Space Applications For Smart Sensors

Bernhard Hufenbach[1], Sandi Habinc[2], Pierrik Vuilleumier[3]
European Space Agency
European Space Research and Technology Centre
{bhufenba, shabinc, pvuilleu}@estec.esa.nl

SUMMARY

With more than 500 conventional sensors on a medium sized spacecraft there is a substantial application potential for smart sensor technology which is not exploited today. This paper gives an overview of Space applications and the Space infrastructure in place. The need for different types of sensor for the various existing Space systems is analysed. The difference of the technical requirements between sensors used for terrestrial and for Space applications are highlighted. Potentials and limitations for the applications of smart sensors in Space systems are discussed. Current initiatives of the European Space Agency on the development of smart sensor systems for future space missions are presented.

Keywords: *Smart Sensor, Space Applications, Visual Systems, Smart Instrumentation Point, Solid State Micro-Gyroscopes*

INTRODUCTION

The availablity of sensors suitable for Space applications is very limited. This situation will in future become even more critical as the market for military electronics (e.g. radiation tolerant electronic equipment), a major technology supplier for Space, is deflating. To benefit from innovative technologies developed for terrestrial applications, a technology transfer (spin-in) from terrestrial to space applications is required. This paper addresses the potential and limitations of such a technology transfer for the case of the smart sensor technology. Some specific smart sensor application examples are given to provide directions for future development efforts.

INTRODUCTION TO SPACE SYSTEMS

The first step towards exploration and exploitation of Space was taken in 1957 by the former Soviet Union with the launch of the first artificial satellite, Sputnik. Although the Space Age is merely 40 years old, applications based on Space technology and knowledge gained from Space exploration are now an important and integral part of our society. The conquer of Space in the late 50th and early 60th was left to the two Super Powers of that time, the United States and the former Soviet Union, and was mainly motivated by strategic considerations related to the Cold War. Today, the world counts 30 Space fairing Nations and Space is increasingly used for commercial purposes. Table 1 lists four characteristics of Space, which offer the potential to exploit Space for the benefit of humankind. The table underlines the widespread use of Space in our daily life and at the same time the even larger potential for further utilisation.

Table 1: Utilisation of Space (from ref. 1)

CHARACTERISTICS	RELEVANT MISSIONS	PRESENT UTILISATION
Global Perspective	Communication Navigation Weather Forecast Surveillance	Commercial Commercial Commercial Commercial/ Military
Above the Atmosphere	Scientific Observations	Research
Gravity Free Environment	Material Processing Fluid Dynamics Biological Research	Research Research Research
Abundant Resources	Space Industrialisation Asteroid Exploration Solar Power Satellites	None None None

The infrastructure in place, which allows for Space utilisation, includes a variety of launchers, Space ferries, satellites, planetary landers and rovers and manned stations. Table 2 provides some statistic data on the

[1] Senior Programme Coordinator
[2] Microelectronics Engineer
[3] Control and Data Engineer

various types of infrastructure elements to size the importance of the infrastructure and underline the explosive growth of Space utilisation.

Table 2: Development of the Space Infrastructure

Infrastructure Element	Characteristic Data
Launchers	• 292 payloads to be launched in 1999 • 33 operational types of launchers worldwide • 24 operational launch sites worldwide • Total of 3974 launches from 1957-1998
Satellites	• Cumulative number of objects launched in Space[4] 1960: 44, 1970: 1200, 1980: 2605, 1990: 4110, 1998: 5122 • 150-175 operational satellites in orbit
Large Space Objects	• ENVISAT Satellite (8.5 t, 10 x 3 x 2 m, 6.7 kW) • Internal Space Station at completion (420 t, 908m^3 pressurised volume, 110 kw, 110 m)
Budgets 1999	• Europe 4950 MECU • USA 25804 MECU • JAPAN 1523 MECU • CANADA 227 MECU • RUSSIA 600 MECU

The further exploitation of the potential Space has to offer is largely dependent on the Space Policy of the Space fairing nations, the availability of financial resources, the existence of risk taking entrepreneurs, but also to a large extent, on the development of innovative technologies. The market potential of technologies that either increase the cost effectiveness of Space operations or enable new type of missions is significant.

