Smart Microsystems Executive Summary Report

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Abstract

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 (e.g. 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.

This ESA study led by SEA with subcontractor BAE Systems investigated the use and design of such Micronodes as part of the ESA General Studies Programme (GSP).

The study has proven the feasibility of creating a modular Micronode architecture that can serve many of the common on-board control processes.

Furthermore, the study has shown that the spacecraft harness mass has been dramatically reduced utilising a decentralised Micronode Architecture over that of a traditional centralised architecture. In the case of the Rosetta spacecraft that used a central Remote Interface Unit (RIU), analysis showed that a reduction of 68% (111kg) could be realised. Power savings of up to 23% can be made in some scenarios.

Utilising a modular decentralised approach has additional benefits to the system such as new autonomous capability enabling ‘situational awareness’ on the spacecraft. For example; in one Micronode configuration a system heating element could be remotely controlled using thermal PID control, acquiring thermistors and pulsing the heater output power lines, with the OBC setting the temperature limit and being informed if any temperature alarm states occur.

This approach reduces the computing consumption of the OBC and also the data flow on the link, thus reducing the overall system power usage. New low-power operations modes for hibernation or safing of the spacecraft can also be realised. The reaction time and overall reliability of the control function is shown to be greatly increased by the use of decentralised localised processing and control.

Localised control also has shorter sensor interfaces and source driver paths which improves the signal to noise ratio and EMC emission.

Using various packaging and miniaturisation techniques such as; Hybrid, 3D Packaging, System in Package (SIP) and ASIC technologies the overall mass and dimensions of the Micronode configurations have been limited to sub 203g and a volume of 111cm^3.

Study Activities

ESA ESTEC requested this study to assess the potential for the decentralisation of spacecraft control functions by Smart Micronodes in order to reduce mass and complexity whilst increasing reliability and autonomy. The study was broken down into the following five main Task areas as follows;

Task 1: Spacecraft Survey

The first task was broken into a number of sub-tasks, which were carried out to;

- Survey past, present and future spacecraft sensors and actuators
- Survey past, present and future spacecraft, automotive and aircraft electrical architectures
- Review all identified spacecraft onboard control functions including their usage, typical centralised architecture, potential decentralised architecture and associated sensors and actuators
- Conduct a decentralisation assessment of each control function
- Conduct a timeliness assessment for the decentralisation of each control function
- Calculate the final score to identify the most promising control functions for decentralisation

The final scoring concluded two control functions had the greatest potential for decentralisation:

- **Power Management**: the supply of power to spacecraft subsystems. This is traditionally done with individual switches and harnesses between the Power Control and Distribution Unit (PCDU) and each independent subsystem. A Micronode-enabled decentralised power management system could use power buses and local switching eliminates the need for individual harnesses.

- **Environmental Management:** the control of the thermal, pressure, strain and other environmental factors. This is traditionally done by individual harnessing of all sensors and actuators back to a single Remote Interface Unit (RIU). A Micronode-enabled decentralised environmental management system could greatly decrease the length of this harnessing by the use of localised acquisition and control.

The differences between the centralised and potential decentralised architectures of these control functions are summarised in Table 1.

