mm. After applying of the silver-plated copper foil, the composite material EMI attenuation exceeds 100 dB, as well as for aluminum, but an increasing of composite material weight after the copper foil application is equal to 20%.

After introducing into the carbon-fiber plastic of aluminum, sprayed at polymeric film, EMI attenuation by the composite material will be equal to 79 dB, composite mass increasing will be at the rate 3%.

Coatings application on the carbon-fiber fabric

Copper coating, applied in accordance with electro-chemical method, at a thickness of 11micron also did not affect the amount of EMI attenuation by the initial carbon-fiber plastic. After increasing the thickness of the coating to 22 micron, EMI attenuation by the composite material increased on 2 dB, and at the thickness of coating equal to 33,6 microns - to 7 dB. The surface density of the carbon-fiber plastic increased on 30% and 44% respectively.

Steel fibers application

Samples of the composite material were obtained by applying of carbon fabric successive layers, polymeric binder and metallic fibers. Layers of the metallic phase in the samples were formed machine coating (air vibro-felting). The content of the metallic phase varied from 4 to 29% (by weight).

Shielding efficiency samples with a filler, formed of fibers ⌀ 40-100 micron, is somewhat lower than in the material of the fibers ⌀ 30 micron (at 3-5dB) and significantly lower (at 10-12dB) than in the material of the fibers ⌀ 10 micron (Figure 4) in case the filler weight is the same.

After the metal fibers introduction into the carbon-fiber plastic, shielding effectiveness in all samples increased with increasing the filler content on 10-18dB. Shielding efficiency increases with decreasing the diameter of the fiber. Optimal efficiency of shielding and mass content of the metallic phase is a sample filled with steel fibers ⌀ 10micron with mass. conc. 4%, which showed shielding efficiency equal to 86dB, that 14dB higher (20%) than in the original sample.

Introduction of additives based on nanostructured carbon

As nanostructured carbon-based fillers were considered carbon nanotubes, onions and nanographite:

The shielding efficiency of carbon-fiber plastic in the initial state is equal to 71-72dB. When introduced into the binder an onions with capsulated cobalt and nanotubes in concentrations range of 0,5-5%, shielding efficiency of the carbon-fiber plastic is almost unchanged and was within 71-74 dB.

When applying a nanographite with deposited copper, as well as without it, SE increased to 75,6 dB only at a maximum concentration in the binder, which was 5%.

In that way, considering technological features of manufacturing of ROV-E SC mock-up, which is three-layered flat panel with carbon-fiber plastic coverings, the most prospective is injection of aluminum, spattered at the polymer film, which showed sufficient level of EMI attenuation with minimal structure mass increase.

T3.4. Passive thermal control system for batteries

The PCM feasibility study using current thermal control techniques to support a variety of MFS components was investigated. Numerical analysis of the Martian environment and various MFS concepts including roof, flap and gimble mounted panels with embedded batteries and electronics was conducted with several thermal control systems including PCM, optical properties, insulation, conductors and heaters. Figure 5 shows the embedded batteries and electronic concepts.

Modelling of each of the considered thermal control solutions revealed that with the exception of heaters to prevent overcooling at night, the use of a local thermal control solution to support embedded batteries in a MFS on a Martian rover is very limited. To prevent overcooling the use of heaters is recommended. While a conventional approach, it is a technique that can be incorporated into a multifunctional structure, PCMs and insulation were found to require too much mass, greater than 1 kg per hour of night. Altering optical properties did not produce enough of a reduction in heat loss.

The main disadvantage of using PCMs as passive thermal control is that they can only be used to their full extent once per Martian day and so have limited use to specific applications. However for the electronics MFS concept the use of PCM was found to be a possible solution. The full range of potential application, in terms of heat output and time were found to be worth greater study as the temperature rise in the electronics is fast but for a short period of time and only affects a localised section of the panel which could be slowed with the use of a PCM.

Structurally, the primary problem to overcome is that of the effect of the density change in the PCM when it changes state. This was shown to lead to large stresses and shear in the structure. To avoid altering the structure and adding mass to the system, the easiest solution is to reduce the amount of PCM in each cell so that they are considered full when the PCM is fully melted. Manufacturing of thermal capacitor is complicated by the need to prevent the liquid PCM from leaking from the incomplete container, the need to remove air from the PCM filled cells and the need to seal the PCM filled cells to prevent leakage. These needs result in an increase in the number of manufacturing stages, the cost of which must be carefully considered.

PCMs were found to require too much mass for this application. An additional trouble to implementation of the concept is that of potential long term harmful effects of the component materials. The concept could potentially use materials that pose a planetary protection hazard. Significant improvements would be necessary in the chemical formulation, lifetime and encapsulation of PCM before they could be considered for any practical flight use.

To understand the use of phase change material based multifunctional thermal structures from a design perspective a standardised modelling tool has alsobeen developed. The objective of this tool it to provide to the user estimates on the viability of the PCM technology and to provide an optimised solution for the given parameters.

5.3 WP4 “Definition and development of the smart skin”

Research activities were oriented toward a MFS with structural, thermal, harness and electronic functions. The physical embedment of all those functions inside the structure proved to be extremely demanding and expensive, and therefore led to the idea of “applying” multifunctionality on the surface of the structure instead of nesting it in the bulk of the material.

From this idea, from the previous positive experiences with flexible electronics, and from the concept of creating a modular, easy to assemble product stems the smart skin concept. The goal was to obtain a thin, flexible sheet of material serving as:

- a flexible printed circuit board;
- a medium to route harness;
- a thermal control system.

To reach these objectives, the smart skin had to comprise: a **substrate**, which ensures the proper geometry and layout while allowing the final manufacture to be flexed; **conductive traces**, which carry signal and (where possible) power; **heaters**, which enable to change local temperatures; **sensors**, which monitor the status of the skin and of the structure where it is mounted; **miniature electronic**, which handles the status of the smart skin itself (status of components, bus messages, interfaces…). Other interesting features to be added and studied as a completion to this particular design were **flexible electromagnetic compatibility solutions**.

Possible envisaged advantages coming from this architecture were:

- reduction of volumes occupied by electronic boxes and harness;
- reduction of assembly complexity and human errors during AIT;
- increase of the number of monitoring points without increasing the number of signal lines;
- spreading of heating function on a wider area;
- introduction of a modular design and/or of the possibility to cope with odd and irregular structure shapes.

The Smart Skin offers a fourfold function: routing of harness, hosting of distributed electronic, heating of surrounding structures and health monitoring. It shall be as lightweight, thin, flat and flexible as possible, in order to save space and mass and to adapt to different supporting frames.

The smart skin has no specific requirement on the overall shape, and therefore the baseline configuration is rectangular, but odd silhouettes with cutouts and “peninsulas” can be devised (Figure 6).

It is based on a multilayer flexible circuit, because usually flexible circuits reduce the size and weight of a finished product (thickness can be as low as 0.10 mm and weight reductions of over 75% have been achieved). Moreover, the flat planar nature of flexible circuits and the high track density achievable allow higher circuit density and eliminate bulky connections and wiring, therefore offering considerable weight and space savings over traditional wire harnesses. Besides this, the ability to fold could expand the boundaries of design, installation ("packaging") and operation. Indeed, unlike a rigid printed circuit board, which can only be positioned in two dimensions, flex circuits can be bent, twisted, and folded to utilize a third dimension. The smart skin module is a flat flexible rectangular polyimide motherboard. Its in-plane dimensions are 400 mm x 285 mm, with a thickness of a few tenth of mm (63 um estimated).

The PCB internal communication is carried out in a few-wire protocol, I2C and CAN protocol. For the sensors, there are three separate buses: two I2C and an SPI.

Regarding the heating devices, it is mandatory to obtain a good and complete embedment into the smart skin. For this reason, the resistive material is sputtered on the substrate before lamination of subsequent layers. Currently, the production of system-in-foil products is not commercially available (it is a laboratory process), and therefore the design of the smart skin focuses on the embedment of resistors to be used as heaters. All other components are mounted using surface-mount packages. The surface mount package type is the mainstream choice for packaging electronic components of every type (including connectors). Its main characteristic is that all connections are made with a lap joint between a component lead and a pad on the surface of the PCB. This method has some clear advantages. For example, since the mounting procedure affects only the external surface and does not interfere with underlying layers, all inner (and reverse side) wiring space is available. Because of this, it is usually possible to wire a PCB in fewer layers than would be true with other connection methods. Another and larger benefit is the fact that surface-mount components are always smaller than their through-hole equivalent, making it possible to fit more parts in a given area.