REQUIREMENTS FOR SPACE SENSORS

The success of space missions depends on performing, monitoring and controlling an extensive amount of functions onboard any spacecraft. Also modern Spacecraft exhibit an increased tendency towards autonomy, most of the on-board functions are still controlled on ground. For the control of a spacecraft a large amount of information has to be obtained by numerous on-board sensors, linked to the control centre on ground and processed. Sensing is not a mere control function on satellites, but in many cases the mission objective itself. The elements of a spacecraft can be divided in the payload, which performs the core mission task, and the platform, which provides all the necessary support functions required by the payload. When discussing sensor requirements for spacecraft it is useful to distinguish payload sensors and sensors to control the function of the satellite platform and payload.

Table 3 provides an overview of typical remote sensing payloads used for science, Earth observation or weather forecast missions. Remote sensing payloads make use of electromagnetic techniques for information acquisition. The various types of sensors differ in the range of the electromagnetic spectrum they operate in. Other types of payload sensors can be found e.g. on-board of a planetary lander for the analysis of probes taken from the surface of other planets or moons.

Table 3: Overview of Remote Sensing Space Payloads

Sensors	Typical Applications
Active Sensors	
Visual Cameras	Carthography, Science, Weather, Reconnaissance
Infrared Cameras	As visual cameras, but less affected by clouds
Microw. Radiometers	Ocean and Atmosphere Research
Telescopes	Science
Passive Sensors	
Radars	Earth Resources
Sounders	Atmospheric Research

The satellite platform provides for the following functions: structural support, attitude and orbit control, thermal control, power supply, on-board data handling and communication. To monitor all these functions, an average spacecraft contains some hundreds of sensors. About 50% of the sensors are temperature sensors required for the thermal control of the satellite and about 30% monitor the voltage and the status of components. Other types of sensors needed include Sun sensors, Earth horizon sensors, magnetometers, star sensors and gyroscopes to measure angles or angular rate between the spacecraft body and a known reference for the control of the satellite attitude. These sensors are often complex systems by themselves grouping many functions and sensing elements. In some cases small numbers of additional sensors might be required such as accelerometers to track the position of the satellite, pressure gauges and flow meters to monitor e.g. the functions of the spacecraft propulsion system, proximity sensors for rendezvous and docking operations and smoke detectors for manned mission.

The driving requirements for sensors used in Space differ substantially from mass produced sensors for terrestrial applications. The most important cost driver for all Space missions is mass. Injecting 1 kg into the Low Earth Orbit costs today ~1000 \$ and into the Geostationary Orbit, used by many communication satellites, ~50000 \$. Mass optimisation is therefore a principal design guideline for all Space hardware. Another driver is reliability. In Space repair and exchange of faulty hardware, as practised for the Hubble Space Telescope, is presently very much an exception. Considering the high costs of space hardware and of transporting the hardware into Space, long faulty-free lifetimes in the range of 2 to 10 years are required to ensure adequate exploitation of substantial investments. An improvement of reliability may be achieved by redundancy on unit or subsystem level. A reliability requirement of 0.9999 (probability of 99.99% that hardware survives the nominal mission life) is common for space equipment.

