"Smart Microsystems" – A Feasibility Study to Investigate the Decentralisation of Space Systems with highly efficient Micronodes using advanced ASIC technologies.

John Cornforth(1), Andrew Bacon(1), I Sturland(2), Roland Trautner (TO) (3)

(1)SEA, Building 660, Bristol Business Park, Coldharbour Lane, Bristol, BS16 1EJ, United Kingdom,
Email: John.Cornforth@sea.co.uk, Andrew.Bacon@sea.co.uk

(2)BAE Systems, Advanced Technology Centre, Golf Course Lane, Filton, Bristol, BS34 7QW, United Kingdom,
Email: Ian.Sturland@bae-systems.com

(3) Onboard Payload Data Processing/Payload Support TEC-EDP, ESA/ESTEC, European Space Agency, Noordwijk,
The Netherlands,
Email: Roland.Trautner@esa.int

ABSTRACT

Space systems traditionally use a small number of centralised computing nodes.

This inherently dictates that sensors and actuators are architecturally separate and are typically connected by harnesses using a star topology, with significant impact on the overall system mass.

Using a centralised system can also lead to increased system vulnerability in case of a computing node failure.

Decentralising many of the functions into a number of very small identical / modular nodes known as "Micronodes" with independent localised control capabilities could provide significant benefits in terms of mass, reliability, and 'situational awareness' on the spacecraft. New low-power operations modes for hibernation of safing the spacecraft can also be realised.

An on-going ESA study [1] led by SEA, including BAe Systems as part of the ESA General Studies Programme is investigating the use and design of such Micronodes.

A miniaturised Micronode design would benefit from utilising a highly power efficient Mixed Signal ASIC containing a Digital control element for communication to the spacecraft bus, internal DC/DC PWM control, volatile and non-volatile memory. Analogue circuitry could include A/D and D/A converters with associated multiplexing if necessary. This ASIC could be integrated either as Bare Die into a packaged 'Hybrid Module' or as a component in its own right. Immunity to single point failures is also a key design point.

First, this paper will briefly introduce the system benefits of utilising Micronodes in modern space architectures. The selected Micronode types will be presented, and their high level architecture will be explained. The most promising electronics and particular ASIC technologies for implementation will be discussed, and initial estimates of the Micronode performances and system level benefits will be provided.

INTRODUCTION

In traditional data processing and control architectures for space systems, one or a few centralised computing nodes are used.

All sensors, actuators, and other data sources and data sinks are connected to these nodes in a star– or multi-star topology. Actuators and associated sensors (like heaters and associated temperature sensors) are usually kept separate, with individual harnesses connecting them to the central nodes.

Consequently, these designs imply complex nodes for providing all required data acquisition, concurrent processing and control capabilities, and significant harness mass for connecting all data sinks and sources to the central nodes. These architectures also imply a certain vulnerability of the system due to the vital importance of the central nodes for all centralised functions.

Following from decentralising techniques and technology utilised in the commercial car industry for example, a network of several dozens of low power single chip controllers (Micronodes) that accommodate highly power-efficient data processing, A/D, D/A, volatile and non-volatile memory, and communications on-chip could be utilised. Each controller will provide interfaces for one or more local or integrated sensors (such as thermal sensors, accelerometers, voltage and current measurements, pressure sensors, etc) and actuators (heaters, etc) for localised control of spacecraft elements and subsystems. These controllers may have an embedded power generation and power management, or a wide single power supply range for provision of external power.

Micronode communication could also make use of wireless technologies or communication could be multiplexed on power lines to eliminate the need for dedicated harness / RF channels or via multi-drop systems such as CANBUS & MIL 1553. The distributed nodes would locally acquire data (temperature, structural stress, vibration level, brightness, voltage / current, other parameters) and control assigned local resources via local actuators (local heaters, actuated radiators / coolers), or autonomously generate out-of-limit alarms to a central node, according to the assigned operations mode (nominal / survival / idle).

A trade-off looking at associated sensors/ actuators for spacecraft and space vehicles was carried out during the study; with a view to maximise mass reduction and sensor/actuator integration and concluded with two types of smart Micronodes listed below to be investigated further;

- A Power Management Micronode
- An Environmental Management Micronode.