The main disadvantages of surface-mount components stem from their small size. First of all it is more difficult to remove heat from SMT packages than it is for their through-hole equivalent (in some cases the heat generated is too high to permit proper operation in an SMD package). Secondly, one cannot neglect the fact that it is hard to access SMD leads with instrumentation probes (diagnostic work and production testing become difficult).

All connections of the smart skin with external cabling, at least for signal traces, are made via Zero Insertion Force (ZIF) connectors, to avoid problems and damages caused by applying force upon insertion and extraction. Low insertion force (LIF) sockets could reduce the issues of insertion and extraction but are not recommendable since the lower the insertion force, the less reliable the connection. Unfortunately ZIF sockets are much more expensive than standard IC sockets and also tend to take up a larger board area due to the space taken up by the hold/release mechanism. However, the need to find a handy and reliable connection method suitable both for lab research and for AIT activities can justify these drawbacks. Additionally, connectors shall have the smallest commercially available pitch (to reduce connector width for a given number of traces to be routed) and thickness. Jumper or interconnect cables can also be designed to reduce weight and overall space, thus suggesting to replace wire harness with Flat Flexible Cables (FFC) made of polyimide flexible strips. The FFC termination can be slightly thicker that the rest of the cable, in order to present a reinforced portion for ZIF interface.

5.4 WP5: Power generation and storage

T5.1. Power generation by means of integrated solar cells

Solar cell integration development aims to provide power to a structure by means of a photovoltaic system whilst being embedded in a composite structure

The process to properly integrate solar cells into a composite material has been developed.

After a thorough search among different solar cells technologies, the most adequate approach has been selected for integration in the Rover multifunctional panel. The PV integration is then carried out in advanced materials: reinforced plastics, namely GRP (glass reinforced plastics), in which an organic resin matrix is reinforced with glass or carbon fibres of different formats and layouts.

A two-stepped integration technique was finally chosen. A CFRP skin is first manufactured in an autoclave curing process. It is then placed on a flat mould, in which the solar cells and glass-fibre woven roving layers are adequately placed (e.g. in order to avoid electrical contact between the PV cells and the carbon fibre). The whole is then bonded by means of a vacuum-bag infusion process, and subjected to a proper curing process for the infused resin.

According to different process parameters and product specifications, an adequate LCM (liquid composite manufacturing) process was identified and set-up, avoiding damage in cells, assuring a good part quality and a proper PV performance, as well as an adequate mechanical performance of the hybrid (GFRP and CFRP) panel skin. Thus, inter-laminar shear strength, tensile strength and panel planarity and flatness were assured by means of mechanical characterization and relieving of internal stresses (Figure 7).

On the other hand, high-efficiency multi-junction space solar cells were identified as the most appropriate ones for the integration in the final prototype. Once the integration/encapsulation process was set-up and perfected, the main challenge has been to work on the interconnecting techniques for the mentioned multi-junction space cells. Through different techniques, comprising indium-silver and tin alloys, an electrically efficient interconnection technique was developed and validated (Figure 8).

Results obtained when exposing the module to direct sun radiation are summarized in Figure 9 below, being the testing conditions: T=19ºC and Irradiation= 795 W/m^2. A good I-V response when subjected to direct sun irradiation was obtained. As output of this activity, the process to embed space qualified solar cells into composite materials has been established.

T5.2 Innovative battery concept with added structural function

The aim of this research was to develop the use of commercial off the shelf (COTS) batteries as both power stores and as a structural element as part of an external panel of a Rover. The battery cell selection was made from a characterisation study which considered various COTS chemistries and designs. The selected cell was the lithium polymer ion VARTA microbattery LLP 503579 DL as shown in Figure 10.

Of the cells considered lithium chemistry offers a superior specific energy and energy density to chemistries traditionally used. The flat prismatic shape also allows for most effective packing in a sandwich panel. Mechanical and thermal and vacuum tests showed the cells are robust both structurally and electrically to the expected environments

A numerical optimisation study was conducted to establish the performance of these cells as a structural element to a MFPS rectangular panel. The study considered parameters as cell number, cell location, cell stack height and cell orientation.

This study of the best arrangement of a set number of cells reveals a conflict of interest. In all cases it is preferential for panel stiffness that the cells be placed a small distance from the inserts. However, to minimise stress in the cells, it is preferable to place them at the centre of the panel. The designer must trade-off between these factors. For both criteria, it is highly preferable that the stack height be higher as this increases the 1st frequency and reduces cell stress.

These results can be said to be expected as they follow the well-established pattern for added masses to panel-like structures. What is distinct about these results is its multifunctional nature. This optimisation applies to the novel case of a non-structural part being embedded into a sandwich panel core. A scenario where the addition of mass is complicated by the removal of structural core and its replacement by a component with poor mechanical properties: The addition of mass at the location where the structure has been weakened.

A test panel was manufactured to ensure assembly of a MFPS was possible and assess if the manufacturing process affects the electrical properties of the cells. It also allowed experimental mechanical testing of embedded cells for comparison to a numerical model. This manufacture and mechanical tests showed that it is possible to create a MFPS with the greatest restriction being the maximum curing temperature being lower than 100 C to ensure the survivability of the embedded cells. This was achieved by using MTA240 adhesive film supplied by Cytec and allowed for a cure at 80 C for 5 hours with no effect on electrical performance. The mechanical tests showed that the cells are electrically and mechanically robust. While they have poor mechanical properties, they are able to withstand significant strain without loss of electrical performance. This, in combination with the numerical results, implies that there is no universal optimal solution for embedding cells and that each case must consider the identified issues uniquely.

T5.3. Solar cell / battery interconnection

This research aims to maximise battery lifetime, reduce size and mass and improve reliability of the electronics. It looks at the maximum power point tracking (MPPT), charger controller algorithms definition and the design of balance-of-systems (BOS) electronics.

On the one hand, the PCDE extracts the maximum available power from the SA. This is not a straight forward question because the SA is constituted by the connection PV cells that may be affected by heterogeneous working conditions.

On the other hand, the BS requires a protection circuit module that works to prevent over discharge, over charge and over current and to provide balancing of the cells.

According to these requirements, a suitable PCDE hardware (HW) design has been carried out in order to enhance overall efficiency and reliability of the power system.

A multiple MPP tracker directly connected to the battery bus has been identified as the most efficient solution. Thus, instead of the conventional S3R 28V regulated bus topology, a new type of SA power regulator (MPPT 20-25V unregulated DC bus) is selected in order to extract all the available solar power under any working condition, including mismatching effects.

The same PCB contains the electronic control and the power supply of the whole PCDE, while the Battery Monitoring System is located on other PCB close to battery pack and controlled by means of Serial Parallel Interface (SPI).

This Battery Monitoring System is responsible for the balancing of PV cells but the charge/discharge protection of the BS is implemented by means of the multiple MPP tracker and the output switch, respectively.

Validation tests have put in evidence the main advantages of the proposed solution. Apart from providing the required battery management functionality (overcharge and overdischarge protection and equilibrium function), the developed PCDE presents a high conversion efficiency (>94%), and an accurate and reliable MPPT even in presence of partial shadows over the PV generator.

5.5 WP6: Mobility design and optimization

The simulation and optimization tool developed evaluates the rover performance for the selected tasks and on the specified terrains. It automatically adjusts all design parameters in parallel in order to get an optimal performance. All parameters are optimized synchronously. The user can specify the design parameters of interest (e.g. rover and wheel geometric dimensions) and desired optimization criteria (e.g. total mass, power consumption and peak drive torques) and related cost functions. Currently several baseline rover kinematics and a wide range of standard terrains, obstacles or cost functions are available. All settings and properties can be easily accessed, modified and adjusted according to the application, mission or the user's needs. Several optimization algorithms are also available.

The selection of the reference scenarios is a very crucial task as they have to represent the large bandwidth of possible tasks but also define the computational effort. A larger set of scenarios allows a more comprehensive and representative evaluation of the rover performance and fitness and increases the reliability and versatility of the obtained rover design. The performance of the nominal rover, optimized 7S (7 scenarios) and the optimized 19S (previous 7 scenarios + 12 additional scenarios) are shown in Figure 11. Compared to the original ExoMars design, the overall performance could be improved significantly, e.g. the summed values of the objective functions could be reduced by approx. 40% by the 7S rover and by additional 10% by the final 19S solution (50% of total value). The overall mass could be reduced by optimizing the kinematics and suspension system by approx. 2kg. The improved performance also results in less restrictive requirements concerning actuator performance, e.g. average power could also be reduced. Therefore, it can be assumed that the total mass can be further reduced, e.g. by smaller required actuators and power subsystem and batteries. Due to the high flexibility of the simulation and optimization environment, it can also be easily used for future space missions with different needs.

