Simplifying Avionics Design and Demonstration: A Unified Module Framework for Spacecraft Avionics

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A successful in-orbit demonstration is the best argument for an innovative spacecraft avionics technology to be widely adopted. Opportunities to demonstrate technologies on larger, classical spacecraft are rare, costly, and usually face long development cycles. Meanwhile, there are plenty of affordable flight opportunities for standardised CubeSat-style nano-spacecraft on almost every rocket launched today. If avionics systems intended for classic spacecraft could be tested and demonstrated in a small spacecraft without much customization, especially in terms of the mechanics and interfaces, the development cycle could be accelerated a lot. This paper presents the work towards addressing this possibility and the resulting Unified Module Framework (UMF) that can be used to provide core avionics modules for a wide range of spacecraft classes and applications. Based on the Advanced Data Handling Architecture (ADHA) initiative by ESA, the feasibility of physically integrating cPCI Serial Space modules, intended for larger spacecraft, into a commercial CubeSat structure is evaluated first. Subsequently, a set of physical constraints are formulated and a design is created that is capable to scale from being used in a standard 3U structure to the integration in a classic box design for larger spacecraft. Secondly, the paper discusses the tailoring of cPCI Serial Space and extensions made, in order to enable building practical systems with UMF. UMF defines some choices for the physical interfaces within the cPCI standard, in order to ensure the electrical and functional compatibility between all modules that use it. Further, cPCI Serial Space does not prescribe a power supply solution for systems using it. UMF addresses this and goes beyond by also including electrical power system components in its architecture. Finally, the paper discusses the practical use of UMF based on an example application, intended to be the first in-orbit demonstration of the proposed UMF framework.

Key Words: avionics, framework, cubesat, cPCI Serial Space, ADHA

Nomenclature

cPCI	Compact PCI
ADHA	Advanced Data Handling Architecture
SWaP	size, weight and power
PCIe	PCI Express
COTS	commercial off-the-shelf
UMF	Unified Module Framework
ICA	Integrated Core Avionics
PLUTO	Payload Under Test Orbiter
PCDU	power conditioning and distribution unit
GSDR	Generic Software Defined Radio
cPCI-SS	cPCI Serial Space
EGSE	electrical ground support equipment
PCB	printed circuit board

1. Introduction

In the development of spacecraft in general, and spacecraft avionics in particular, early in-orbit demonstrations are extremely valuable to generate flight heritage quickly – not only for further establishing well-tested components, but also to accelerate development of new, unproven components with potentially high risk of failure, either through innovative technologies or simply through the inclusion of non-radiation-hardened commercial off-the-shelf (COTS) components. Especially in situations where such avionics components are intended for larger, classical spacecraft there are promising benefits when testing those ahead of the actual mission, for instance in a smaller-scale demonstration mission.

Nowadays, with the availability of CubeSat style spacecraft and the growing supply of affordable rideshares for CubeSats, there are in theory plenty of potential flight opportunities for relatively affordable demonstration missions. For this to be feasible, it is required that little to customization be necessary for such components, and especially their electrical and mechanical interfaces, to be able to be integrated both in their designated final spacecraft, as well as a small-scale demonstration satellite ahead of time.

For their avionics, especially industrial manufacturers and larger public space missions typically rely on a backplane architecture with modules (such as for example cPCI Serial Space (cPCI-SS)). Enabling designers to fit such modular backplane architectures into a CubeSat style formfactor, while trying to keep modifications on electrical and mechanical interfaces to a minimun, and enabling an architecture that is scalable to various satellite sizes would be one solution to enable the proposed early technology demonstrations.

In this paper, such an approach is discussed under the application of cPCI-SS with the introduction of a novel design for a Unified Module Framework (UMF) and the respective modules, along with the challenges and the first planned demonstration mission for this approach.

cPCI-SS is endorsed by ESA through the Advanced Data Handling Architecture (ADHA) initiative, which focuses on reducing volume, mass, and power of the Data-Handling System and is in line with our aims of an overall integrated avionics solution that reaches for the exact same goals.[1)]

1.1. State-of-the-art

Compact PCI (cPCI) Serial as a high-speed successor to the well-established cPCI is one of multiple standards for inter-module communication inside a computing system. Next to standards such as OpenVPX and MicroTCA, cPCI Serial puts special focus on reduced design complexity and low development cost, while maintaining a high standard in terms of size, weight and power (SWaP) and reliability in extreme (and radiation-heavy) environments.