Decentralised Power Management Micronode

The decentralised power management Micronode is intended to significantly simplify and reduce the mass of power harnessing for space vehicles by allowing the use of a ‘Power Bus’ architecture rather than an individual connection for each subsystem to the Power Control & Distribution Unit (PCDU). This Micronode is also intended to increase the reliability of subsystem power systems by the addition of electrical and thermal monitoring sensors. Finally, by using a standardised design, these Micronodes can reduce the design and development time for space vehicle subsystems by providing an ‘Off the Shelf’ (OTS) power supply/ EMC Filter and switching solution.

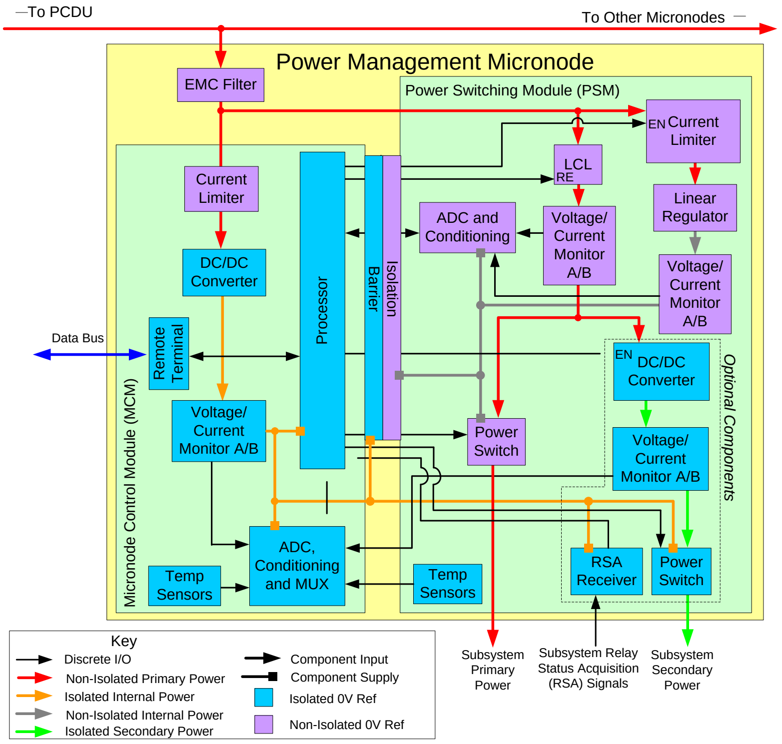

Figure 1: Power Management Micronode Preliminary Architecture

Decentralised Power Management Micronode Advantages Summary

- Health and status monitoring of the bus and the subsystem power consumption.
- Reduction in the amount of harnessing and number of connectors between the PCDU and subsystems by allowing direct connection to a power bus routed around a spacecraft, removing the need for the individual connections between subsystems and the PCDU.
- The use of a single large power bus can also reduce conduction losses and shielding requirements.
- The move of health monitoring and power switching to the Micronode reduces the complexity of the PCDU, encouraging a more modular architecture.
- A reduction in the time taken to develop subsystems as the power switching, filtering and monitoring could all be handled by the Micronode. A single Micronode could be used to provide power to multiple co-located subsystems, giving a reduction in the mass for filtering and DC/DC conversion.

Decentralised Environmental Management Micronode

The decentralised Environmental Management Micronode is intended to significantly simplify and reduce the harness mass and processing requirements of environmental control for space vehicles. Environmental control includes but is not limited to thermal, pressure, strain and vibration, which is intended to be supported on a modular basis, i.e. a Micronode could be devoted to thermal control for a subsystem or a mixture of thermal, pressure, strain and vibration control for a Thruster. Thermal control has been identified as having the greatest impact and so this shall be supported as a baseline. This Micronode is also intended to increase the reliability of environmental control systems by the addition of local power monitoring for actuators, and shorter analogue lines for sensors. Finally, by using a standardised design, these Micronodes can reduce the design and development time for space vehicle subsystems by providing an OTS environmental control system that is adaptable to varying requirements.