Using the hardware more efficiently also allows avoiding oversized components like actuators. This leads directly to a slender and lighter design of the overall rover. The developed torque control algorithm distributes the drive torques among the six wheels in an optimal way and avoids therefore critical situations (e.g. exceeding bearing capabilities of terrain) or minimizes the total required drive torque. The algorithm has been tested and validated by simulation. It performed very well on all evaluated terrains e.g. by successfully climbing up a chimney using its swing arms and deployment joints respectively to keep contact (see Figure 12). The fault tolerant control deals with malfunctioned steering and wheel actuators and allows operating the handicapped rover safely by reconfiguring the remaining rover joints and wheels respectively. The algorithm has been implemented on the refurbished ExoMars breadboard and tested and validated by simulation and testing. The algorithm performed well for all tested scenarios and even with 3 blocking actuators the algorithm proofed to be capable of following a desired trajectory (see Figure 12).

The developed rover design and chassis kinematics allow for efficient driving and operation on planetary surface but depend to a large extent on appropriate actuation. Wheel and actuator performance have been always a crucial issue for rover development.

5.6 WP7: Breadboarding

T7.1 Internal panel incorporating health monitoring and electronic functions"

The demonstrator is composed of a support panel and smart skin.

The IPB has been designed by TAS-I, and the support panel has been manufactured by Tecnalia:

- Dimensions: 590 mm (long edge) by 400 mm (short edge)
- Skin material: Fibers NGF YS80A, Resin Cytec LTM123, Filler: GRAPHENE 122
- Honeycomb: I.MA.TEC 3003-1/4-002-4.2, thickness: 21 mm

The support structure has been manufactured; however, the complete prototype has not been integrated, because there has been a big delay in the manufacturing of the smart skin module. Validation of the prototype hasnot been performed in the frame of the project.

From the EMI – EMC point of view, aluminium sputtered in a polymer film was selected as the most appropriate option (aluminium foil covering the Smart Skin). As the Smart Skin was not available, mock-ups of the elements were manufactured to be tested individually.

- supporting sandwich structure covered with 14 mkm aluminum foil (into the outer cover), 490x700 mm.;
- sample SS screen material is aluminum reinforced adhesive foil FBP-14 (ФБП-14, ТУ У 25.2-14023884), 490x700mm, that protect SS from the top;
- CFRP skin (0,85 mm), 490x700 mm;
- CFRP skin covered with 14 mkm aluminum foil, 490x700 mm.
- CFRP skin (300x300 mm)
- Doped CFRP skin (300x300 mm)
- Aluminium honeycomb (300x300 mm)
- CFRP sandwich panel (300x300 mm)

These tests were necessary to prove out the identity of the test results, in spite of the fact that they are made of carbon fillers, binder and honeycomb filler of different brands, and to make a conclusion that original SS mock-up is functional based on obtained results.

The measurements were executed with use of fielding bench that was manufactured for these works. Measurements were executed in frequency band of 1-12 GHz

SE of all samples tested is almost similar and equals to 58±5dB, that means all materials meet requirements of ECSS-E-20A standard: «Electronic blocks and cables that are exterior relative to spacecraft basic structure shall be equipped with individual shields (casings), which provide EMI attenuation to relative power of 40 dB».

SS, which from one side is covered with shield of FBP-14 foil and from the other the three-layered panel is attached, meets requirements of ECSS-E-20A standard, that will ensure fulfillment of the requirements of EMI-EMC to SS.

T7.2: Self powered external panel with storage capabilities.

The external panel aimed to create a self-powered panel with storage capabilities. This combined research from solar cell integration, battery as structural element and interconnection development between solar cells and batteries into a multifunctional power structure (MFPS). The panel's facesheets also contain the improvements in the thermal conductivity (Figure 13).

It is composed of a sandwich panel 482 mm long, 368 mm width and 22 mm thick. In the external facesheet, PV cells are integrated; 14 Multijunction PV cells, 3G30A from AZURSPACE arranged. Each PV cell has a size of 40 mm x 80 mm and a nominal power of 1.1 W. For the power storage, 96 commercial Varta LPP 503579 batteries are embedded in the aluminium core of the sandwich panel. The batteries are stuck in groups of 16 batteries.

The design of the panel has been driven by several requirements. These include maximising the power storage capability, minimising mass and volume while maintaining structural integrity of the panel for the expected environments of a mars rover mission. To achieve this, computational studies have been conducted to ensure the prototype will survive the thermal and mechanical environments with a 1.5 safety factor applied to the failure limits. The results of the analyses have shown that the addition of the multifunctional technologies had little effect on the design of the prototype. No interactions, adverse or otherwise, between the power generation and power storage multifunctional technologies were discovered during the course of the design.

Initial functional tests allow validating the suitable performance of batteries, PMU and BMS, extracting maximum power from the input and delivering the required power at the output, while maintaining battery integrity.

At the beginning of the test campaign, the prototype (including the power generator) was working properly. Therefore, it was understood that all subsystems withstood the manufacturing process. However, The PV generator failed during the detailed functional testing. . The failure analysis indicates the electronics worked properly and that the PV cells integration procedure should have not damaged the PV generator as demonstrated in the small scale prototype. Failure hypothesis points towards problems in the PV cells interconnection.

The validation test campaign conducted showed it was possible to operate the panel in the required temperature envelope of 0 – 30 C. The structure and the batteries survived the non-operating temperature range (-55 and 65 C temperature excursions). A malfunction of the MPU was found during the cold case. After the failure analysis, it was found that a mistake in the routing of the electronics was made (standard PCB approach followed). This problem can easily be solved in the future updating the routing.

The prototype survived a vibration environment of up to 15 g and 11 grms in the out of plane orientation and 10 g, 9.2 grms for in plane orientations. For all the environmental tests the embedded battery cells have shown to remain unaffected and balanced at 3.8V.

During the vibration testing, the PMU debonded from the skin. The analysis of the failure indicated it corresponded to a cohesive failure, meaning the adhesive worked properly and the substrate failed. The low interlaminar resistance typical of this kind of material (cyanate ster resin with high conductivity fibre),further decreased due to the addition of the graphene material, could be the cause of the failure. This aspect would need to be further investigated (additional trials would be required).

In order to compare the benefits of the integration of multiple functions in a single structure, a preliminary rough estimation of the mass and performance of the developed panel (Prototype 2) has been compared with the ones provided by similar subsystems manufactured following the traditional approach. For the MFS, values measured in the prototype have been taken into account, whereas for the "traditional approach" features of the 8S3P module from Saft as a typical battery powered module using lithium ion chemistry have been taken. For the power generator 3,5 kg/m^2 and 200 W/m^2 have been considered. In the analysis, only the supporting structure, the PV generator and the battery have been taken into account important **mass savings are obtained (36 %).** The main mass saving comes from the removal of the battery casing. The **volume** saving of the integration of the batteries in the core of the panel is estimated in **45%** of the total panel volume. In addition, the **performance of the system has also been improved**. In Table 2, a summary of the mass and volume assessment performed is provided.

The **mobility system prototype** aims to show the performance of the concept and simulation tool developed in WP6 through validation tests.

No full rover chassis and kinematics is developed within ROV-E. To represent the chassis kinematics and to guarantee the required guidance and degrees of freedom, an appropriate support structure is required. The developed mobility system and hardware consists therefore of two parts: The actuator unit itself and a single wheel test facility.

The actuator design and its performance evaluation have to be addressed with special care and extensive testing is inevitable. Within ROV-E a novel actuator and a feasible test facility to evaluate the actuator and wheel performance on planetary soil simulants have therefore been developed (see Figure 14). The main aim of these activities is to provide a novel actuator with increased performance and reduced mass and volume and therefore be tailored to the needs of planetary rovers. The rotary actuator has been designed for the special needs of planetary exploration and the harsh space environment has been considered from the very beginning. The actuator unit is based on a RoboDrive ILM38x06 BLDC motor and a single HFUC11-100 Harmonic Drive ® gear stage.

The actuator is fully self-contained and includes all bearings, sealing system, commutation sensors and contact flanges. The whole unit has a conduction enclosure for EMC reasons as well as a minimum material thickness for radiation/shielding and thermal aspects. An absolute position sensor can be optionally integrated at the output side, e.g. for steering or deployment joints. Due to the scalability of the underlying actuator concept, units of larger (or even smaller) size can be derived easily. Light-weight design has been implemented to the uttermost extent. Weighing only 360 g this actuator is capable of providing a nominal output torque of 5 Nm and 11 Nm repeated peak torque. The peak torque can be further increased to 25 Nm for a short time, e.g. in case of emergency. The actuator allows driving at high speed (wheel rotational speed up to 140 rpm). Due to the outstanding performance, its reliability and its very low weight, it is well suited for planetary rovers.