Another cost driver for space hardware is related to the efforts required to ensure correct operation in the harsh Space environment. Satellites operate in vacuum and are

[4] Source: The United Nations Registry of Space Objects

exposed to large temperature gradients and radiation stemming from the cosmic rays background and the highly energetic particle wind generated by solar activity. The radiation background intensifies in the so called Van Allen Belts layered at various altitudes around the Earth. Radiation, especially harmful for satellite electronics, can cause two different types of effects. Firstly, random events can occur in the electronics when hit by a particle. This ranges from non-destructive loss of information (memory 'bit flip') to destructive CMOS latch-up. These effects must be addressed at design level by careful parts selection and/or protective counter measure. The second category of radiation effects limits the lifetime of electronics in the long term. The small energy quanta, deposited in the electronics by incident particles, accumulate over time and eventually impair the function of the device. This total radiation dose becomes a sizing parameter for the mission lifetime. Although radiation is a major threat, satellites that measure it in situ are still the exception. Particle counters or dosimeters exists but have a too large impact on the satellite for being used as standard measurement equipment.

Four different approaches may be used to make Space hardware radiation tolerant: use of shielding (adds mass to the system and is only effective in certain orbits), use of radiation resistent technology (military technology), extensive testing and selection from mass market electronic equipments and use of radiation tolerant system architectures (e.g. redundancy, error collection codes or protection againts latch-up).

Table 4 provides an overview of the elements of the Space environment and typical effects on Space hardware. Consideration of potentially adverse effects of the Space environment on components is required in the design phase and in addition extensive testing in a simulated Space environment is needed to verify compatibility. The space environment, in the particular the radiation, often drives the design of sensors and makes them bulky, power-hungry and expensive.

Table 4: The Environment of Space Hardware

Spacecraft Environment	**Typical Effects**
During Launch	
Quasi-Static Loads	Mechanical damage
Vibrations (Sinusoidal and Random Vibrations, Acoustic Noise, Shock)	Loosening of fixations
In Orbit	
Thermal/Vacuum Environment (Thermal Vacuum Cycles)	Degradation of sensors due to contamination (outgassing)
Radiation (Van Allen Belts, Galactic Cosmic Rays, Solar Proton Events, Solar UV)	Degradation of electronics
Micrometeroid/Orbital Debris	Mechanical destruction
Mechanical Loads due to Spin	Misalignement of sensor axis

The need for special environment protection of Space sensors limits drastically the possibility for direct in Space application of sensors developed for terrestrial applications and creates an innovation barrier since for introduction of new technologies in Space extensive and costly verification is required.

To benefit from the low unit costs of terrestrial hardware produced in series, attempts have been made to 'spatialise' hardware in some cases (make it compatible with the Space environment by e.g. additions to the design or simply by additional verification testing). This has been especially successful for a new class of Space missions, for which higher risks might be accepted due to smaller size and lower development budgets. Similar efforts in this direction might prove to be of interest for introducing the smart sensor technology in Space.

POTENTIAL AND LIMITATIONS OF SMART SPACE SENSORS

Prior to discussing the application of smart sensors in Space, it is helpful to propose a definition for smart sensors. A smart sensor cannot have a unique definition and we should consider 'smart' as a relative trend qualifier, meaning evolution of existing sensors. In the space field, we could propose the following definition: A smart sensor offers more performance or functionality, than an ordinary sensor or offers the same performance and functionality at lower costs. Consequently, introduction of smart sensors on-board satellites offers two new avenues of opportunity. First, they allow for sensing the same signal as today but with better performance and/or with reduced accommodation requirements (mass, power and volume) and at lower costs. Second, they enable new types of measurements, enlarging the system capability. Following this definition, **miniaturisation** appears like a must for space born smart sensors. It allows for integrating more functions in a unit with the same mass and power requirements or for obtaining the same measurements with a smaller impact on the system.

To realise a cost reduction, it is important to understand that not the direct procurement costs of the sensor, but the induced costs related to the sensor impact on the system drive the overall costs. Therefore, to reduce costs, mass and power requirements of the sensor have to be minimised as discussed above. Moreover, integration and testing costs of the overall satellite are in direct relation to the number of sensors and represent a significant part of the total.