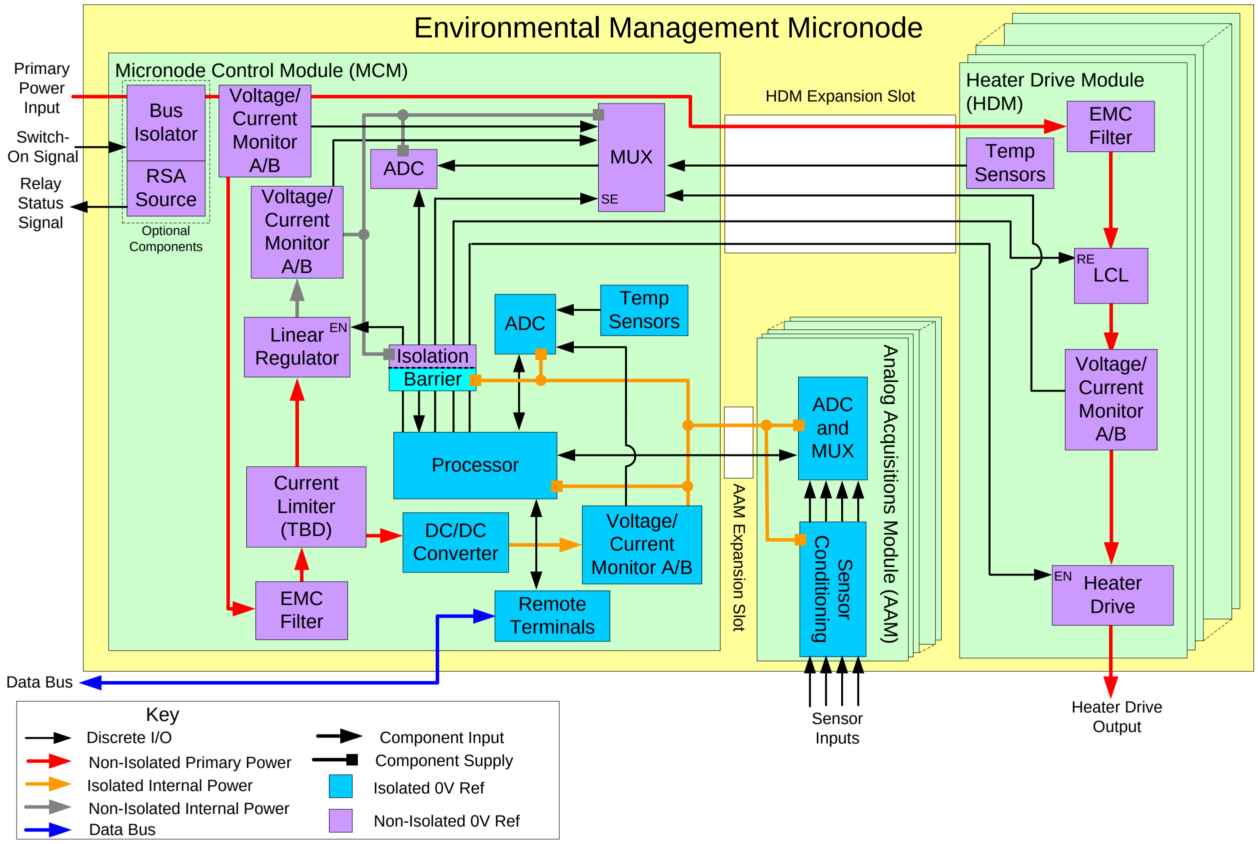

Figure 2 : Environmental Management Micronode Preliminary Architecture

Environmental Management Micronode Advantages Summary

- An Environmental Micronode can be used to handle the process of acquiring environmental sensor data and controlling actuators whilst only reporting back summary TM data to the avionics. This would reduce the processing requirements on the avionics and increase the overall autonomy of the environmental management.
- A decentralised system reduces the amount of high current harnessing required between the avionics and actuators and analogue harnessing between sensors and the avionics (which also reduces exposure to noise, allowing for more accurate sensor readings).
- A decentralised system reduces the complexity of the PCDU by eliminating the need for separately LCL protected actuators supplies (as commonly used for heaters), which also makes it highly compatible with the decentralised power management Micronode.
- Potential use for a large number of monitoring nodes or specific sensors (like accelerometers) embedded on-chip which could be used during AIT activities (like vibration testing) but not during normal spacecraft operations.