In order to test and evaluate the actuator performance an appropriate test facility has been designed, manufactured and set-up. The Single Wheel Testbed (SWT) is integrated in the

Planetary Exploration Lab of DLR-RMC (see Figure 14). It is attached to a mobile crane which allows using the entire soil bin and testing on different planetary soil simulants in parallel. The device is solely driven by the actuated wheel: The actuator unit can be attached to the wheel leg and is controlled by a COTS motor controller. In order to test the actuator performance for representative scenarios, the actuator is equipped with a wheel and driven on the desired soil simulant. In order to adjust the translational speed of the sledge, the sledge is attached to the steel cable of the drawbar-pull device. By uncoiling this cable at controlled speed and by setting the wheel rotational speed, the wheel slip can be adjusted precisely. The wheel load can be adjusted by adding weight plates to the load bars of the support plate or to the offload mechanism. The offload mechanism is realized by a steel cable and a combination of pulleys.

The SWT allows testing and measuring all relevant performance aspects of rover wheels and wheel-soil interaction.A relatively hard soil and a very soft soil have been selected to cover a large section of possible soil conditions. Next, the wheel dimensions, the wheel loads and the velocities have been chosen. On each of the soils the performance has been evaluated at different wheel loads (75 N, 125 N and 175 N), translational velocities (0.05 m/s, 0.065 m/s and 0.08 m/s) and slippage values.

On hard soil, the actuator performed very well for all scenarios (see Figure 15). Only at high wheel loads and large slip values, the actuator reached its actual limit of 11Nm repeated peak drive torque and therefore the repeated peak drive torque of 11Nm could be successfully validated during the test campaign. It shall be mentioned that for safety reasons the actuator drive torque is limited by the motor controller and its peak current. On soft soil, mobility proved to be strongly limited by the wheel design and dimensions and the bearing capability of the soil, respectively, even though the actuator was well within the limits: The wheel has only been able to drive at low wheel load and the wheel had to be able to run freely and must not be attached to the drawbar-pull device. No drawbar-pull force could therefore be measured. For all other tests the wheel failed to drive forwards. Even for an immobilized wheel, the actuator was still able to rotate the wheel without problems and the tests failed only due to the resulting extreme sinkage. The Single Wheel Testbed proved to be well suited for actuator testing. It allows testing the actuator and rover performance based on a single unit. Testing a single unit not only reduces breadboarding efforts; it also requires less testing area, less quantities of soil simulant but mainly reduces cumbersome soil preparation. The developed SWT allows cost efficient testing and speeds up testing significantly. The governed data is not only valuable for actuator testing. Moreover, it can support e.g. wheel design or the development and validation of appropriate rover simulation models and wheel-soil contact models.

5.7 WP8: Exploitation and dissemination

T8.1.Technology assessment

The technology assessment was prepared including a detailed review of the project highlighting key results found and the benefit and drawback that the technologies can currently achieve. An economical evaluation is also presented which shows the associated costs of the technologies implemented on the three MFS prototypes created against traditional means. This was completed with respect to material, manufacturing, operational, and maintenance costs. This is done for the 3 specific prototypes delivered in WP7; Internal panel incorporating health monitoring and electronic functions, Self-powered external panel with storage capabilities, and the Mobility design and optimization.

The detailed review shows that although promising the use of PCM and dismounting adhesive technologies are not currently at suitable readiness level to be implemented onto a MFS. Further work is required to overcome the containment issue when embedding the PCM into the honeycomb core. The remaining technologies considered were sufficiently developed to be incorporated onto the three prototype breadboards.

The economical evaluation shows that once all the problems encountered are overcome, the smart skin on the internal panel prototype could provide a conservative mass saving of 60% and a reduction in harness volume of 31 cm^3. The implementation of a smart skin also would also reduce the installation workload significantly to a single bonding step from 36 previously. This installation saving along with the volume saving could be increased as the circuit density was not maximised and could integrate further components if required.

The manufacture cost of the smart skin is approximately 17 kEUR and uses the same standard materials and machines to manufacture current flex-PCBs. Because the smart skin is considered a single module maintenance other than simple component repair would require the replacement of the whole skin incurring large costs and would require the successful development of the dismounting adhesives currently unavailable. Other approaches are being considered such as clamping the smart skin with fasteners with research on going. The main benefits and drawbacks are summarized in Table 1.

It is also useful to notice that the flexible PCB technology used to manufacture the smart skin is suitable for a very high circuit density, which is not exploited in the IPB demonstrator: the smart skin can embed much more connections in the same substrate, with the same mass estimate.

Regarding differences in installation and usage with respect to the equivalent state of the art, the smart skin includes all the cabling and connections necessary to feed and pilot its on-board hardware. To manually install the smart skin, a single bonding (gluing) step is needed. On the other hand, the installation of an equivalent number of sensors and heaters would require the preparation, layout and mounting of four heaters, their four power lines, fourteen sensors and their fourteen signal lines (36 steps). The smart skin, being highly integrated, reduces the workload (manpower) needed to reach the same hardware layout. Moreover, while reducing the crowdedness of the system, it also avoids a great number of manual connections, therefore minimizing both the mass associated with connectors and the possibility of human error (e.g. miswiring).

At the same time and because of its intrinsic integration, the smart skin is to be considered a single module when addressing maintenance activities.

TAS-I has some experience with manual rework and repair actions performed on single components of a smart skin-like product in standard laboratory conditions, with conventional tools found in an electronic lab. Those maintenance activities were successful and straightforward, and it can be assumed that similar activities could be performed during AIT. Nonetheless, the opinion of TAS-I is that it would be more convenient to remove the whole module and replace it with an identical spare. The new module could be tested beforehand and installed in place of the faulty or damaged one, while the latter could be examined or repaired off-line in a laboratory.

Of course, to enable this approach, the development of a dismountable adhesive was a relevant part of ROV-E activities, for which, at the moment, no exhaustive solution has been found. As a remedy, TAS-I is evaluating the possibility of clamping the smart skin only through the fasteners initially intended for electrical bonding, but this hypothesis raises some concerns regarding the survival of the assembly to vibrations and the quality of contact between smart skin and panel. As of December 2013, no final answer can be given, since mechanical and thermal tests have not been performed yet.

Related to the **Self powered external panel with storage capabilities** and in order to compare the benefits of the integration of multiple functions in a single structure, a rough estimation of the mass and performance of the developed panel (Prototype 2) has been compared with the ones provided by similar subsystems manufactured following the traditional approach. For the MFS, values measured in the prototype have been taken into account, whereas for the "traditional approach" information has been taken from literature (8S3P module from Saft, lithium ion chemistry). The mass of this battery with similar storage capacity is 4,5kg. For the solar panels, the following figures have been considered: 3,5 kg/m^2 and 200 W/m^2.

For the MFS, the following considerations have been performed:

- The number of PVcells integrated in the available area has been maximized (32 PV cells).
- The storage capacity of the 96 battery cells is considered: 462 Wh
- The mass of the electronics is not considered in the analysis. In both cases (MFS and traditional), the same design and manufacturing approach has been followed. Therefore, the mass would be similar and has not been taken into account. It is though that in future developments, the housing used in the "traditional" approach could also be removed installing a foil as cover (as the one proposed in Prototype 1) to protect the electronics from EMI-EMC. This aspect would need to be validated with the specific electronics. It seems that, in principle, there is room for improvement.

Rough estimations indicate that **mass savings around 36 % and volume savings around 45 %** could be achieved by means of the application of the multifunctional technology**.** The main mass saving comes from the removal of the battery casing. As a consequence, the **performance of the system has also been improved**

When the panel is assembled there are no operational differences to a traditional design as the requirements have been met including electrical capacity of the embedded battery cells.

The maintenance of the embedded cells is currently impossible where a failure of a cell would cost approximately \$13, 11 cm^3, and 24g as an additional cell is added in the traditional manner whilst the failed cell is left in situ. Additional harness wiring costs would also be incurred, however through rigorous mechanical testing the cells have shown to be robust and none have failed during the manufacture or validation tests in the final external panel prototype.

A modular approach should be followed when using multifunctional technologies. As aforementioned, this approach will facilitate the integration, reduce the touch labour, reducing the potential “human induced” problems during the integration.