Because this approach aligns perfectly with the design requirements of the space segment, the application of this bus standard to the development of spacecraft and avionics in particular was a logical consequence. For this reason, cPCI-SS was introduced, tailoring the details of vanilla cPCI Serial to the specific interface requirements of space applications.

As such, cPCI-SS omits some not required features such as USB and SATA in favor of additional generic backplane connections. It further generalizes other signal lines originally designated to a specific link such as Ethernet or PCI Express (PCIe), and introduces important redundancy for popular protocols, such as SpaceWire, through a dual star architecture and additional monitoring and control pins.[2)]

As of today, cPCI-SS is most commonly used in industry and large-scale research missions with conventional medium- to large-scale satellite buses. The standard is therefore less approachable for lower-end satellite teams such as universities or research institutes. On the other hand, access to small-size satellite demonstrators for larger satellite missions and their designers is, while desirable for the sake of early technology demonstration, limited for the same reason. In both cases, the reason is that cPCI was not originally intended for the use in small-scale spacecraft and is not tailored to the mechanical, but also potential electrical requirements. In fact, cPCI leaves a large portion of the electrical aspects undefined, which will be addressed in more detail in a later section.

1.2. CPCI for scalable avionics

When it comes to scalable satellite systems and scalable avionics in particluar, modularity is a necessity. At the same time, scalability means that a wide range of configurations and satellite dimensions should be covered in order to make scalable avionics really an advantage above custom, per-mission solutions.

Its various advantages described above regarding support for space protocols, redundant architecture and modularity, as well as the wide adoption within industry and the endorsement through ADHA, make cPCI a particularly interesting choice. Especially the backplane architecture and connectors appear worth to make accessbile for small satellites and CubeSats. From a power perspective, the connectors allow for high current transfer while the larger PCBs reduce the overhead for connections thus increasing the overall system power density. Furthermore, it enables overall more demanding applications as well as larger solar arrays delivering more power than was previously feasible on such a small satellite.

1.3. Challenge

The integration of the cPCI formfactor into a framework that complies with the requirements of the CubeSat standard comes with several mechanical and electrical challenges.

cPCI Serial and Serial Space cartriges incorporate the 3U and 6U Eurocard form factor ($3U = 100\,mm \times 160\,mm$). This is not to be confused with the "Unit" standard for CubeSat dimensions,[3)] and in fact, these two formfactors are by default incompatible with one another. However, they are not significantly different either, such that it was imaginable that with slight mechanical (and electrical) modifications, cPCI-SS could be fit into a 3U+ Cubesat formfactor. Here, the smallest baseline to integrate such cartriges is the 3U CubeSat formfactor; meaning that the proposed UMF framework must be adapted with 3U as a baseline, and be scalabe to 6U, 12U and other formfactors from there. A survey among the most popular vendors of CubeSat structures reveals that mechanical modifications had to be applied to the standard Eurocard formfactor, which will be discussed in detail further below.

Another task was that cPCI-SS does indeed define the logical arhcitecture of a modular on-board computing system, but leaves a lot of freedom in the definition of the physical interfaces. Further, the design definitions on the power system are not covered by cPCI at all, so these have to be considered as well,with the limitations of the 3U+ formfactors in mind.

2. CPCI Tailoring and Extensions

The CPCI Serial base standard has several options that a system may use or not. CPCI-SS removes some options that are not useful in a space avionics context. It also adds a second System Slot to enable redundant systems.

Some aspects are mentioned in the standard but not sufficiently detailed to design a complete system. There is currently no corresponding specification for the Power Supply and the description of the Shelf Controller is limited to its logical function and which signals it should monitor and control.

The Unified Module Framework makes selections for the remaining options and adds definitions where needed to enable complete system designs. The goal is to do this without losing compatibility with the CPCI-SS standard. More precisely that:

- UMF modules can be used in CPCI-SS systems
- Commercial CPCI Serial equipment like backplanes and housings can be used for prototyping or as ground support equipment

2.1. Tailoring

The CPCI Serial Space standard defines both mechanical and electrical requirements. Considering the mechanical requirements, UMF only targets modules in the 3U size for now. Larger 6U modules are more difficult to integrate in a CubeSat form-factor and usually have power requirements that would quickly overwhelm such a small spacecraft. Rear and standard mezzanine boards are currently not considered, but could be addressed by UMF in the future.