Environmental Micronode Associated Sensors and Spacecraft Interface Specifications could be;

- Contacting thermal sensor/ Voltage probe/ Current probe/ Strain Gauge/ Accelerometer/ Pressure Sensor/ Chemical Sensor/ Particle Sensor/ Humidity Sensor
- Thermistors; Type ANY (YSI-44907/-44908, 10KOhm @ 25°C)/ ANP (PT1000)
- Analogue Inputs; Type AN1(-5V to +5V)/ AN2 (0V to 5V)/ RSA (Relay Switch Status 0V contact)/ BLD (Bi-Level Digital Acquisition)
- Typical Heater Outputs; Pulsed (ON/OFF), Pulsed Width Modulated (PWM), Linear and including associated Latching Current Limiter (LCL) protection

It is difficult to speculate at this stage in the study what the final volume, mass and power consumption of the Micronode might be. However, LCLs for heaters/coolers require high power components, so it is unlikely these elements could be integrated into a single IC. However, the processor and sensor acquisition system could be quite miniaturised. Therefore, at least part of the Micronode could take advantage of miniaturised IC, hybrid and MEMS technology. It may even be possible to integrate most of the low power components on a single ASIC.

Approximately 9% of spacecraft mass is harnessing, of which the majority is used for power distribution and environmental monitoring purposes. Whist each discrete I/O line for analogue environmental sensors may have little mass; the large numbers required on space vehicles for effective monitoring can add up to a significant mass and difficulty in routing back to the avionics. As an example, the BepiColombo Remote Interface Unit (RIU) being built for the Mercury Planetary Orbiter (MPO) by SEA has a 14kg mass; it has inputs for over 360 2-wire thermistors, 56 analogue inputs, 144 relay status signals and 32 bi-level digital TM inputs. It also has over 200 high power outputs not including 24 Thruster outputs, as can be seen from the large number of connectors in the figure below:

Figure 3 : BepiColombo RIU Engineering Model Showing a Large Number of Analogue I/O Connections for Environmental Sensors.

The same is true for small space vehicles, but instead of connecting to an RIU the analogue sensors are generally connected to the On-Board Computer (OBC) adding greatly to its mass, interface complexity and volume. This discourages plug-and-play flexibility of avionics systems and so an environmental node that could expand monitoring with only the addition of another power and data bus connection would enable the modification of avionics architecture to a more generic form; increasing reuse.

There are significant additional benefits for the decentralisation of the environmental control processing, allowing a further simplification of avionics and adding potential for autonomous control modes which could be useful for the cruise stage of exploration vehicle missions. With the use of TM and alert signalling there should be no decrease in reliability of the control functions or introduction of Single Point Failures (SPF).

There is an additional benefit from combining the advantages of the Power and Environmental Management Micronodes by the ability to supply high current environmental actuators like heaters and coolers off a decentralised power bus.

The decentralised Power Bus could also be segregated further to have a ‘Quiet Sensor Power Bus’ and a ‘Dirty High Power Bus’ used to drive heaters and mechanisms.

If the Micronode can support all of the interfaces normally supported by RIUs, not including the propulsion management, it may be possible to eliminate the need for an RIU in future space vehicles.

Micronode Architectures

In order to meet the requirements for minimised volume, mass and power consumption both the Environmental and Power Micronode architecture will need to be as tightly integrated as possible. It is envisioned that the sensor acquisition ADCs, data processing and interfacing are all implemented on a single multi-chip module. To increase the modularity of the Environmental Micronode, commonly used sensor and actuator interfaces shall be implemented onto stackable miniature PCBs, as shown in Figure 4. This will allow the end user of the micronode to choose which interfaces are to be included allowing for a easily customisable solution to support a wide range of spacecraft.