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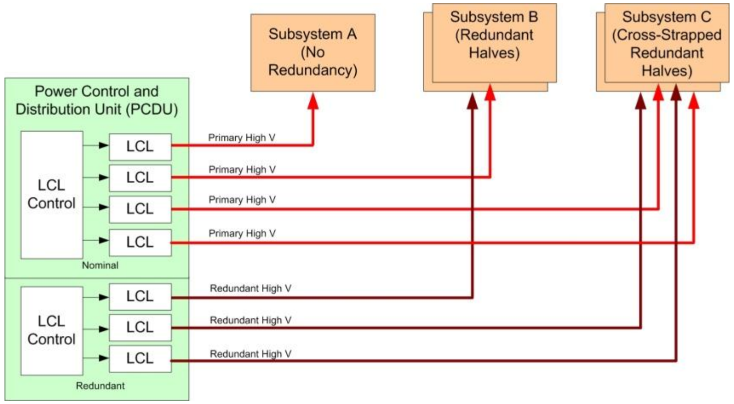
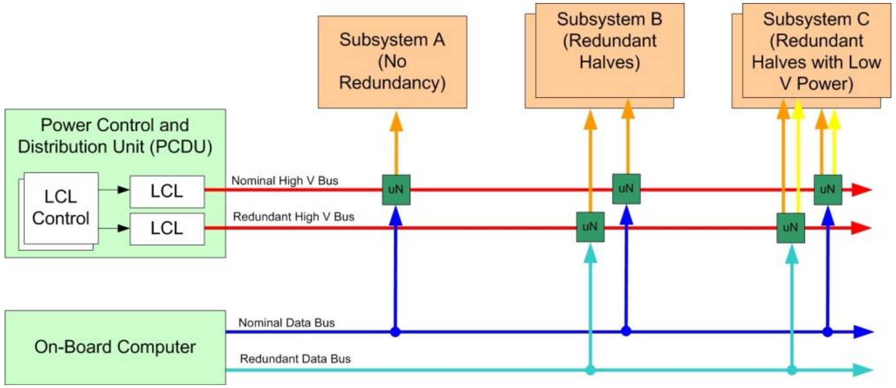
<tr><th>Control Function</th><th>Traditional Centralised Architecture</th><th>Proposed Micronode Enabled Decentralised Architecture</th></tr>
<tr><td>Power Management</td><td>
</td><td>
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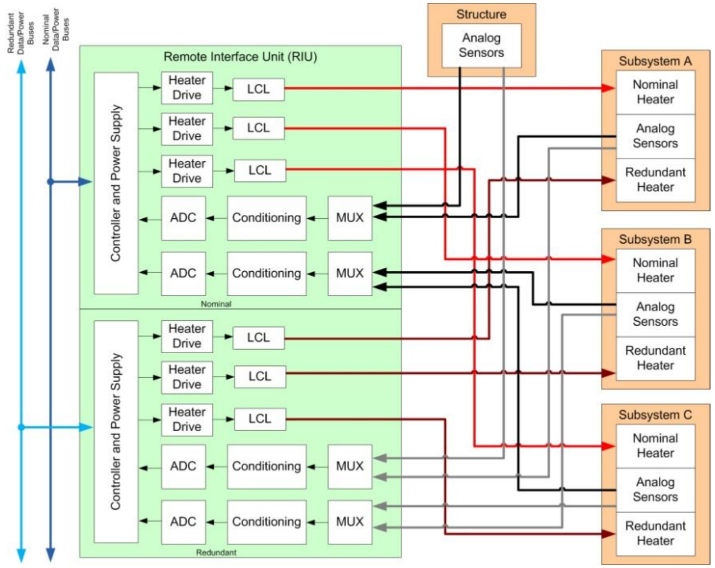
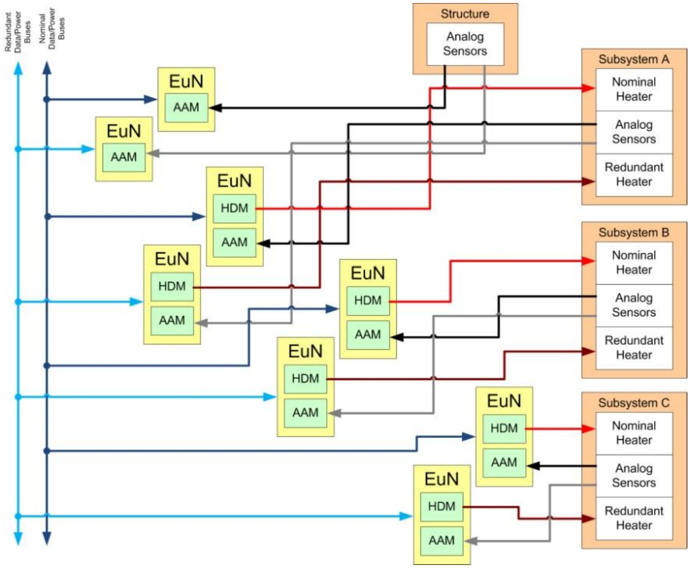
<tr><td>Environmental Management</td><td>
</td><td>
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Table 1 : The two spacecraft control functions with the greatest potential for decentralisation by Micronodes

Task 2: Micronode Requirements

A number of critical requirements for Micronodes that service the chosen control functions were identified. In discussions with the ESA Technical Officer it was decided to initially concentrate on the requirements for small satellites (<500kg) and exploration missions (including the Martian surface). A selection of these requirements is given in Table 2.