The developed **mobility system prototype** has shown that although traditional brushed motors are currently preferred due to their heritage the ILM38 BLCD motor developed in this project has shown superior performance and as such additional gearing can be omitted from a traditional design reducing design, material (in terms of mass and volume), manufacture, and maintenance costs. There is also an operational cost improvement as BLCD motors are well suited for vacuum applications and can also operate at greater speed. The SWT developed as part of this project has reduced validation testing costs significantly which accelerates rover mobility development and allows testing at low cost to be conducted at an earlier stage of a project.

T8.2. Exploitation plan

A Technology Implementation Plan has been prepared which explores the opportunities for exploitation of the results of the ROV-E project; this includes use of the research for both the academic and the industrial context, the intended exploitation by the project partners and the opportunity to employ and build upon the technologies that have been developed in the context of ROV-E project.

T8.3. Dissemination activities

An update of the dissemination plan has been submitted Activities carried out and foreseen in ROV-E are summarized in the chapter below.

6 Description of the expected final results and their potential impacts and use

6.1 Expected final results and their potential impacts and use

Developments carried out in ROV-E project point towards weight reductions and optimized performance of elements and rover equipment, being able to include more scientific payload to the same limitation of weight, or reduce the cost of the mission for the same scientific payload. A mass reduction will decrease the fuel required to access the outer space, aspect that is considered determinant in this kind of missions. On the other hand, a maximum functional ratio has been achieved. A step forward in the integration of functions has been performed.

Rough estimates indicate important mass and volume savings could be obtained by means of the application of the multifunctional technologies: **36 % mass reduction and around 45 % in volume** (see details provided in the previous chapter).

Although the developments are focused on rovers, the novel techniques and methodologies (e.g. smart skin, integration of solar cells + battery in the panel) could also benefit commercial space missions thus generating a very significant impact on Europe's capability to access and exploit space. If technologies developed in ROV-E proof to be viable and if the ROV-E technology are further developed to withstand the TRL increase to level 7 (including reliability aspects), then telecommunication or navigation satellites (or constellations), representing almost the only semi-series production of space industry, will greatly benefit from such a technology, because a mass reduction could enable multiple launches with the same vector, therefore reducing the overall costs.

A main result is the identification of a Space Sector composite based on a prepreg that can be used to manufacture laminates which have significantly **improved thermal conductivity** compared with that of a conventional carbon fibre-reinforced laminate whilst maintaining the quality of the manufactured prepreg and laminate without significantly compromising the mechanical properties or adding a large cost to the finished product or significantly increasing the mass of the finished component.

The product developed in this project will be applicable to any structural application in the space sector where thermal conductivity is important such as where any heat source may be mounted such as an electronic device, it will mean that composites could be used in applications which would previously have been made from aluminium alloys giving potential for significant reductions in structural mass for space devices such as satellites and, as for the overall topic of this project, lunar or Martian rovers.

Results are proposed to be used during development of new generation spacecraft. New light materials can be created only on the basis of carbon plastic because it has maximum specific strength characteristics. The disadvantages of carbon fiber constructions are its lower EMI shielding effectiveness competently to traditional aluminum one. Therefore, experimental studies of carbon plastic covers were performed in initial condition and with electrically conductive filler. Studies of carbon plastic structure have shown that their

shielding effectiveness meets the requirements of the ECSS-E-20A standard and is not less than 40 dB in power in the frequency range from 1 to 12 GHz.

The output of the research also gave a greater understanding of the **use of phase change materials as a passive thermal control solution**. This understanding can be used to develop tools for designers to use for initial high level analysis on the use of PCM multifunctional structures. A standardised modelling tool was created and provides a user with estimates on the viability of the technology whilst also providing an optimised solution for the given input parameters. It is designed to be a rapid use tool to enable a designer to quickly gain the information necessary for the inclusion of a multifunctional thermal capacitor in a thermal control concept review.

It has been demonstrated PCMs are not a suitable technology for exploration rovers. However, potential use on satellites where orbits are at a much shorter period would widen the possible useful applications as it could be utilised more often but would depend on specific mission and thermal requirements. With regards to the technology readiness level, it is expected further development will solve the containment problems when using PCM as part of a multifunctional structure. If this is achieved it will allow in the short term experimental validation tests to confirm the performance of PCMs as part of a MFS. Positive results of this will allow passive thermal cooling to be embedded into a MFS. This could aid in the thermal control of components that are located directly above a sandwich panel structure such as electronic boards. PCMs are not suitable for Mars rover applications.

As for the **smart skin board**, the ultimate goal is to create a new product: a flexible PCB that can populate the structures of a space system (satellite or exploration vehicle), relying on it for mechanical support, and adding other functions with a minimum mass increase.

In particular the smart skin could be designed to match almost any geometry, and could bring power and signal lines throughout the system, while including heaters for thermal control purposes. Furthermore, the presence of distributed (decentralized) intelligent modules (microcontrollers) can reduce the workload on the main control unit, and improve the logics used to perform activation and deactivation of heaters, thus leading to energy savings.

As another key result, there is the fact of having a proven, commercially viable process to manufacture such an integrated flexible PCB, although several problems have been faced during the manufacturing process. The manufacturing process requires further development and needs to be optimized. At the time being, simple flexible boards are quite diffused as a way of improving packaging, but the enhancement of their functions, i.e. the embedment of passives or active components, is still at laboratory stage (basic R&D). TAS-I expects to settle, together with a skilled manufacturer, a repeatable process to build such an enhanced fPCB.

The potential use of the smart skin is to substitute conventional printed circuit boards in such a way to distribute those same functions on the structure of the space system, reducing connections and freeing up volume. The same concept is suitable not only for space systems, but also for other transportation systems.

The potential impacts are a saving in mass (and a better exploitation of volumes), the possibility to distribute sensors and heaters more easily in crowded systems (no need to manually install and connect each item, substitution of point-to-point connections with serial buses), and the enhancement of integration activities, because a single module can be applied on a substrate performing in a single action the installation of electronic boards, sensors, heaters and cabling.

Apart from the aspects strictly related to the flexible multifunctional boards, the presence of a thermo-structural substrate (panel) with improved thermal conductivity properties can be exploited both in conjunction with the smart skin (as a way of improving temperature uniformity below the board, and decreasing the delta temperature between the two faces of the panel), and as a self-standing new material available for future space systems.

The process to integrate **PV solar cells** into a composite material has been set-up. The development has been validated at scaled prototype level although problems were found in the definitive external panel prototype.

The development of the **innovative battery concept with added structural function** has shown that manufacture and assembly procedures exists that can produce a viable panel with embedded battery cells. Experimentation on the cells and a sample panel has revealed that the cells are mechanically robust. The design optimisation results imply that there is no universal optimal solution for embedding cells and that each case must consider the identified issues uniquely. The lessons learnt from this analysis and the characterisation of the battery cells inform potential users on how to make best use of the technology.

A proper functioning of the **self-powered external panel with storage capabilities** would allow mass and volume savings around 36 % and 45 % respectively This multifunctional development could be used not only in rovers but also in spacecraft and in terrestrial applications.

The developed **simulation and optimization environment** is fully operational. It allows a fast and comprehensive evaluation and optimization of the overall mobility system of planetary rovers and supports the chassis design from the very beginning. It has been successfully validated and applied to optimize the chassis design of several rover designs and the rover performance has been increased while reducing the total mass. Cost-intensive and cumbersome breadboarding and test activities can be reduced significantly. As it can be easily reused for all other planetary or terrestrial rover developments, future planetary exploration missions can strongly benefit thereof. The developed advanced control strategies are also well suited to increase reliability and performance of planetary rovers. The fault tolerant control allows safely operating malfunctioned rovers whereas the torque control mainly contributes to minimize power consumption and to distribute drive torques in an optimal way. Both control strategies have been validated by simulation. The fault tolerant control has been implemented and tested on the ExoMars breadboard and both control strategies can also be easily applied to other planetary rovers.

The developed **mobility system** and hardware consists of the actuator unit itself and an appropriate single wheel test facility. The **Single Wheel Testbed** is tailored to the needs for rover mobility testing. The main advantages of testing a single unit is that the operational point can be accurately adjusted and that the performance of the isolated wheel actuator can be evaluated and no parasitic elements or effects influence the measurements. Testing time and effort are reduced significantly as the system is userfriendly, can be run by a single operator and the effort for the cumbersome soil preparation can be reduced. A **novel actuator** unit for planetary rovers has been developed, tested and validated. The technology allows high torques at low speed in one application while it is capable of providing high dynamics in another application. The actuator unit is very small and light-weight design has been implemented to the uppermost extent. It has been designed for the harsh space environment and due to its outstanding performance and scalability it is well suited for a very wide field of future space applications.

The web page of the project: www.rove-project.eu.

