A LIGHT-WEIGHT AND MODULAR HIGH-PERFORMANCE PAYLOAD COMPUTER FOR REAL-TIME ON-BOARD SIGNAL PROCESSING AND AUTONOMOUS DECISION MAKING

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ABSTRACT

Thales Alenia Space Deutschland GmbH (TAS-D) and their partners are developing a modular high-performance computer for space payloads requiring real-time multi-sensor signal processing. The primary purpose of this computer is to enable space-based, real-time and safety critical multi-sensor data fusion and interpretation such as required by orbital debris removal missions and high-fidelity air traffic surveillance applications. Other demanding processing needs are also being investigated and the system's modularity should allow easy adaptation.

1 INTRODUCTION

TAS-D are developing technologies aimed at providing global air traffic surveillance and communication for aircraft equipped with no more than standard VHF radios and mandatory ADS-B transponders. ADS-B, short for "Automatic Dependent Surveillance Broadcast", is a recent air traffic surveillance standard to enhance the performance of existing radar installations, and will become mandatory in most parts of the world by 2020.

With the antenna footprint from Low Earth Orbit being much larger (approx. 3000km radius compared to terrestrial receivers, which see traffic within a radius of about 300km), space-based receivers pick up many more ADS-B telegrams, requiring more sophisticated processing techniques than needed for ground-based systems. Because the service depends on the real-time availability of data with tight latency requirements, and because the raw data is extremely high in volume, ground processing of ADS-B and VHF signals is not practical.

In a similar scenario, high-performance optical navigation required by missions relying on real-time on-board decision making can also not rely on ground data processing. Robotic missions for active space debris removal, planetary landers, asteroid landing- and deflection missions and spacecraft requiring aerobreaking and aero-capture trajectories in the outer atmospheres of other planets are beyond the range of real-time communication because decisions need to be made in less time than the round-trip light time.

Thales Alenia Space Deutschland and their partners therefore are developing a space-qualified computer capable of such performance. It is designed to provide fast, real-time signal de-garbling, image processing and multi-sensor data fusion functions to advanced guidance, navigation and control (GNC) subsystems.

An experimental precursor, known as SABIP, has recently been completed and is shown in Figure 1.

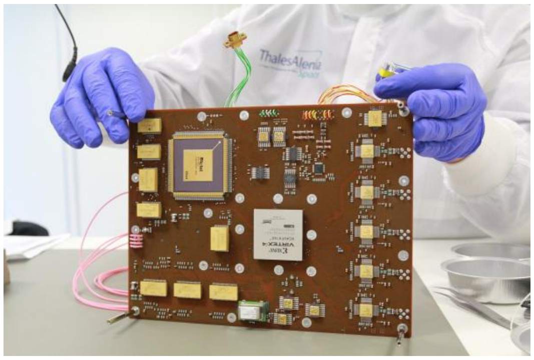

Figure 1: experimental unit SABIP.

2 USE CASES

The following use cases were analyzed to derive requirements from. However, this is by no means a limitation of applications.

2.1 Global Air Traffic Control and Flight Tracking

Air Traffic Management (ATM) integrates the three disciplines Communication, Navigation, and Surveillance.

Automatic Dependent Surveillance Broadcast is a data link principle based on aircraft broadcasting their own surveillance information using burst telemetry containing existing aircraft on-board data during all phases of flight on a regular basis. The signal includes flight related information such as position, speed and flight number; enabling air-to-air and air-to-ground surveillance. ADS-B Mode S 1090ES data signals are broadcast (ADS-B out) in the lower L-band (1090 MHz) with typical periodicity of 0.5s to 5s, with a power from 125 Watts to 500 Watts for commercial transport aircraft with intercontinental range.

ADS-B is primarily a terrestrial based system. Terrestrial based ADS-B services are currently deployed as an add-on to radars or as an alternative in regions were a traditional ATM system based on radar stations is not cost effective. The ADS-B services will thus extend ATM services in those areas where a ground based infrastructure can be installed.

While terrestrial systems offer many advantages in terms of performance and maintenance, they cannot operate beyond the line of sight. For most areas of the world, the installation of an ATM network based on radars or terrestrial ADS-B stations is not cost effective, too complex or not feasible. Around 90% of the world surface has no radar coverage and no or unreliable real-time push-to-talk voice communication. Consequently, procedural ATM has to be applied. This is particularly true for the oceanic areas, but also for continental areas such as Africa, South America, South East Asia, and the North and South Pole. A complete surveillance of these remote areas (so called non-radar airspaces, NRA) by terrestrial services is not economical, confining the reach of advanced Air Traffic Control (ATC) operations to the land masses where VHF towers, radar and/or ADS-B are deployed.