Category	Requirement
Lifetime	Shall meet a minimum of 3 operational years; Should meet a maximum of 15 operational years; -including a minimum of 12 months storage in a controlled environment.
Thermal	Shall meet the range of -55°C to +100°C storage; Should meet the range of -120°C to +100°C storage; Shall meet the range of -40°C to +60°C operating; Should meet the range of -120°C to +85°C operating.
Radiation	All components shall be rated Total Ionising Dose (TID) >20krad(si); All components should be rated TID >100krad(si).
Power	Shall be compatible with 24 to 36V unregulated and 28V regulated inputs; Should be also compatible with 50V regulated inputs. Shall support a 1A Latched Current Limiter (LCL) for power distribution; Should support a 2.5A Latched Current Limiter (LCL) for power distribution; Should support a secondary voltage (5V5, 3V3 or 1.5V) power distribution output up to 10W.
Interfaces	Shall support MIL-STD-1553B and OpenCAN Data bus interfaces; Should support 'PowerLink' 2-wire power and data bus interface; Shall support 'at least' 8 ANY, ANP and AN2 analogue sensor interfaces; Should support type AN1, RSA and SHP interfaces.

Table 2: Summary of identified Micronode requirements

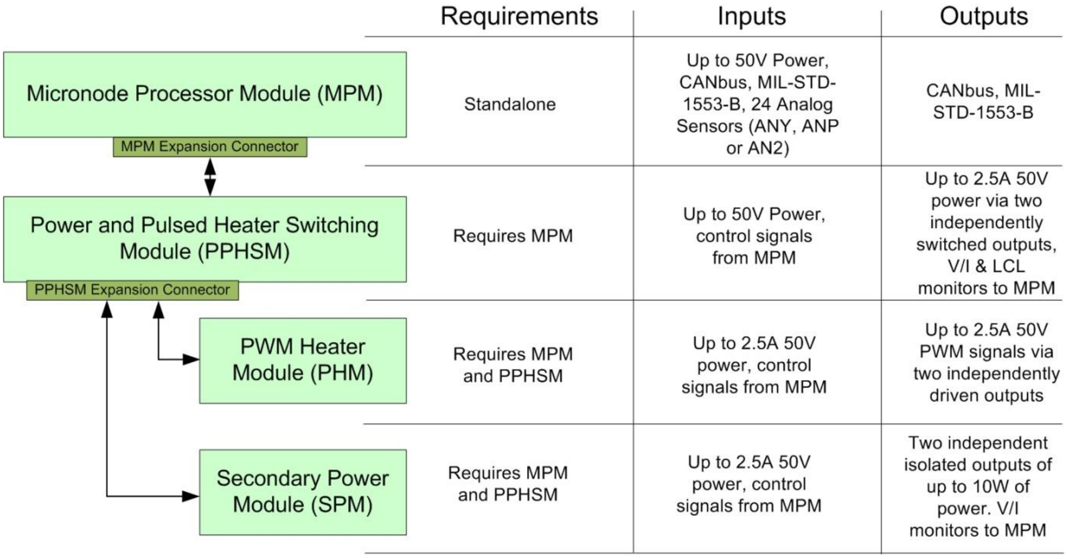
Task 3: Technology Survey

Off-The-Shelf (OTS) and State-Of-The-Art (SOTA) technology were surveyed for all the components anticipated to be required for Micronodes. An initial selection was conducted based upon the criteria of performance, power consumption, temperature range, radiation hardness, package size and ITAR status. Three components were identified as potentially requiring further development beyond what was available OTS:

- **Capacitive isolators** would be highly suited for providing galvanic isolation in Micronodes as they are smaller and consume less power than opto and magnetic isolators. BAE Systems used their experience in space rated MEMS to investigate the potential for creating a radiation hardened capacitive isolator, concluding that this was feasible.
- **Miniaturised DC/DC converters** are required to reduce the power consumption of converting primary input voltages down to a level suitable for the Micronode processing electronics. However the currently available space rated 1-10W DC/DC converters have a large footprint when compared to other components, most are subject to ITAR restrictions and generally come in heavy metal casings. A custom made DC/DC converter with a small footprint suited to Micronodes was investigated and found to be feasible.
- **Microcontroller** level processing would be ideally suited to the requirements of Micronodes as there will be a relatively small number of inputs and outputs (8 to 30) to process at any one time. However current sources of radiation hardened microcontrollers are limited and are subject to ITAR. There are two European space rated microcontrollers currently under development that could be suitable for Micronodes, the ESA uC and Sitael V8uC.