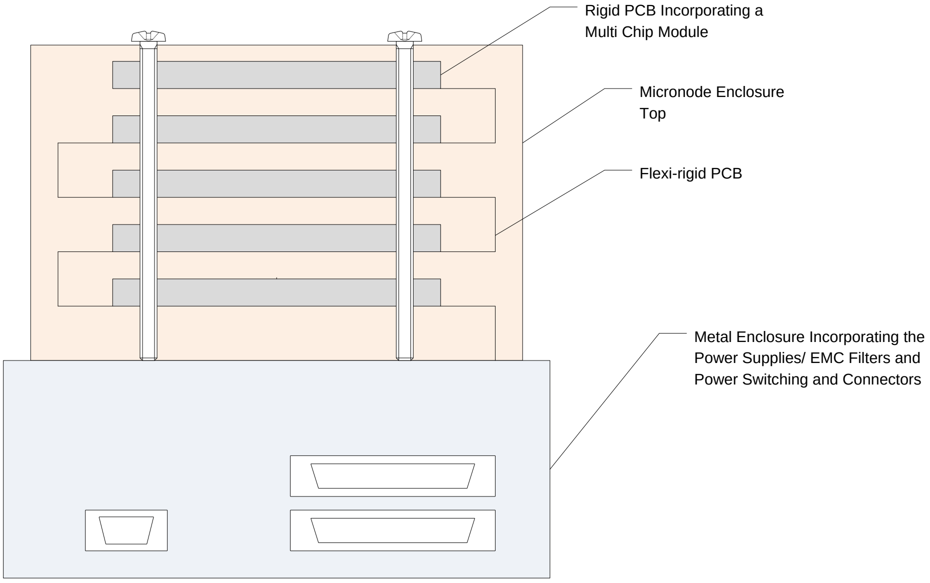

Figure 4 : Potential stackable module layout for an expandable and customisable set of sensor and actuator interfaces on the Environmental Management Micronode

Communication Needs

Both Micronode types will need to be able to communicate at all times with the OBC in order to receive telecommands, send telemetry data and issue alerts. The vast majority of spacecraft use the MIL-STD-1553B protocol for handling intra-spacecraft telemetry and telecommands; therefore it is desirable that the Micronodes support this as a legacy option. However, the OpenCAN protocol has a number of benefits in terms of reduced mass and overheads which makes it ideal for use by the Micronodes. Additionally, the PowerLink space data transmission over power line system, under development by SEA for ESA, has the additional benefit of not requiring any separate data harnessing.

PowerLink would be ideally suited to the power micronode which is likely to only need low data rates and would already have a direct connection to the power bus. Other low power interface types such as I2C will be assessed as part of the study.

Ideally MIL-STD-1553B, OpenCAN, I2C and PowerLink data buses could all be supported by the micronodes, giving the end users the flexibility to choose the most suitable option, but this may be limited by the space available inside the Micronodes and the power requirement for the respective communication protocol. As a preliminary baseline OpenCAN would be supported.

The peak data rates have been provisionally estimated at 0.5kb/s for the Power and 2.5kb/s for the Environmental Micronode. This is assuming a telemetry packet is sent once per second with all of the sensor and actuator data, status flags, a timestamp and the overheads for the extended OpenCAN protocol. This would allow many Micronodes to be connected to a standard MIL-1553B or OpenCAN 1Mbit/s data bus.

Radiation

For spacecraft components the radiation Total Ionising Dose (TID) is a function of the environment and the lifetime.

The annual TID for a satellite in a sun synchronous orbit at an altitude of 700 km altitude and a node time of 10.30 with 2 mm thick aluminium shielding equates to a yearly radiation dose of 3460 rads. For a 4 mm shielding it drops to 837 rads. All Micronode components would need to be rated for 30kRads as a minimum which gives an order of magnitude margin when using 2mm of shielding.

In addition to the TID, the Micronode will need to be robust to Single Event Effects (SEE) of a certain size. While LEO missions are concerned primarily with high energy (trapped) protons up to 60MeV, once outside the Earth's belts the SEE environment will be dominated by high energy ions from the Galactic Cosmic Ray background (>100MeV).

SEE include both soft upsets on digital electronics (SEU) and transitions/spikes (SET) in analogue electronics. These are normally addressed by technology improvements at the device level (technology selection or more normally layout/functional redundancy) or by system level mitigations such as memory scrubbing and Error Detection and Correction (EDAC) at the circuit design level.