A space based solution deploying ADS-B receivers on LEO satellites could enable universal surveillance services by providing true global ADS-B coverage (see Figure 2). While this solves the particular problem of surveillance, it leaves pilots and controllers unable to communicate with one another sufficiently quickly and with sufficiently universal access to allow for radar-like air traffic control procedures to be executed.

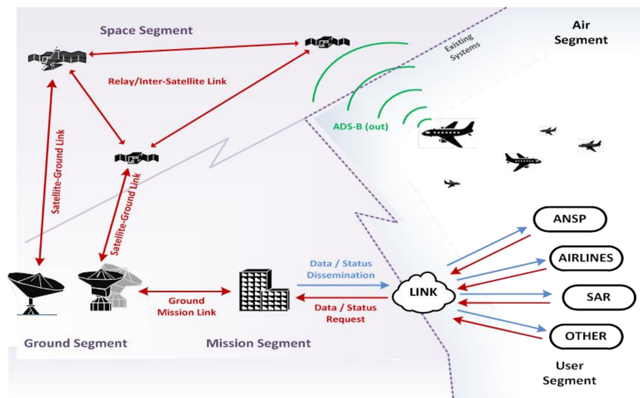

Figure 2: Space-based Air Traffic Surveillance Concept.

Similar to Space-Based ADS-B, a satellite-based Airband VHF Voice system, through receivers aboard LEO satellites, would be able to pick up transmissions broadcast by aircraft without the need to retrofit these aircraft in any way. The proposed system would be able to receive, and transmit to, standard VHF radios already installed on nearly all aircraft. Integration with ATC is facilitated to the VoIP backbone already in place for modern VHF towers. This is why Airband VHF via Satellite may be designed to behave as if it were just another VHF-tower: except being a "virtual" VHF antenna located in the sky, with a much larger footprint.

Such surveillance functionality beyond presently existing and proposed solutions requires the system to be able to distinguish between many simultaneous transmissions (degarbling) within the antenna footprint, be able to steer the antenna footprint electronically, compensate for Doppler shifts and isolate areas of interference.

Building a cost-effective satellite payload capable of providing these functions while being fit for a low-cost multi-purpose constellation, the required computational power must be provided by an inexpensive, compact and highly reliable package. This is beyond the capabilities of traditional spacecraft on-board computers but well within the performance of consumer and MIL grade electronics.

2.2 Active Removal of Orbital Debris

Similar performance is required by missions where a spacecraft is intended to approach orbital debris for the purpose of its removal.

Orbital debris, also referred to as space debris, space junk or orbital junk, are all man-made objects presently in orbit around Earth which serve no useful purpose. They can range in size from millimeters (such as paint chips or MLI fragments) to several meters (such as defunct satellites or spent rocket stages).

As the number of debris objects increases beyond a certain threshold in an orbital region, the debris object count will continue to increase even if no more launches were to occur. In what is known as the "Kessler Syndrome"[1], fragments collide with other fragments, causing a run-away fragmentation process.

Removing objects cheaply and efficiently is therefore paramount for sustaining space flight in the future, yet it is no easy task. To carry it out economically and with a risk significantly lower than doing nothing, the space system must be produced cheaply, yet operate safely, reliably and autonomously.

Sensors on board the spacecraft must reliably and remotely identify an uncooperative target, determine its orbit and attitude accurately enough for safe vicinity operations and properly maneuver into place to begin removal operations. These tasks, along with subsequent maneuvers with an object of unknown mass properties in tow, require computationally intensive sensor data processing, for example, real-time on-board image analysis and object recognition.

2.3 Planetary Exploration

Autonomous navigation of a similar kind must be carried out by exploration rovers for safely driving on distant planets. Here, obstacle avoidance is as important as visual navigation by map reference, object manipulation and science sensor data fusion and pre-processing.

Autonomous navigation in space may help interplanetary probes to fly precision hypersonic maneuvers in planetary atmospheres for aerocapture and pin-point landing on planets. Such missions have recently become desirable to safe fuel, land heavy payloads near a target site in difficult terrain and to rendez-vous with assets already landed on the surface. Here, obstacle avoidance on terminal descent relies heavily on integrated sensor data fusion, real-time image processing and terrain navigation.

To lend that kind of processing power to vehicles operating in interplanetary space, outside the protection of the Van-Allen radiation belts, requires novel ways of radiation tolerant behavior above and beyond what's required for Low-Earth-Orbit missions.