6.2 Main dissemination activities and exploitation of results /foreground.

Dissemination activities are detailed in Table 3 and Table 4.

Some of the activities carried out in ROV-E project, form part of the following PhD thesis:

- DLR: "Detecção, diagnóstico e reconfiguração de falhas para projeto otimizado de veículos espaciais seguros aplicados à PMM e a rovers planetários"
- TAS-I: "Integrated Multifunctional Systems: Four prototypes including thermal, electrical and control aspects". Thesis including a description of part of the activities conducted in ROV-E will be made available to the public at the beginning of 2015.

The embargo on the dissemination of documents describing the smart skin has been a choice due to the need of advancing and experimenting manufacturing processes before the publication of material on this topic. In particular, TAS-I intends to submit publications regarding manufacturing and testing of the smart skin mounted on the IPB panel at the end of the test campaign.

At present Cytec are not in a position to disseminate the findings of this work and exploitation outside of the ROV-E consortium will be limited owing to structural changes within the company. In the longer term the material developed within the ROV-E project will potentially be made available to customers who are looking for the advantages which have been demonstrated.

Figures

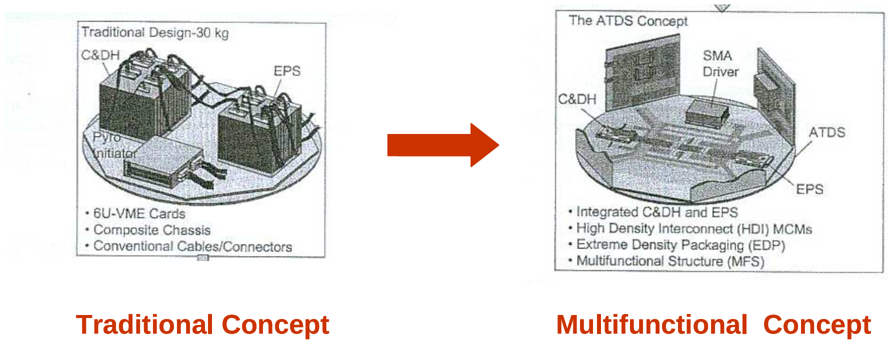

Figure 1: Traditional vs multifunctional concept.

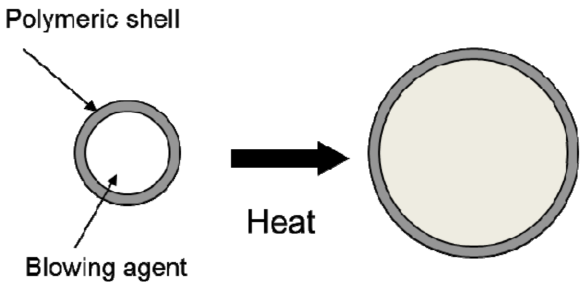

Figure 2: Followed strategy

Figure 3: General view of the sample with the transmitting and receiving antennas.

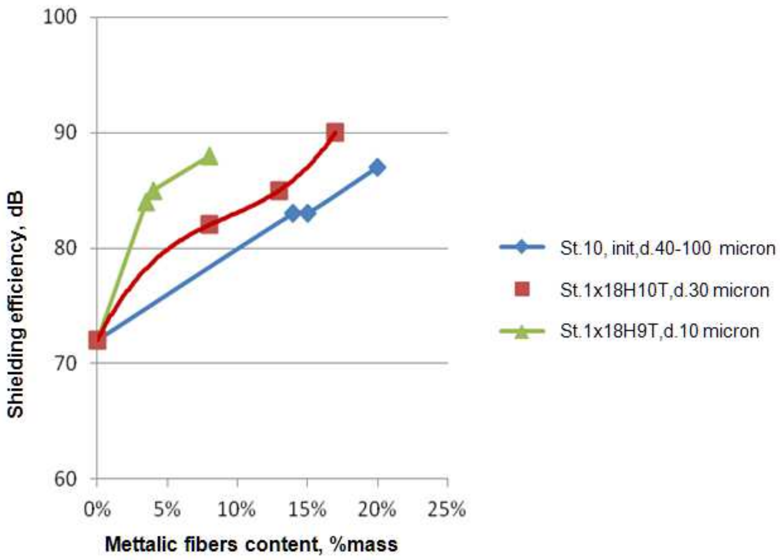

Figure 4: Shielding efficiency dependence of carbon-fiber plastic with the filler, formed from steel fibers, on the diameter of the fiber

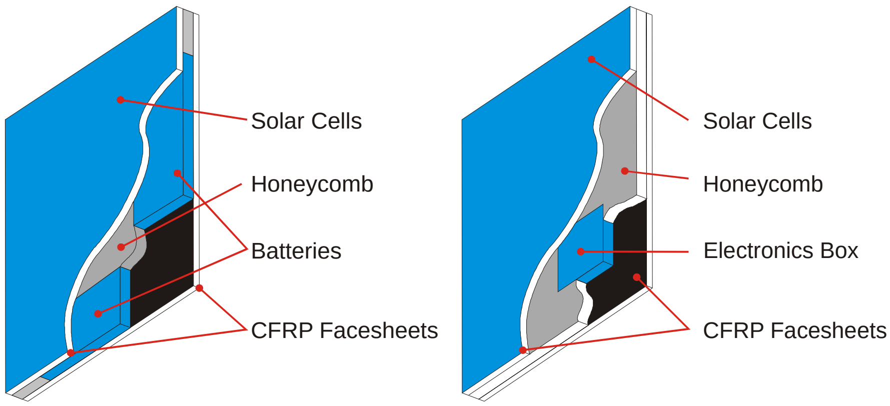

Figure 5: Illustration of the MFS applications

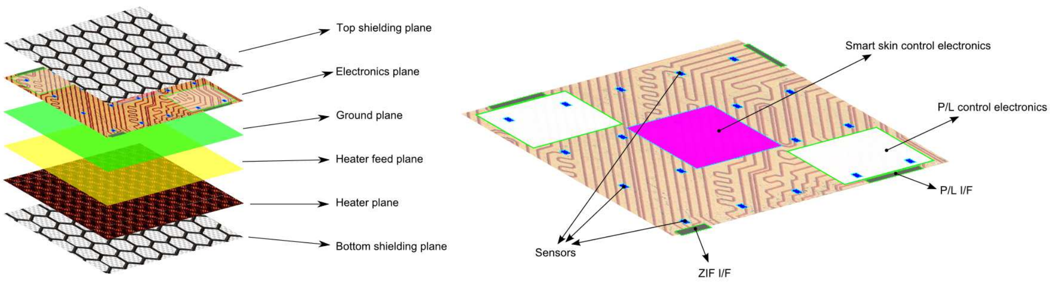

Figure 6: Schematics of the Smart skin.

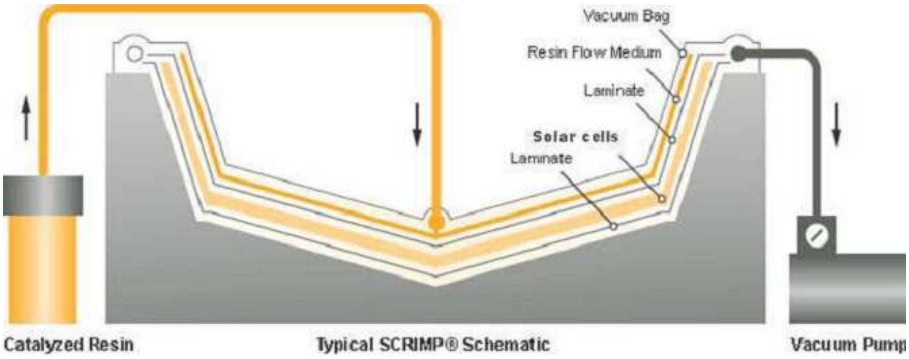

Figure 7: PV technologies integration process scheme.

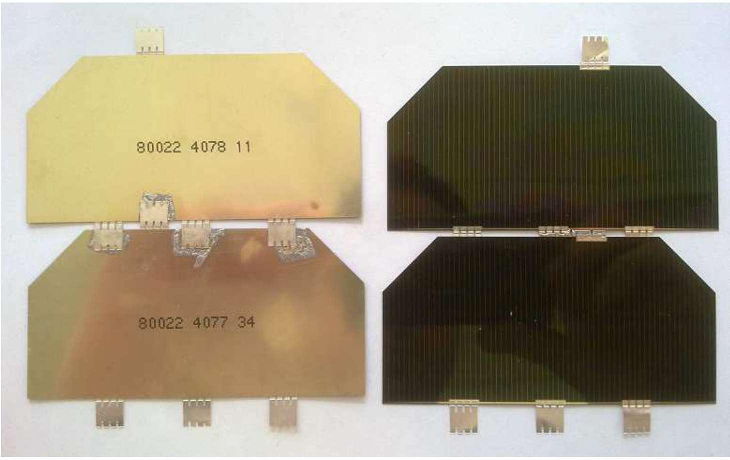

Figure 8: Interconnected multi-junction space solar cells.