Task 4: Architectural Micronode Design

The Micronode architecture is a highly modular "plug and play" design that can be combined to create different Micronode configurations. Based upon the spacecraft architecture and control function review, the following functions are implemented by the modular architecture illustrated in Figure 1:



	Requirements	Inputs	Outputs
Micronode Processor Module (MPM)	Standalone	Up to 50V Power, CANbus, MIL-STD-1553-B, 24 Analog Sensors (ANY, ANP or AN2)	CANbus, MIL-STD-1553-B
Power and Pulsed Heater Switching Module (PPHSM)	Requires MPM	Up to 50V Power, control signals from MPM	Up to 2.5A 50V power via two independently switched outputs, V/I & LCL monitors to MPM
PWM Heater Module (PHM)	Requires MPM and PPHSM	Up to 2.5A 50V power, control signals from MPM	Up to 2.5A 50V PWM signals via two independently driven outputs
Secondary Power Module (SPM)	Requires MPM and PPHSM	Up to 2.5A 50V power, control signals from MPM	Two independent isolated outputs of up to 10W of power. V/I monitors to MPM

Figure 1 : Micronode modularity concept

Micronode Processor Module (MPM)

The MPM is the core Micronode component, intended to be a completely standalone system to handle external data interfacing, control of other micronode modules and external analog sensor inputs via the ANY (thermistors), ANP (PRTs) or AN2 (0 to 5V) interface. This concludes that the MPM could be used on its own as a Smart Controller of up to 24 analogue i/p sensors. CANOpen and MIL-STD-1553-B data buses are supported.

Power and Pulsed Heater Switching Module (PPHSM)

The PPHSM expands the actuation functionality of the Micronode and connects directly to the MPM via an internal expansion connector. The PPHSM has a high current power input (supporting up to 2.5A and 50V) which supplies power to the PPHSM, MPM and other optional modules (so only a single power input connection to the micronode is required). The PPHSM has a 2.5A Latched Current Limiter (LCL) and two independently switched outputs that are switched to satisfy pulsed heater requirements whilst providing high reliability required for switching external subsystems. The current draw of the outputs and supply voltage will be measured by the PPHSM and transmitted to the MPM for analysis.

PWM Heater Module (PHM)

The PHM connects via an internal PPHSM expansion connector. The PHM has two independent PWM outputs which drive two heaters up to 50V and a total of 2.5A (if the PPHSM outputs are not being used).

Secondary Power Module (SPM)

The SPM expands the subsystem supply capability of the PPHSM by offering two, independently switched, and isolated secondary power outputs. The SPM monitors the voltage and current of the outputs, sending data back to the MPM.

Future Expansion Modules

The modular architecture allows for simplified further expansion in the future, for example; Valve actuator controller, relay status acquisition, digital sensor acquisition, smart sensor frequency output receiver, high temperature (thermocouple) sensor acquisition and a sun sensor interface receiver.

Baseline Design

An initial design based upon component selections from the technology survey was conducted to create a baseline design for each of the Micronode modules. A summary of the designs and configurations is stated in Table 3:

Configuration	Functionality	Mass	Power @50V	Dimensions
Standalone MPM	• Acquire 24 analogue sensors.	80g	264mW (Inactive) 2.85W (Peak) 270mW (Average)	40x40x28.5mm
MPM and PPHSM	• Switch up to 125W of primary power to two subsystems or pulsed heaters; • Acquire 24 analogue sensors.	143g	414mW (Inactive) 5.62W (Peak) 1.1W (Average)	40x40x48.2mm
MPM, PPHSM and PHM	• Drive two 30W PWM heaters; • Switch up to 125W of primary power to two subsystems or pulsed heaters; • Acquire 24 analogue sensors.	180g	414mW (Inactive) 5.988W (Peak) 1.18W (Average)	40x40x60.8mm
MPM, PPHSM and SPM	• Switch 10W of secondary power; • Switch up to 125W of primary power to two subsystems or pulsed heaters; • Acquire 24 analogue sensors.	203g	414mW (Inactive) 8.432W (Peak) 1.112W (Average)	40x40x69.2mm

Table 3 : Baseline Micronode design configurations performance summary

A summary of the functionality of the Micronode configurations is illustrated below in Figure 2:

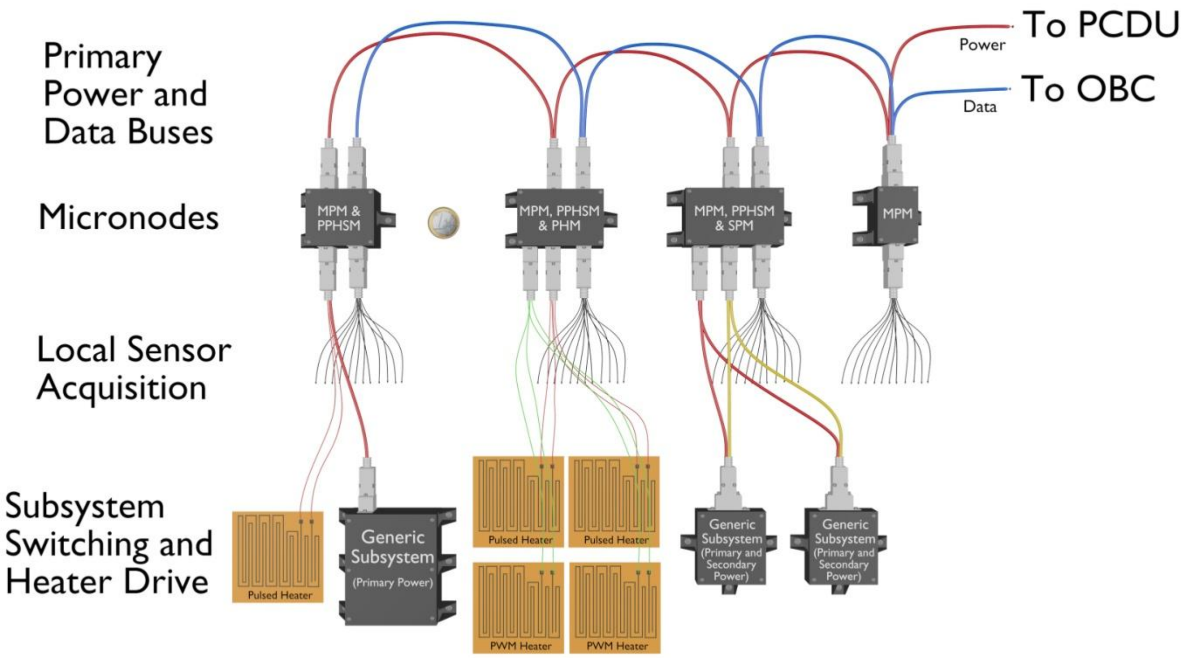


Figure 2 : The baseline Micronode configurations and their interconnections

Task 5: Impact Analysis

The baseline design was analysed to determine the advantages and disadvantages of using a Micronode enabled decentralised architecture when compared to a traditional RIU enabled centralised architecture. Table 4 illustrates the results of a comparison between the mass and power per sensor / actuator for all the Micronode configurations against the BepiColombo Mercury Polar Orbiter (MPO) RIU which is a good representation of a SOTA centralised architecture.

Configuration	Mass/Sensor	Power/Sensor @28V	Mass/Actuator	Power/Actuator @28V 0.6A Out
BepiColombo RIU	10.09g	15.09mW	51.67g	1.554W
MPM	3.33g (-67%)	11.63mW (-23%)	No Actuators	No Actuators
MPM+PPHSM	3.33g (-67%)	11.63mW (-23%)	71.5g (+38%)	569mW (-63%)
MPM+PPHSM+PHM	3.33g (-67%)	11.63mW (-23%)	45g (-13%)	521mW (-66%)
MPM+PPHSM+SPM	3.33g (-67%)	11.63mW (-23%)	50.75g (-2%)	1.132W (-27%)

Table 4 : Comparison of mass and power per sensor / actuator (not including harnessing) between Micronodes and the BepiColombo Remote Interface Unit (RIU)

For all except the mass/actuator, Micronodes provide significant gains over the RIU, but this is not the complete story as it does not include the masses and power losses in the harnessing. As the primary goal of Micronodes is to reduce the mass of the harnessing a monte carlo simulation that included the harnessing was created using MATLAB. This simulation randomised the positions of spacecraft elements including the PCDU, RIU, On-Board Computer (OBC), subsystems, heaters and thermistors and attempted to create the most efficient centralised and decentralised harnessing scheme between these elements. The average mass and power consumption of the complete system was calculated over a series of 50 runs using three different sized spacecraft as inputs (bus size, number of heaters, subsystems and heaters), with the results shown in Table 5:

Spacecraft (S/C) Scenario	ExoMars Rover (small)		BepiColombo MPO (Medium)		Rosetta Orbiter (Large)	
S/C Total Mass	200Kg		1150Kg		1500Kg	
S/C Total Power	200W		500W		2000W	
	Mass	**Power**	**Mass**	**Power**	**Mass**	**Power**
Centralised Architecture	8.75Kg	3.65W	29Kg	9.13W	163.4Kg	33.6W
Decentralised Architecture	4.75Kg	4.28W	11.2Kg	9.88W	52.2Kg	33.3W
Change	-4Kg	+0.63W	-17.8Kg	+0.75W	-111.2Kg	-0.3W
Change (%)	-45.7%	+17.3%	-61.4%	+7.6%	-68.1%	-0.9%
	% of S/C	**% of S/C**	**% of S/C**	**% of S/C**	**% of S/C**	**% of S/C**
Centralised	4.4%	1.8%	2.5%	1.82%	10.9%	1.68%
Decentralised	2.4%	2.1%	1%	2%	3.5%	1.67%
Change	-2%	+0.3%	-1.5%	+0.18%	-7.4%	-0.01%

Table 5 : Mass and power impact simulation results (including harnessing) for environmental and subsystem switching control functions using example ESA spacecraft

The results show that changing from traditional centralised harness architecture to a Micronode-enabled decentralised one can result in an over 7% decrease in spacecraft dry mass. In some cases the power consumption can be increased by up to 0.3%, but the additional power generating mass is unlikely to outweigh the benefits of reduced overall mass. The majority of this additional power consumption comes from inefficient power conversion in the PPHSM due to the lack of suitably sized DC/DC converters but this could be addressed with further design work.

Micronode Summary

Figure 3 shows a 3D rendering of the baseline Micronodes and Table 6 summarises the predicted performance benefits of the Micronodes at the spacecraft level.

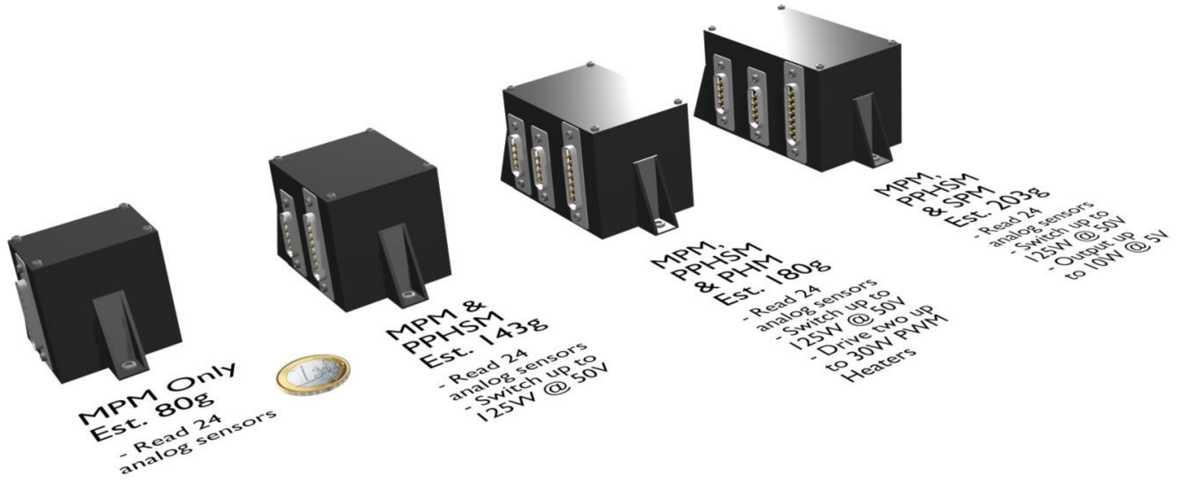


Figure 3 : The family of Micronode baseline configurations and their functionality (to scale)