Figure 1 summarises smart sensor characteristics, which are of primary interest for space applications. Next to lower mass and power, four additional characteristics are listed. Real-time and adaptive both characteristics which represent more the second part of the smart sensor definition given above as they enlarge the system capability and reduced data rate and after sensing computation characteristics which can either reduce accommodation requirements or increase the system capability.

Sensor Characteristics	System Level Potential	Related System Level Trades
• Real-time • Adaptive	• Enabling technology	• S/C Autonomy • Communication Link Scenario
• Reduced data rate • Reduced after-sensing computation	• Mass and power reduction • Increased information rate	• S/C Autonomy • Data Handling System Architecture • Communication Architecture • On-board memory
• Lower Mass and Power	• Mass and power reduction	• Data Handling System Architecture

Figure 1: Smart Sensor Characteristics

Effective exploitation of the smart sensor technology on-board a satellite is dependent on a number of system trades, which are affected only partially by the application of the smart sensor technology itself. These system trades concern mainly the degree of spacecraft autonomy and the satellite data handling system architecture. Understanding of these trades is essential as it must be the objective to optimise the overall satellite system and not only a sensor or sensor subsystem. A good example for understanding the need for analysing the end-to-end impact of smart sensors on the system is the trade on the allocation of processing tasks, which is related to both, the degree of satellite autonomy and the data handling system architecture. Processing of sensor information in the case of a satellite mission can be performed in the sensor processor itself, in the central processor of the data handling system or on ground after transmission of the raw data. Application of a sensor with integrated processing capability is only effective, if space processing of the sensor information is desirable. Figure 2 shows the main drivers towards the need for space processing. It is obvious that the need for space processing increases with a higher degree of satellite autonomy. However, the degree of satellite autonomy is influenced by factors quite independent from the smart sensor technology itself (e.g. mission objectives and need for real-time operations, satellite costs and complexity, availability of communication links). Generally, simple satellites tend to be autonomous as they cannot effort the cost related to ground operations and very complex systems as they require real-time operations.

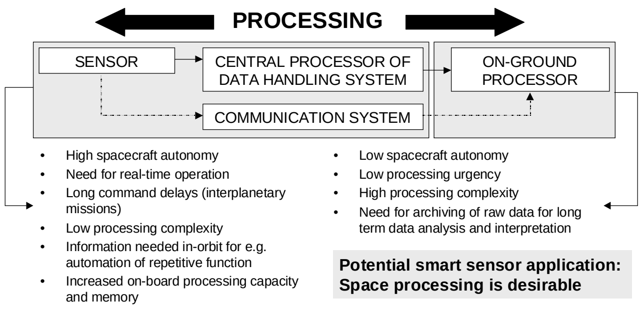

Figure 2: Trade on Allocation of Processing Tasks: Space versus Ground

If space processing is desirable, the next question to answer is whether local processing at the sensor or central processing in the processor of the data handling system is more effective. Regarding this trade, no general conclusions can be drawn as it depends strongly on the individual case. Figure 3 summarises the parameters, which drive the solution to be chosen in one or the other direction. As a simple conclusion it can be stated that smart sensor technology might find applications, where end-to-end system gains can be realised (e.g. mass and power gains on satellite level) and not only components or subsystem functions are optimised.

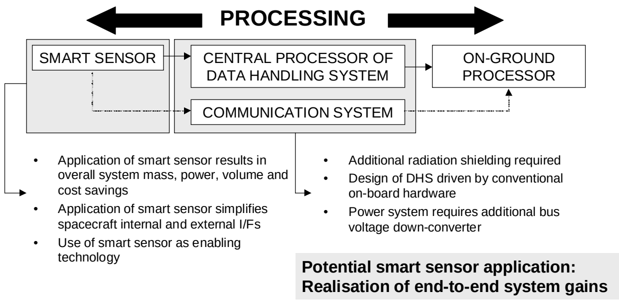

Figure 3: Trade on Allocation of Processing Tasks: Local versus Central Processor

ESA SMART SENSOR DEVELOPMENTS

The smart sensor technology has not yet found widespread application in conventional satellites. However, some first remarkable efforts have been initiated by the European Space Agency to facilitate the introduction of this new technology into future systems. Below, three rather different kind of examples are given to underline the large number of applications in Space, where smart sensor technology can provide for creative and innovative solutions:

(a) visual monitoring camera
(b) smart instrumentation point bus
(c) solid state micro-gyroscopes.