3 SYSTEM ARCHITECTURE

Thales Alenia Space Deutschland and their partners are developing a space-qualified computer capable of delivering performance required by the above examples. It incorporates the experience gained with an experimental payload, known as SABIP, which was designed, built and tested to demonstrate the basic feasibility of multiple beam antennae and real-time multi-channel signal processing in space.

Building on SABIP, the new computer provides the capability and reliability required by real-world, safety-of-life applications beyond mere flight tracking.

3.1 Modularity, OMAC4S & Space CPCI Serial

To be able to adapt easily to the various mission scenarios, the computer system relies on a modular architecture based on a newly developed, open modular standard for space applications (called OMAC4S). The electrical interface standard developed for OMAC4S is a modified variant of compact PCI [2] and referred to as Space CPCI Serial. The standard is developed jointly with Airbus Defence and Space, Fraunhofer, MAN Electronics and others with support from the German Aerospace research centre DLR.

These standard interfaces allow anyone to develop compatible, space-qualified modules for other applications and make the inclusion of TAS-D's high performance computer modules inexpensive and reliable.

3.2 Principle Architecture

The High Performance Parallel Payload Processor (HP4) computer is powerful yet light-weight modular system built around a multi-core CPU paired with a powerful FPGA. It is comparable in performance to a modern dual-CPU workstation for signal processing yet consumes lower specific power while offering full redundancy with the option of adding additional sensor interfaces. It is designed to process multi-sensor data streams and electronically control subsystems such as antenna arrays for dynamic beam adaptation or orbit control sub-systems for real-time maneuvers.

The high performance computer consists of a backplane and a number of processing boards ("nodes") reflecting the specific mission and required (cold) redundancy. For the Sat-ADS-B application the computer comprises the following nodes:

- Power supply
- RF-ADC
- FPGA
- CPU

The Power supply node allows to connect the computer to the unregulated power bus of the spacecraft, and is chosen according to the typically employed voltages (28V .. 100V)

The RF-ADC node provides the RF analogue front-end for a multi-beam ADS-B antenna (1090MHz). This board also digitizes each RF-channel by means of a high-speed serializing ADC.

The FPGA node performs the low-level signal processing such as signal acquisition and decoding. Input and output data rates are in the range of 1.5Gbit/s per channel.

The CPU node performs the high-level computation and the on-board preprocessing of the low-level decoded data. In the case of the ADS-B application this leads to a data rate reduction by a factor of 80 .. 200. This node also holds the basic control unit for remote monitoring and control by the spacecraft and from ground, even if the CPU and the other signal processing boards are non-operating.

For the SatVHF application the RF-ADC node is replaced by a board for receiving the channels of the aeronautical VHF band and an DAC-RF node is added which realizes the transmit function to aircraft. The FPGA and CPU nodes run the firmware to manage and relay the voice communication services provided by SatVHF.

To achieve the required radiation tolerance with commercial components to operate in space, novel, software-based radiation effect mitigation methods need to be implemented.

In order to mitigate the mass penalty implied by the modular construction, the concept of a modular housing is being investigated, essentially building-up the computer housing from the individual nodes. For further mass savings the node-housings shall be realized by CFRP by extending its basic characteristics regarding conductivity, EMC shielding and thermal heat flow to cope with the charging effect, high frequencies, and transportation of dissipated heat generated by the computer nodes.

3.3 The Open Architecture of the OBC-SA project

In the last three years the OBC-SA project [3] prototyped the principal technical components of a open and modular architecture for space computers. The principal system structure of the OBC-SA framework is shown in Figure 3.

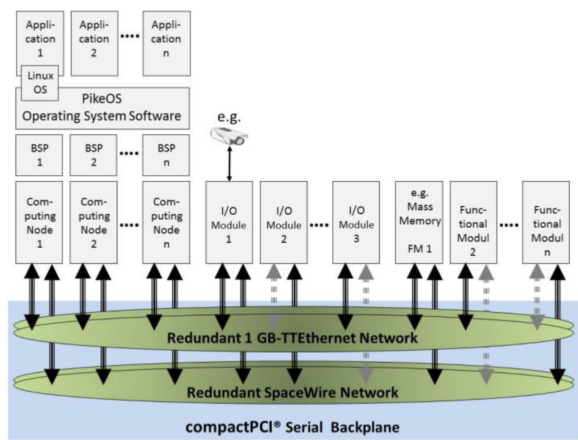

Figure 3: OBC-SA framework based on the Compact-PCI Serial standard

The redundant TTEthernet and SpaceWire networks on the backplane of the OBC-SA system are formed by two redundant router modules. Each module contains the routers for both networks and is located in a separate backplane slot. The routers are connected to each other and have point-to point connections to all other slots of the system thus forming a star network topology. The open and modular structure of the OBC-SA framework enables composing the IT infrastructure of a satellite by integrating standardized processing nodes of different performance and functionality, subsystems as e.g. mass memory modules, and interface modules for specific instruments. By adding redundant processing nodes or subsystems together with appropriate fault tolerance mechanisms, the availability and reliability of critical functions can be configured according to specific mission requirements. One of the most important features of the OBC-SA framework is the backplane based implementation of the unified high speed and fault tolerant interconnect architecture based on TTEthernet and SpaceWire. The two network types provide different throughput and also different service quality. The SpaceWire network with data rates of a hundred Mbit/s is used to connect modules via the widely used European communication standard for space application.