SEE effects also include the potentially destructive effects of Single Event Latch-up (SEL) where a high energy particle can cause a conduction path through the device from its power line to ground leading to burn-out. Such effects are best handled through component technology selection, although latch-up protection circuits external to the device can be used at the expense of additional circuitry and acceptance of a functional outage. For ASIC development, use of the DARE libraries would be maximised wherever possible.

Mechanical

The most severe mechanical environment likely to be encountered is during launch and separation from the launcher.

A flexible Micronode may be launched on different launchers for different spacecraft and therefore must be compatible with the launch loads of a wide range of launchers. Typical launcher mechanical environments with which they will have to be compatible are those of Ariane 5, Vega, Soyuz, Dnepr, Kosmos, Atlas, Zenit and Rockot.

The accommodation of the micronode will be the primary form of radiation protection, thermal management and launch load protection. Ideally for this level of protection 1 to 2mm of aluminium is adequate, but this may end up being a large fraction of the total mass and so an informed trade-off of alternatives will be carried out.

A low form factor is desired to increase the surface area in contact with the spacecraft structure to aid with heat dissipation. If the enclosure gets too tall the sides would need to be stiffer (hence thicker) to dampen external shock and vibration.

EMC/EMI

The Micronode will need to fully comply with the ESA standard ECSS-E-ST20-07 for electromagnetic compatibility.

Assembly, Integration and Test

An additional requirement criteria identified by SEA and ATC is that of reduction in time and complexity of any Assembly, Integration and Test (AIT) activities. The reduction in the number of harnesses and connectors will assist the AIT team which ultimately saves on mission costs and schedule risks, especially during Thermal Vacuum testing.

Figure 5 illustrates the complexity of integrating units at system level when there are a considerable number of harness connections between them.

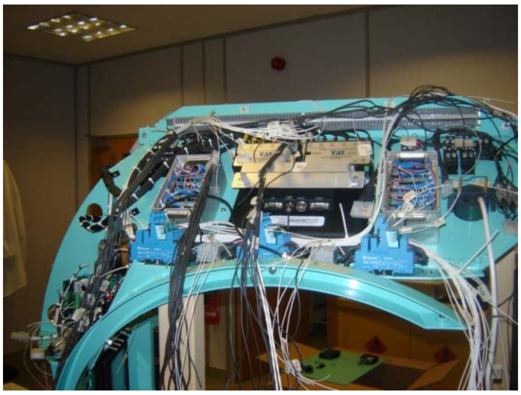

Figure 5 : Reducing the number of harnesses reduces AIT time

MICRONODE PACKAGING OPTIONS

Packaging of microelectronic components and MEMS devices is designed to protect the devices from the external environment and provide an appropriate mechanical and electrical interface to the rest of the system. For both MEMS and microelectronics the packaging dominates the overall cost. An important distinction between commercial and space applications are market volume. High volume markets can justify high NRE costs to achieve lower unit prices. This leads to extensive use of cheap plastic packages where-ever possible. On the other hand space volumes (even for commonly used components) will always be low, resulting in application of different technologies (ceramic or metal packages). Fortunately as discussed below some other attributes (e.g. environmental, vacuum, mechanical and radiation tolerance) are likely to mean that ceramic or metal packages are the most appropriate technical choice too.
A general trend in both MEMS and microelectronics is towards integrating multiple die (and even discrete components) in a single package. There is a broad spectrum of technologies but mainly they all lead to much higher levels of integration and smaller size. This can be very simple e.g flip chip or multi-chip module technologies were two or more die are mounted within the same package on a common interconnect, all the way through to complete System in Package (SiP) Solutions.

MEMS packaging is usually non-standard with each device having its own unique requirements extending well beyond the choice of package material. MEMS chips usually include sensitive moving parts that can easily be damaged unless properly protected by the package. The thermal and mechanical properties of the package are also very important. External mechanical forces must not affect the electromechanical operation of the device. Thermal expansion mismatch often dominates overall sensor performance.

MEMS devices may also call for hermetic seals - key resonant based devices including higher performance accelerometers, gyroscopes and absolute pressure sensors depend critically on achieving high mechanical Q. This is often dominated by losses due to gas damping effects, which can to an extent be alleviated by a vacuum packaged solution.