(a) Smart Sensors in Monitoring Applications

Visual monitoring of spacecraft is an emerging field were smart sensor technology is already having a significant impact on the reduction of mass, volume and power resources and is enabling new applications previously not possible. In order to understand the benefits of smart sensor technology in this field, a brief definition of the subject is provided, followed by an introduction to Active Pixel Sensors and their usage in space. Next, an ongoing smart sensor development is described, followed by an application example and identification of future developments.

Introduction to Spacecraft Monitoring Using Visual Systems

The purpose of external spacecraft monitoring is to provide feedback of spacecraft status during deployment of e.g. antennas, instrument booms and solar panels. The classical approach using indirect information collection from sensors is becoming impractical when spacecraft and space stations grow larger and have more appendices. A new approach has therefore been introduced using visual systems for direct visual confirmation of spacecraft conditions. The use of visual monitoring gives additional benefits such as detection of vibrations and structural deformation, in-orbit spacecraft surface damage analysis, and failure diagnostics.

Since visual information is used for monitoring the spacecraft, the same system can also be used for taking pictures of for example separations between launcher and spacecraft or spacecraft and planetary probes. The availability of pictures of the launcher and spacecraft in orbit with earth in background, has a great public relations value and is becoming more important for commercial Space missions. Finally, an image tells more than thousand words, but it also requires more data to be transmitted, necessitating image compression when many images are needed. The requirements on visual monitoring smart sensors can be summarised as follows:

- Radiation hard or radiation tolerant
- Low power, small mass and volume
- Small and low costs
- Versatility in interfacing to: Onboard data handling and control system, and spacecraft communications system
- Payload computer for image processing such as compression
- Requiring only a small number of external components

By using smart sensor technology the introduction of visual monitoring can have a minimal impact on spacecraft design. The objective of an on-going development is to produce a single-chip smart sensor camera suitable for visual monitoring, image gathering on planetary probes and rovers, where size and power consumption has to be minimised. To accomplish this, a step away from traditional space technology had to be made, as will be discussed hereafter.

Active Pixel Sensors in Space Applications

Cameras for space applications have traditionally been based on Charge Coupled Device (CCD) technology, but this technology is now getting competition from CMOS Active Pixel Sensor (APS) technology. The APS technology offers certain benefits that are directly relevant for potential applications in space. It offers the possibility for integration of system and sensor on a single chip, with resulting gains in system dimensions, mass, and power consumption. Future generations of CMOS sensors hold the promise of radiation-tolerance, which makes them all the more interesting for these niche applications.

The most basic application for APS sensors, visual monitoring, has already been demonstrated in space. The first visual monitoring system that was developed for the European Space Agency is the Visual Telemetry System (Ref. 2), jointly produced by MMS (UK), Delft Sensor Systems - OIP (B), and IMEC (B). It was designed for the ENVISAT Earth observation mission, which is a spacecraft that has many antennas and booms that need to be observed. The VTS cameras were based on an already existing IMEC CMOS APS sensor, the Fuga15 (Ref. 3). Since the Fuga15 was not designed with space applications in mind, the VTS required a separate unit to interface the cameras to the onboard data handling system of the spacecraft and to perform image compression.

The system was finally not installed on ENVISAT due to integration and schedule difficulties. The spacecraft was not designed with visual monitoring in mind, making the late add-on integration cumbersome. The system was however launched on a different mission. On October 30th, 1997, the VTS acquired and transmitted near-life images from the separation between the TEAMSAT satellite and the upper launcher stage on an ARIANE 5 flight.