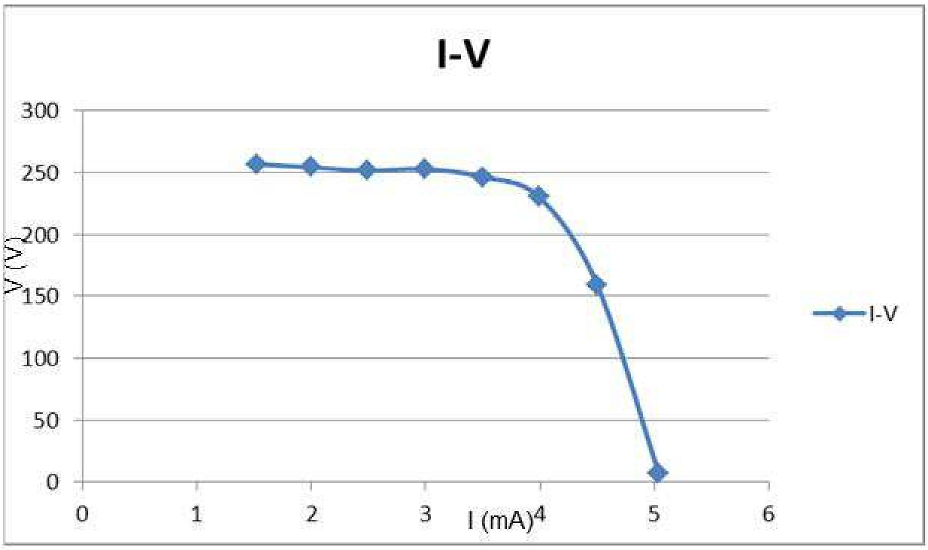

Figure 9: I-V output curve for the small scale prototype.

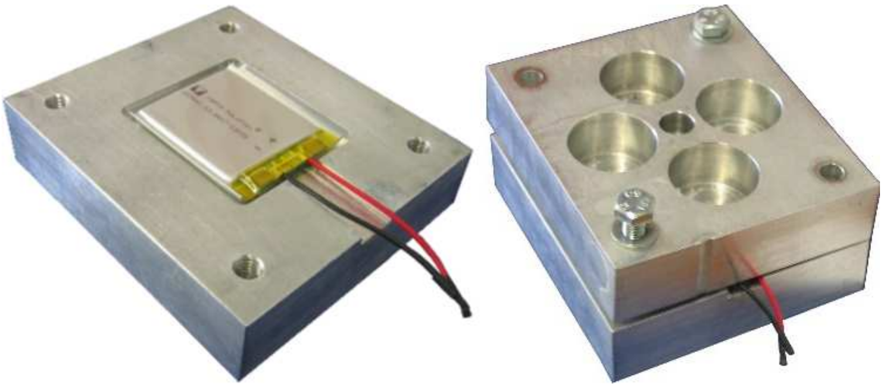

Figure 10: The random vibration battery jig and selected battery cell.

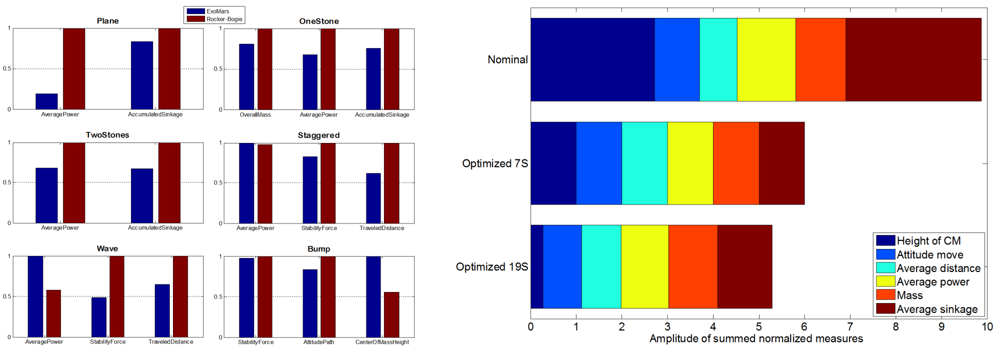

Figure 11: Comparison of performance for optimized ExoMars and Rocker-Bogie rover for 7S (left), and for nominal, optimized 7S and 19S ExoMars suspension (right)

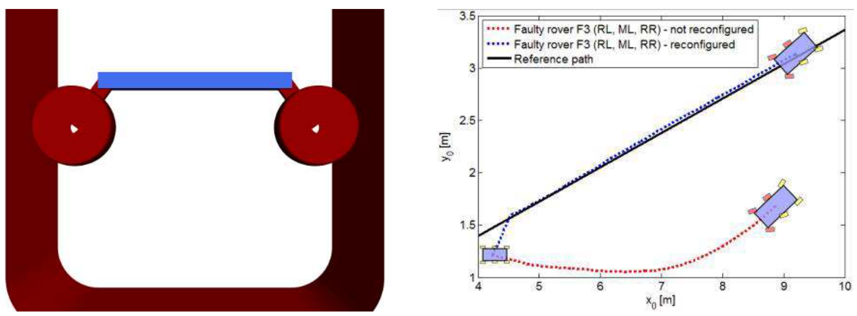

Figure 12: Rover with swing bogies climbing up chimney (left) and path following with malfunctioned rover (right)

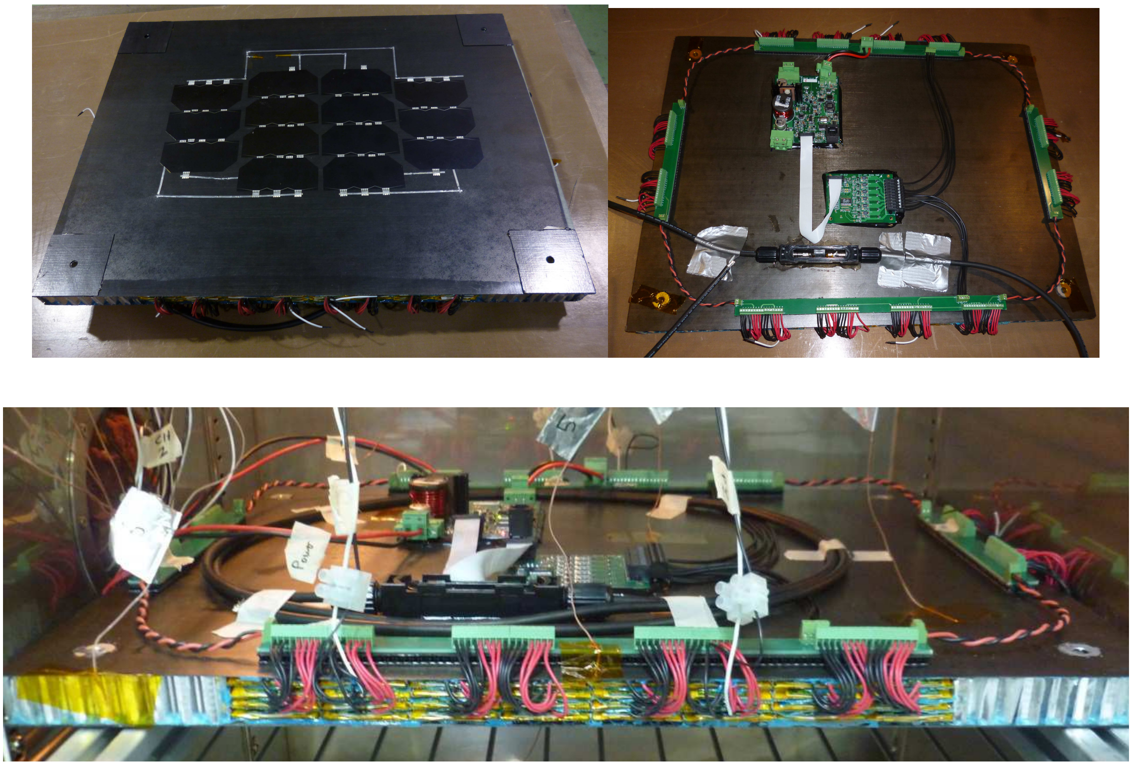

Figure 13: Views of the external prototype. a) detail of the power generator, b) electronics integrated in the inner skin; c) power storage integrated in the core of the panel.