The electrical requirements of CPCI-SS leave some flexibility on how to power the modules. They can either be powered by a common bus that is supplied by redundant power supplies or by individual power outlets. UMF does not change the power interface of the modules. However, using a shared power bus for the modules is not foreseen. Instead, individual outlets are utilized to power each module and can also be used to separate the modules into two redundant groups powered by their own power supply. The 5V standby rail is currently not used.

There are several control signals that are used as intended or at least supported and reserved for future use. The PS_ON# signal can be used by the Shelf Controller to individually turn modules on and off. The PWRBTN# signal can be used by the Shelf Controller to initiate a soft shutdown of the system by the System Slots. There is no intimidate use case for this signal, but it could be useful in the future. Similarly, there is no immediate use case for the PWR_FAIL# signal, which can indicate a problem in the power supply to the System Slot, but originates in the Shelf Controller.

The Platform Control Signals are used as recommended by CPCI-SS. Especially the Wake / Watchdog signal is foreseen as output from the modules to the Shelf Controller, which enables it to act as a watchdog for each module.

CPCI-SS defines two data interface classes: the Management Interfaces and the High Speed Interfaces. In both classes UMF selects a single interface type.

The Management Interface can be used for low-level control and monitoring of the modules. Three interface types are available in parallel: I²C, Serial GPIO and CAN. Only CAN is used by UMF, as it is the most robust and widely available interface. Many space qualified microcontrollers and processors have built-in support for CAN.

For the High Speed Interfaces the choice is between PCI Express, Ethernet, and SpaceWire. Compared to the Management Interface these interface types are not available in parallel. In theory a system could use a mix of interface types on a slot by slot basis. In practice PCI Express is currently very uncommon in the space domain. Most space qualified processors (such as the Frontgrade GR740, BAE Systems RAD5545 or ABDS SCOC3) that could be used in a module in the System Slot provide only one or two Ethernet interfaces, but multiple SpaceWire interfaces. SpaceWire interfaces and routers are also easy to implement in FPGAs with limited effort. Therefore UMF currently uses SpaceWire exclusively for the Dual Star and Mesh Interconnects.

The Shelf Controller and the module in the System Slot have to support the Management Interface. The module in the System Slot has to support a number of high speed interfaces in the dual star interconnect, sufficient for all peripheral modules in the system. A peripheral module must support either at least the Management Interface or the redundant SpaceWire interface in the dual star, to ensure a connection to either the Shelf Controller or the module in the System Slot. The modules in the System Slots and the Peripheral Modules may additionally use the SpaceWire links of the Mesh Interconnect.

2.2. Extension

The Unified Module Framework goes beyond what is defined in CPCI-SS in order to enable building complete systems. The two areas that need further definition are the Shelf Controller and the power supply.

For small systems with few modules, having a dedicated Utility Slot and Shelf Controller module would mean significant overhead. Therefore a hybrid of the System Slot and Utility Slot is introduced as Controller Slot that can host a System Controller module that can act as a Shelf Controller. The System Slot already provides power connections and access to the

Pin	A	B	C	D	E	F
3 - 08	GND	IO	IO	GND	IO	IO
3 - 07	IO	IO	GND	IO	IO	GND
3 - 06	GND	PS_ON#_B	PRST#_B	GND	WAKE#_B	RST#_B
3 - 05	PS_ON#_8	RST#_8	GND	IO	IO	GND
3 - 04	GND	PS_ON#_6	RST#_6	GND	WAKE#_6	PS_ON#_7
3 - 03	PS_ON#_4	RST#_4	GND	WAKE#_4	PS_ON#_5	GND
3 - 02	GND	PS_ON#_2	RST#_2	GND	WAKE#_2	PS_ON#_3
3 - 01	PS_ON#_A	PRST#_A	GND	WAKE#_A	RST#_A	GND

G	H	I	J	K	L	Pin
GND	IO	IO	GND	IO	IO	3 - 08
IO	IO	GND	IO	IO	GND	3 - 07
GND	PWRBTN#_B	PWR_FAIL#_B	GND	IO	IO	3 - 06
IO	IO	GND	IO	IO	GND	3 - 05
GND	RST#_7	WAKE#_7	GND	IO	IO	3 - 04
RST#_5	WAKE#_5	GND	IO	IO	GND	3 - 03
GND	RST#_3	WAKE#_3	GND	IO	IO	3 - 02
PWRBTN#_A	PWR_FAIL#_A	GND	IO	IO	GND	3 - 01

Fig. 1. Control signal allocation to connector P3.