Although APS technology was used in the VTS development, the overall system and camera dimension were large and impacted negatively on spacecraft design. The goal for current and planned developments is to remove the need for a separate processing unit and to produce a standalone smart sensor camera that can be directly interfaced to the communication subsystem of the spacecraft.

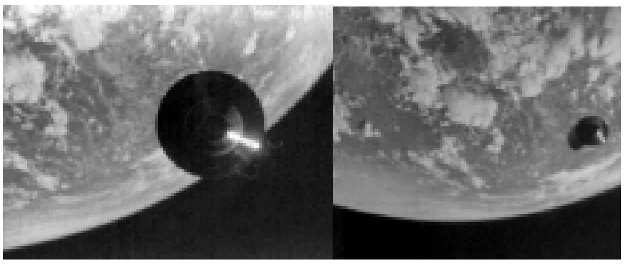

Figure 4: Separation between TEAMSAT spacecraft launcher, images taken with VTS cameras

Figure 5: Visual Telemetry System camera

Integrated Radiation-tolerant Imaging System

A CMOS APS smart sensor targeted towards space applications, the Integrated Radiation-tolerant Imaging System (IRIS), is being developed in several steps. Firstly, a new imaging sensor part has been developed, based on an integrating APS previously developed by IMEC, the IBIS-1 (Ref. 4 and Ref. 5). The first new sensor (named IRIS-1) has been tailored to meet specific requirements posed by the European Space Agency, such as an increased resolution of 640 by 480 pixels, on-chip analogue-to-digital conversion and the possibility for fast sub-windowing. The key specifications of IRIS-1 are the following:

- 640 x 480 pixels, 14 micrometer pitch
- Integrating 3-transistor photo diode pixel, double sampling column amplifiers
- 8 bits digitisation on-chip
- 10 images per second
- Optional colour filters

In the second step, the sensor is integrated with all timing and control logic required to operate the sensor itself and to support multiple variants of serial and parallel interfaces and protocols. Although the smart sensor can be used in a multitude of applications, special attentions has been given to the aspect of interfacing it with modern spacecraft communication systems. The resulting smart sensor (named IRIS-2) will be a system-on-a-chip capable of taking images and directly communicating with the spacecraft. The additional key specifications of IRIS-2 are the following:

- Windowing and interleaving, digital pixel averaging
- Standard spacecraft interfaces
- Serial digital command interfaces
- Serial and parallel digital pixel data interfaces
- Analogue pixel data output
- Raw data or spacecraft standard packets

The next generation IRIS-3 smart sensor will also support local image storage, capable of handling between ten and hundred images depending on the compression factor used for the image compression. The imager, together with a dedicated compression device and local static or dynamic memory, will enable new applications by providing advanced low rate grey scale video capability while maintaining simple user interfaces adapted to spacecraft requirements.

The IRIS devices are being developed by IMEC (B) and manufactured in commercial mixed-signal CMOS processes from Alcatel Mietec (B). System level reliability is enhanced by internal watchdogs, parity checks on most registers and finite state machines, and by voting mechanisms for the most important long-term settings. The only electrical parts required to turn an IRIS smart sensor into a camera are line drivers and receivers, and passive components.

Future developments are oriented towards near-video rate colour imaging with picture sizes of 2048 by 2048 pixels, digitised to ten or twelve bit resolution. The target is to have a colour reconstruction and processing done on the same chip as the sensor and to perform spatial and temporal image compression in a companion device, similar to what is being developed for grey scale imaging today. To further reduce camera mass one needs to address the mechanical implementation in addition to the reduction of the number of electrical components as being done in ongoing developments. Three dimensional multi-chip modules offer the possibility to design small cameras even if based on many components. Combining the two approaches, mechanical and electrical miniaturisation will ultimately lead to spacecraft monitoring cameras that will only carry a small cost overhead when integrated on a spacecraft.