The 1Gbit/s TTEthernet network provides Gigabit performance and, more important, it can guaranty hard real time communication and a tight synchronization of the communicating nodes and the subsystems. This feature is especially important in time critical robot control applications. The processing nodes and subsystems may connect either to both or only to one network. To take advantage of the fault tolerant feature of the networks, the nodes or subsystems must be connected to the two redundant routers of the system. The basic hardware layer is now topic of an standardization activity called Space compactPCI serial.

4 MECHANICAL CASE AND INTERFACES

Since more than 10 years HPS GmbH is developing and testing CFRP electronic housings with different aspects. The incentive of this development can be summarized to some key aspects:

- weight saving due to higher stiffness with carbon fibers in comparison to aluminum housings
- same thermal performance as an aluminum housing
- cost reduction due to a modular design approach of the CFRP housing in case of series production.
- avoiding CTE mismatch in case of mounting on CFRP panels.

The challenges faced during the various performed box developments can be setup into several areas:

- Thermal performance v.s. mechanical performance
- EMC performance
- Radiation protection
- Structural integrity
- Definition of a cost effective manufacturing process
- Applying of new technologies and materials

In a first project *Spacecraft EMI Control in the Presence of Composite Materials* (ESA contract # 18985/05/NL/JA) the electrical behavior of an elegant bread board was elaborated and first manufacturing aspects were addressed. The reference housing was an ultra-light weight aluminum housing SUMER DPU case on the SOHO probe. A picture of the CFRP and the aluminum housing is shown in Figure 4.

Figure 4: EMI CFRP- and reference-housing

In this project for the main cells a winding procedure with an UHM fibers has been applied. For lids and feeds an HTM fiber in a usual prepreg process was used. The resin was a hot curing epoxy doped with carbon nanotubes (CNT). In a test campaign at EMC laboratory of SERCo in Ottobrunn various test were performed.

The electromagnetic shielding efficiency of both box materials is comparable. The tested aluminum case is approximately 10 dB better up to frequencies of about 300 MHz. In the GHz range the CFRP case is roughly 10 dB better than the aluminum case because there are no screwed joints that act as slot antennae.

The mass of the box could be reduced by 24%.

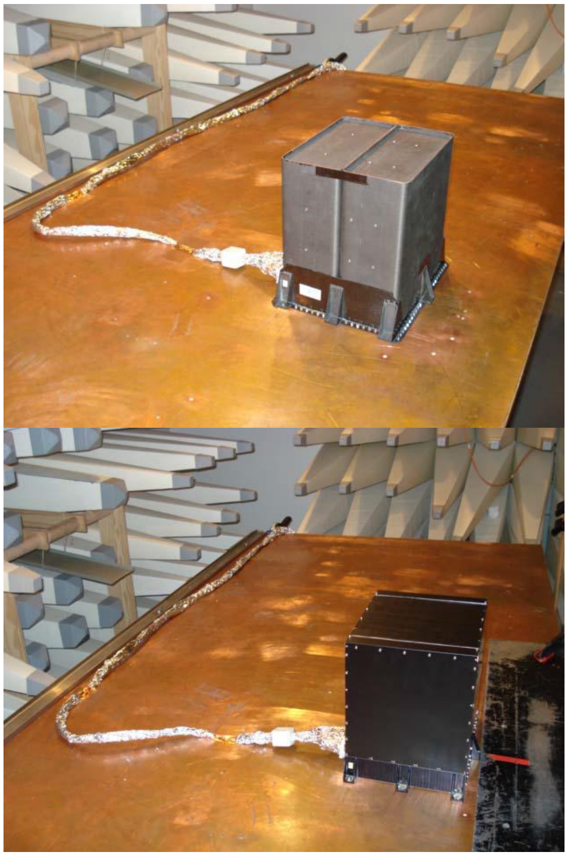

Figure 5: EMI CFRP housing (top) and reference housing (bottom) in the EMC test chamber

Based on the experience of the EMI housing in a program called *Verification of Resin Transfer Molding (RTM) as Alternative for Space Component Manufacturing (VERASCOM)* (ESA Contract # 19394/05/NL/PA) also the SUMER DPU was chosen as reference. In the scope of this contract the focus was on an alternative manufacturing process: RTM. As comparison w.r.t. mechanical behavior the EMI housing (see project above) was vibration tested in parallel. Structural integrity of both structures was achieved. See Figure 6 for the CFRP housing manufactured by RTM technique on the shaker.