Analysis	Summary
Mass Impact	- A direct comparison to traditional RIU based centralised sensor / actuator harnessing architectures showed that mass savings of up to 68% are possible when using Micronodes. - This can lead to total spacecraft mass reductions of over 7% which can be directly translated into reduced launch costs or increased payload sizes.
Power Impact	- In some scenarios there is an overall power saving when comparing Micronodes to RIU's which can be as large as 23%. - In several scenarios there is a power penalty (maximum of 17.3%) but this can be eliminated through further design optimisation.
Harness Length impact	- In all scenarios Micronode enabled architectures use significantly shorter total harness lengths (up to 70%). - Shorter harness lengths will reduce overall harness cost as well as the AIV time and effort which can be a significant factor in total spacecraft cost. - Significantly shorter analog sensor harnesses will improve noise immunity and increase accuracy.
Reliability	- All micronode module combinations when considered individually (i.e. not as a network) have mission reliabilities >99.3% over 3 years and >96.2% over 15 years. - In the BepiColombo scenario a dual redundant micronode network would have an estimated mission reliability of 98.2% over a 7.5 year mission. This is a large gain over the mission reliability of 75.8% for a dual redundant RIU.
FMEA	- A dual redundant Micronode network would be single point failure free and would have no catastrophic failure modes (this includes single point failure of a whole Micronode network or damage to other spacecraft systems).
Response Time	- Micronode based distributed processing allows the response time to any sensor driven event to be faster than with a centralised RIU style polled system.
Complexity	- As Micronodes will be capable of running autonomously there is no need to synchronise control loops with the OBC. This can allow the OBC to be de-scoped to decrease power or refocused onto other tasks. - The reduced complexity of a single Micronode when compared to a RIU will simplify AIT and fault finding procedures.
Situational Awareness	- The complexity of adding additional sensors to heaters and subsystems is greatly reduced by use of plug and play. - Multi-perspective control loops involving a mixture of sensor and actuator types will be easier to implement as everything is local to the Micronode.
Survival Capability	- All baselined components are radiation and vibration tolerant and are rated for an operational temperature of at least -55°C to +125°C. - Micronodes should be capable of operation in low, medium, high, geostationary and escape Earth orbits as well as interplanetary space, planetary orbits (with the possible exception of Jupiter without additional shielding) and the surface of the Moon and Mars.
Subsystem Autonomy	- Micronodes have been designed to handle the complete environmental control of a spacecraft autonomously. - They should also be able to provide additional autonomous protection for connected subsystems.
Modularity	- Micronodes have been designed to be highly modular with many different sensor and actuator combinations possible with the baseline modules. - The expansion connectors between modules will allow for other optional modules vastly increasing the number of potential configurations. The use of a software

Analysis	Summary
	scripting language is envisioned to prevent the need for hardware changes or requalification with different sensor/actuator combinations. • This level of modularity and the use of data and power buses will allow additional Micronodes to be added during integration and fast exchanging of a faulty unit, preventing expensive delays.
New Operational Modes	• Micronodes can enable new or enhance existing operational modes including: – Autonomous low power survival temperature maintenance. – In-flight reprogrammable sensor/actuator control loops. – Switchable accuracy heaters. – External subsystem power monitoring. – Power bus voltage remote monitoring. – Automated activation of subsystems. – AIT modes specifically for pre-launch diagnostics.
Mechanical	• Due to the use of space qualified components and design; the Micronodes are not anticipated to have issues with vibration, shock or thermal stresses.
Cost	• The modularity, wide functionality and adaptability of the Micronodes encourages reuse and decreases the amount of re-qualification when compared to a centralised system which must be redesigned or modified to suit the number of sensors and actuators on each spacecraft. • In the baseline design parts reuse is maximised and the number of Micronodes required for each spacecraft means that component MOQ are less likely to be encountered. • The inter-OBC compatibility means that excess Micronodes built for one mission could be used on another.

Table 6 : Summary of Micronode predicted performance and impact on spacecraft design

Micronode Development Roadmap

A complete Micronode development programme could be planned to cover three phases. This would split the overall cost up into discrete non-overlapping phases as follows:

Phase 1	• FM unit design trade-offs; • Prototype manufacture and test of required new Micro and MEMS components; • Electronics Bread-boarding to EM level using commercial components.
Phase 2	• FM, EGSE and software design; • EQM build and test; • Qualification of Hybrid and SiP packaged parts to ESCC standard; • Update of new Micro and MEMS to FM standard and full characterisation; • Generation of FM product definition documentation and qualification plans.
Phase 3	• Process Definition Document to define basis for FM manufacture. • Generation of FM production test equipment from EQM EGSE. • FM production planning. • First batch FM manufacture and test • FM Delta Qualification for production processes.

Table 7 : Micronode Development Programme