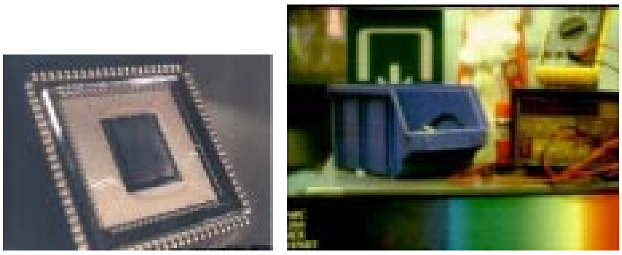

Figure 6: IRIS-1 sensor AND Image captured with IRIS-1 sensor

Visual Monitoring Camera

The first application to use the new IRIS-1 smart sensor is the Visual Monitoring Camera (VMC) that has been developed for the X-ray Multi-mirror Mission (XMM[5]) and is base lined for missions such as CLUSTER-2[5] and PROBA[6]. The objective of the VMC is firstly to observe the separation between the XMM spacecraft and the upper stage of the ARIANE launcher vehicle, and secondly to observe the deployment of the solar panels. Also, it is important to provide visual feedback for public relations purposes. Two cameras will be mounted looking along the shaft of the spacecraft in the direction of the launcher. The VMC had to be developed and integrated with spacecraft in less than half a year, and had to be interfaced directly to the instrument controller using a traditional spacecraft interface and power distribution

---

[5] ESA Science Mission to be launched in 2000

[6] ESA Technology Demonstration Mission to be launched in 2000

system. There was no space or budged for an additional processing and interface unit, as was the case for VTS development.

To enable large images to be relayed to ground, the image frame needs to be buffered to allow low rate readout of pixel data. Frame buffering is currently not supported by the IRIS-1 chip, but is planned for a future development. In the meanwhile, the frame needs to be buffered using an external controller, which is being the case for the VMC. The VCM contains on-board memory for frame buffering, which is controlled by an FPGA. The key features of the VMC are the following:

- IRIS-1 or FUGA15 sensor (colour or grey scale)
- Autonomous or command-interactive
- One image per second download speed and local buffering of one image
- Interfaces: TTC-B-01 up to 1 MHz or RS-422 like up to 3.125 MHz
- Power consumption: 5.0 W at 28V or 2.0 W at 10 V
- Dimensions: 6x6x10 cm, 430 g

(b) The Smart Instrumentation Point Bus

The smart instrumentation point (SIP) is aiming at replacing conventional temperature sensors and allowing for the in-situ measurement of total radiation dose. It is an example for the exploitation of smart sensor technology for reducing primarily the mass and costs of the satellite.

Typically, thermistors are used via a channel multiplexer commonly called RTU (for remote terminal unit) that performs the analog-to-digital conversion and serialisation over a housekeeping bus. This strong centralisation has many impacts. The whole mission depends upon a single ADC chip and its redundant backup. These many low-level interfaces can only be tested during integration of the complete system when any delay cost is the highest. The cabling of these many sensors has such a mass impact that their number must be limited to a bare minimum. Many temperature sensors are accommodated for ground testing purposes only and removed for launch. Next to the loss of system observability, crucial in troubleshooting, this extra task is a cost element that increases the risk for workmanship flaws.

The SIP relies on mixed digital-analogue technology and advanced packaging to host a range of instrumentation function in a very small package (20x7.5x5mm). It is primarily a temperature sensor with built-in analogue-to-digital conversion and a serial bus interface. The small aluminium blocks can be glued at relevant location throughout the satellite for monitoring temperatures. The serial bus interfacing allows for reducing the overall harness compared to the point-to-point thermistor cabling to the RTU. The system impact is small enough to also use the SIPs as the thermal testing instrumentation, keeping these on board for the launch. Next to its main temperature measurement function, the SIP includes a RadFet sensor and allows its acquisition through the serial bus. This provides for the measurement of total radiation dose on board and allows for a more cautious utilisation of the system. For example, measuring the dose received by an active computer allows changing preventively to its backup before the failure occurs when to dose has been exceeded. Moreover, dose data can prove essential for investigating failures. It is also enhancing the flight heritage of components with actual data. Figure 7 compares the architecture of the SIP and the conventional approach and summarises the advantages and disadvantages of both. The SIP bus is presently in the prototype development phase and a flight demonstration is foreseen on board pf the PROBA satellite to be launched in 2000.