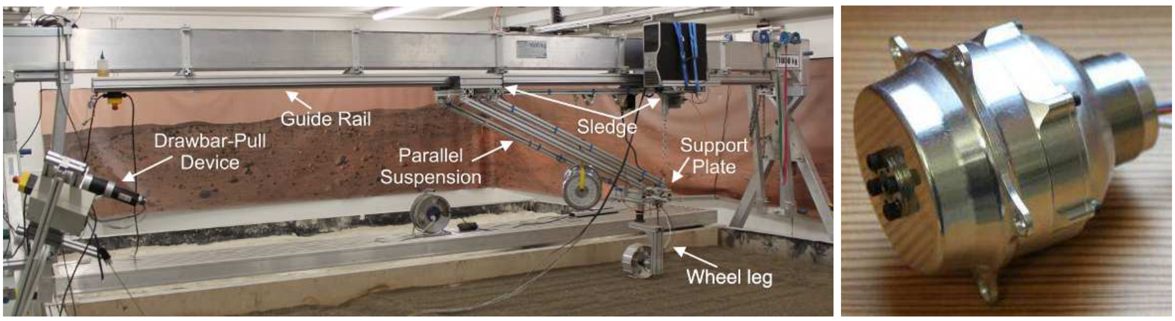

Figure 14: Single Wheel Testbed (left) and actuator unit (right)

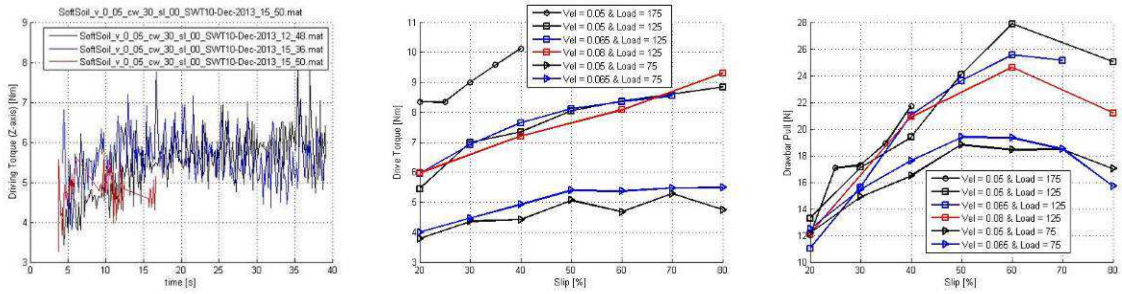

Figure 15: Actuator performance for various operating points on soil: Required drive torque (soft soil left) vs. time, required drive torque vs. slip (hard soil centre), and resulting available free pulling force (hard soil right) vs. slip

Tables

Benefits	Drawbacks
Extremely thin (reduced volume, lightweight)	Experimental manufacturing process (needs tuning)
Extremely flexible (substrate bendable to 1 mm diameter, complete board can conform to curved shapes)	Exposed to EM environment (no metal casing, needs innovative shielding approach)
Highly integrated (embeds electrical lines and heaters, eliminating harness; avoids point-to-point connections of sensors and heaters)	Works as a monolithic piece (reworking and repair issues may lead to the substitution of the whole module)
Modular and scalable (several items can be connected to cover a larger area, or part of the circuitry can be isolated to obtain a smaller version; faulty module can be replaced by identical one)	

Table 1: Benefits and drawbacks of the Smart Skin.

	MFS	Traditional approach	
Area panel [m^2]	0.18	0.18	-
Volume [cm^3]	4184	7460	44% Reduction
Mass [kg]	3.39	5.27	36% Reduction
Power generated [W]	35.20	35.48	
Storage [Wh]	462	467	
PV generator mass [kg]	0.34	0.62	
Battery mass [kg]	2.34	4.5	

Table 2: Mass and volume assessment.

Partner	WP	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages
TECNALIA	WP3 WP5 WP7	Multifunctional Structures for next generation Mars Exploration Rovers	G. Atxaga	Composites Science and Technology	Foreseen	Elsevier		2014	
SOTON	WP3.4.1	Thermal Control of Mars Based Multifunctional Structures	J A Foster	Acta Astronautica	Foreseen	Elsevier	EU	2014	-
SOTON	WP3.4.2	Multifunctional Thermal Structures using Phase Change Materials	J A Foster	IEEE Aerospace and Electronic System Magazine	Foreseen	IEEE	USA	2014	-
YUZ	WP3	Multifunctional Materials for Provision of SC Shielding			Foreseen			2014	
DLR	WP6	Fault-Tolerant Control Strategy for Steering Failures in Wheeled Planetary Rovers	Leite A.C	Journal of Robotics	Vol. 2012	Hindawi Publishing Corporation	USA	2012	Article ID 694673

Table 3: List of CURRENT AND FORESEEN scientific (peer reviewed) publications

Type of activities	Partner (Main leader)	WP	Title	Date	Place	Type of audience	Size of audience	Countries addressed
Web	TECNALIA	WP8	www.rove-project.eu					International
Web	TECNALIA	WP8	Info in Wikipedia: http://en.wikipedia.org/wiki/Seventh_Framework_Programme#ROV-E					
Brochure	TECNALIA		Space Research projects under the 7th Framework Programme for Research.					International
Conference (poster)	DLR	WP6	Challenges in robotics: down to earth: “Multifunctional mobility design of planetary exploration rovers”	November 21-22, 2011	Oberpfaffenhofen Germany			
Conference	TECNALIA	WP3.1	Graphene 2012: “Improvement of thermal conductivity in graphene reinforced cyanate ester resin”.	April 2012	Brussels, Belgium	Academic Conference		International
Conference	TECNALIA		2nd FP7 Space Research Conference: “Lightweight Technologies for Exploration Rovers”	November, 15-16, 2012	Larnaca, Cyprus	Academic Conference		International
PhD Thesis	DLR	WP6	Detecção, diagnóstico e reconfiguração de falhas para projeto otimizado de veículos espaciais seguros aplicados à PMM e a rovers planetários	2012	São José dos Campos, Brazil	Scientific Community	N/A	
Conference	DLR	WP6	Sysid 2012 (16th IFAC Symposium on System Identification), “Parameter identification and contact modeling for planetary wheeled rovers in soft soil”	July 11-13, 2012	Brussels, Belgium	Academic Conference		International
Conference	Yuzhnoye	WP3	7th International Conference: Materials and Coatings in extreme conditions: Development of new shielding materials for electronic equipment of	September 23-28, 2012	Ukraine	Scientific Community, Industry		Russia, Ukraine, Belorussia
Conference	DLR	WP6	DINAME 2013 (Proceedings of the XV International Symposium on Dynamic Problems of Mechanics), “Planetary Rover Optimization Tool (ROT)”	February 17-22, 2013	Buzios, RJ, Brazil,	Scientific Community, Industry		International

Type of activities	Partner (Main leader)	WP	Title	Date	Place	Type of audience	Size of audience	Countries addressed
Conference	DLR	WP6	ASTRA 2013 (12th Symposium on Advanced Space Technologies in Robotics and Automation),“ Automated design of lightweight exploration rovers	May 15 - 17, 2013	Noordwijk, the Netherlands	Scientific Community, Industry		International
Conference	DLR	WP6	ASTRA 2013 (12th Symposium on Advanced Space Technologies in Robotics and Automation), ““The Dilemma Diagnoser Approach and its Application to the Fault-Tolerant Control of Planetary Exploration Rovers”	May 15 - 17, 2013	Noordwijk, the Netherlands	Scientific Community, Industry		International
Conference	SOTON	WP5.2	World Academy of Science: Optimization of Multifunctional Battery Structures for Mars Rovers	June 2013	Paris, France	Academic Conference	30+	European
Conference	SOTON	WP3.4WP5.2	IAC:ROV-E Activities at Southampton University	sep-13	Beijing, China	Academic Conference	30+	International
PhD Thesis	TAS-I	WP4	Integrated Multifunctional Systems: Four prototypes including thermal, electrical and control aspects.	December 2012 (released to public on Jan 1st 2015)	Turin, Italy	Academic, public		International
Presentation to potential	TECNALIA	WP7	Presentation to potential customers (TAS-I, CASA Espacio, Astrium CRISA)			R&D and product specialist		
Conference	Yuzhnoye	WP3	Fourth International conference «Space Technologies: present and future» : "«Carbon-plastic composites with shielding properties"					
Conference	Yuzhnoye	WP3	Conference «Человек и космос» (2013) «EMI shielding by three-layered honeycomb structures »,					

Table 4: Dissemination Activities