Ceramic and metal packages provide complete hermetic sealing. For high power components metal packages provide better heatsinking capabilities than ceramic. Modern ceramic and metal packages can offer complex interconnect and multiple die solutions resulting in System in Package (SiP) levels of integration. However the NRE on bespoke ceramic packages is much more than for metal packages. Internal routing in metal packages can easily be accomplished by the use of internal Multi-Chip Modules (MCM) technology. In either case, the internal routing between multiple chips can greatly reduce the I/O pin count, which in turn reduces size, complexity and ease of testing.

3-D Packaging technologies

Many companies are investigating different 3-D packaging solutions to achieve even higher levels of integration. There are numerous variants of the technologies, but broadly speaking solutions fall into two camps. Firstly there are those with stacked die architectures. Typically MEMS die are larger than their corresponding ASIC so that ASICs mounted on MEMS die are becoming common. Interconnect between the two (or more) can simply be carried out by multiple height wire bonds, flip chip or solder ball methods. The second method uses interposers to provide complex and potentially more reliable interconnect between die. Both glass and silicon interposers are receiving much attention. Key technologies to master are through wafer vias. Through silicon via (TSV) is receiving most attention because the mainstream advanced semiconductor roadmaps also require this level of integration. Through Glass Vias (TGV) is much less common despite its applicability to common MEMS devices made using industry standard wafer bonding techniques like anodic bonding.
The ultimate 3-D packaging technology is realised by Wafer Level Packaging (WLP) offering a very high level of integration, where two or more wafers are bonded together before the chips are diced. In the case of a MEMS device the MEMS parts and ASIC parts may be produced as separate wafers but they are bonded together while both wafers are complete wafers. Subsequent dicing produces a MEMS device and it's ASIC as a single chip.

Even higher levels of integration are possible with WLP. Some MEMS devices, such as gyroscopes, require a vacuum for correct operation. This can be provided by a welded lid on a metal package, as previously discussed. An alternative is to produce a whole wafer of vacuum lids in silicon or glass. Then, under vacuum, the lid wafer is bonded to the MEMS wafer to produce individual vacuum lids for each chip on the wafer. Subsequent dicing produces chips which do not require further expensive vacuum packaging.
This wafer level capping can also contribute significantly to improved cleanliness – meaning that for example comb drive devices such as accelerometers can be realised in much higher yields.

Taken to the extreme WLP could provide MEMS devices with ASICs, vacuum lids and connections to the outside world – all at the wafer level. Subsequent dicing produces die-sized fully functional devices that do not require further packaging. Whilst offering the ultimate in packing densities this theoretical consideration needs to be tempered by manufacturing volumes. Getting high enough yields in both an ASIC and MEMS based wafer process, with the same sized wafer is only likely to happen for very high volume applications, where the 6 sigma SPC and other yield enhancing techniques can be applied.
None the less some of the benefits of WLP will be beneficial to the space MEMS market.

MICRONODE ASIC REQUIREMENTS 'WISH-LIST';

The following 'WISH-List' is a starting point to identify potentially useful Micronode ASIC functionality;

- Micro-controller (ie. LEON 'Lite' FPGA Core)
- Logic programmable cells
- Oscillator (>4MHz <12MHz)
- EEPROM/ PROM/ RAM allowing for in flight S/W uploads from the OBC
- Low Offset Low Drift Rail to Rail Operational amplifiers with adjustable gain
- Multiplexers with built in protection (similar to SMD 5962-96742)
- PWM controllers for DC/DC PSU and POL (similar to SMD 5962-02511)
- Communication Interface (CAN/1553/RS485/I2C/SPI/Spacewire/Data over Power)
- Maximise the use of the ESA DARE Library wherever possible
- 12/16 bit ADC and 12 bit DAC
- Analogue Signal Interfaces for Type ANY/ ANP/ AN1/ AN2/ RSA and BLD
- General I/O voltages tolerant to 5V and 3V3
- Lifetime in excess of 7 years in orbit +2 years on the ground
- Thermal operation -40°C to +70°C with a non operating range of -50°C to +125°C
- Reliability ≥ 0.95

REFERENCES

[1] Smart Microsystems for Space Applications Statement of Work: AO/1-6702/11/NL/AF