In a Germany national founded program *CARBO SPACE - CNT-Hochleistungswerkstoffe* (Förderkennzeichen 03X0051B) the influence of different nanotubes was examined in detail. Beside a large sample test program again an electronic housing was manufactured using winding and prepreg techniques. Within this project the TRL could be increased significantly.

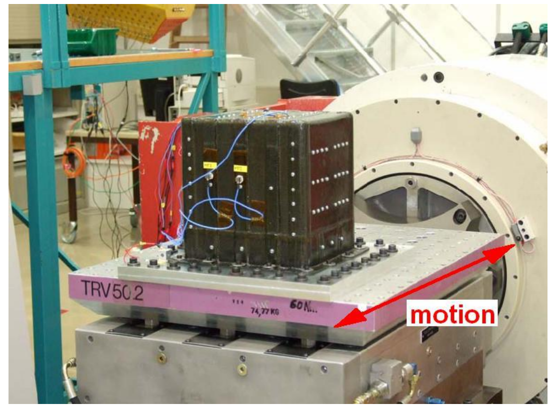

Figure 6: RTM CFRP housing on the shaker

Figure 7: CARBO SAPCE CFRP housing

The missing thermal evaluation was elaborated in an ESA project, led by the Portuguese Institute INEGI, called *Thermally Conductive RTM CFRP* (ESA Contract #1-7543/12/NL/CP). HPS has been responsible for the requirements, mechanical design and thermo-mechanical analysis. The focus in this project was the improvement of thermal and mechanical material properties due to a high pressure RTM process. Moreover a full test campaign including mechanical, TVC and thermal balance tests were performed. The reference box changed to a series electronic equipment: a power supply box with a power loss of 30W. Especially the thermal performance was a high challenge. The tests showed similar performance to the original reference flight housing. The goals were achieved and, similar to the mentioned projects, a mass saving of 20% has been demonstrated.

Currently HPS is developing an effective radiation protection for such kind of electronic housings under an ESA GSTP contract.

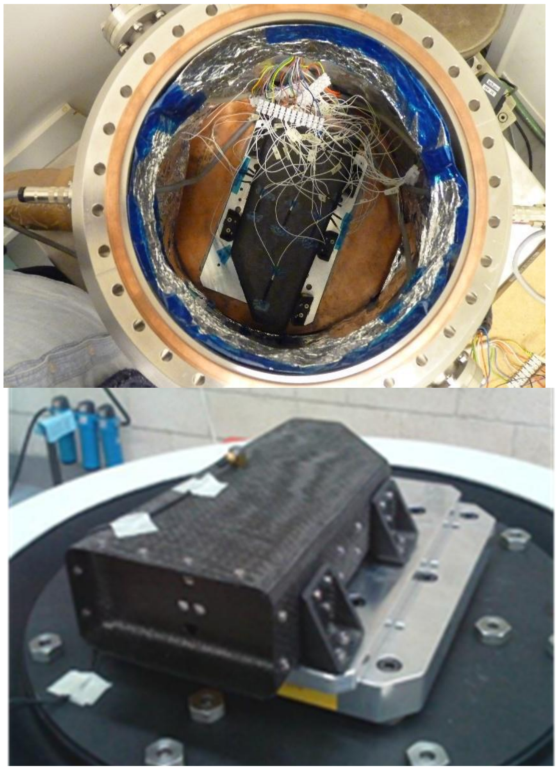

Figure 8: RTM box CFRP housing top in the TV chamber right on the shaker

5 CONCLUSION

Thales Alenia Space Deutschland, Fraunhofer FOKUS and their partners are now able to build a computer capable of delivering the performance required for global asset tracking, real-time sensor data fusion and image analysis and autonomous navigation and decision making. In addition to this, HPS is now in the position to design and manufacture a CFRP electronic housing which will avoid the CTE mismatch between a CFRP panel and electronic equipment with sufficient mechanical margins and a thermal conductivity comparable to common aluminum housing. The expected mass saving is in the range of 20% to 25 % compared to a similar aluminum housing.

We therefore regard the subsystem described herein as one of the enabling elements of ambitious robotics and data gathering missions.

Acknowledgement

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