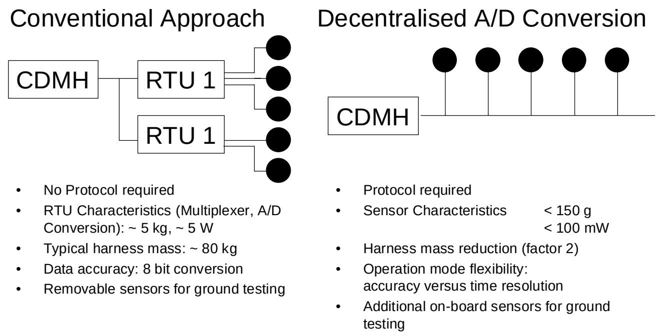

Figure 7: Comparison of the SIP Bus Architecture with a Conventional Bus Architecture

(c) Solid State Micro-Gyroscopes

Solid state micro-gyroscopes developed for the commercial market, automotive in particular, are being studied towards their application in space. They will probably not outperform traditional mechanical gyroscopes in the short term but may enable different control schemes for better system fault-tolerance and reliability or for complementing existing attitude sensors. Solid state micro-gyroscopes are an example for the application of smart sensor technology in order to add functionality to the system.

Although attitude angular rate is a fundamental parameter for a satellite, the limitations of today's mechanical gyroscopes, in particular the limited lifetime implied in any moving part, have prevented systematic and continuous measurement. System implications are far reaching; complexity is often generated on board to work around this major lack of observability and one can argue that this eventually drives the level of ground operation and the related costs. Solid state micro-gyroscopes could simplify the detection of attitude anomalies. For example, a reaction wheel or thruster failure could be detected earlier by angular rate measurements than by attitude measurement due to the propagation delay of the latter. It is interesting to re-visit recent partial or total satellite failure, assuming the presence on board of such a micro-gyroscope.

CONCLUSIONS

Applications of smart sensor technology in Space are today an exception. Although the potential is large, innovation barriers inherent to the Space market limit a full exploitation of this technology. Developments targeting specifically Space are costly and economically critical considering the small size of the Space market. They might be justified for small companies specialising on the production of high technology equipments in low numbers as needed for the typically one-of-a-kind Space mission. Another approach to benefit from the smart sensor technology could be to spatialise terrestrial hardware. In particular radiation testing of mass produced items for the identification of radiation tolerant equipment might proof to be a viable and effective approach.

REFERENCES

[1] Space Mission Analysis and Design, W. J. Larson and James Wertz, Space Technology Library, published by Microcosm, Inc., Second Edition, 1992

[2] Visual Telemetry System Demonstrator, ESA/ESTEC Contract 11637/95/NL/FM Final Report, Matra Marconi Space (UK), August 1997

[3] Random addressable active pixel image sensors, B. Dierickx, D. Scheffer, G. Meynants, W. Ogiers, J. Vlummens, invited paper AFPAEC Europtop Berlin, October 1996, SPIE proceedings vol. 2950

[4] Near 100% Fill Factor Standard CMOS Active Pixel, B. Dierickx, G. Meynants, D. Scheffer, IEEE Workshop on CCDs and Advanced Image Sensors, June 1997

[5] Offset-free Offset Correction for Active Pixel Sensors, B. Dierickx, G. Meynants, D. Scheffer, IEEE Workshop on CCDs and Advanced Image Sensors, June 1997