CAN bus of the Management Interface. The additional control signals (RST#_x, WAKE#_x, PS_ON#_x, etc.) are allocated to the user I/O pins on connector P3. The pin mapping is shown in Fig. 1.

For compatibility with CPCI-SS this means that:

- The System Controller module can be used in standard CPCI-SS System and Peripheral Slots as the additional signals are treated as user I/O.
- The System Controller module can be used as dedicated Shelf Controller.
- A CPCI-SS System or Peripheral Board could be plugged into the Controller Slot if it does not use the user I/O pins on P3.

A possible overall concept for power handling and status control for multiple modules is shown in Fig. 2. The power conditioning and distribution unit (PCDU) is intergrated into the system as a module and provides two independent protected and automatically resetting power lines for the radio and the System Controller. These power lines are turned on as long as the power subsystem is operational and return to the on status automatically after any fault event. Furthermore they can be commanded off via discrete digital signals from a command-bypass-decoder in the radio as an additional means of resetting for the Sytem Controller or the radio. For all other modules in the system, the PCDU provides a shared 12 V power rail and the module status is controlled via the PS_ON# signal by the System Controller. The System Controller is also connected via CAN bus to the PCDU for control of all PCDU functions and telemetry connection. During system start-up the PCDU checks the status of the battery and then provides power to the System Controller and radio, enabling basic operation. The System Controller then proceeds to power up other systems via the PCDU CAN bus and PS_ON# signals.

2.3. Mechanical Adaptation

The goal for the revised mechanical outline of the UMF was to use a single printed circuit board (PCB) layout for applications ranging from 3U CubeSat to stand-alone application on a larger satellite while staying compatible with the connectors and housings used in the cPCI-SS standard. This is shown in Fig. 3.

The cPCI-SS standard uses the standard EuroCard formfactor of 160 x 100 mm² while a typical 3U CubeSat has a footprint of 100 x 100 mm². The internal volume of the structure is reduced even further by the thickness of the primary structure. Inquiries at multiple CubeSat structure suppliers resulted

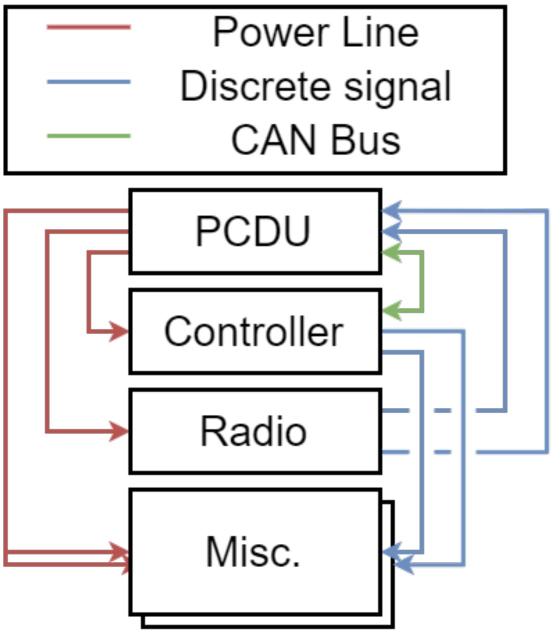

Fig. 2. Signal and Power flow concept for ICA.

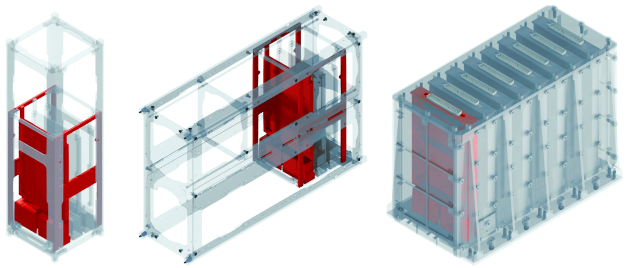

Fig. 3. Overview of possible UMF module applications ranging from 3U CubeSat to stand-alone box. UMF module shown in red.

in varying internal measurements, but a width of 94 mm could be accomodated in almost all structures. Additionally, the horizontal orientation in a 6U CubeSat for flexible accomodation with other components should be possible, resulting in an additional notch in the boards to accomodate structural elements. The resulting board outline is shown in Fig. 4. Three different levels of keep-out area are defined: the mandatory keep out in dark red for interfacing with the secondary structure and the P1 and P2 connector, the design specific keep-out for the frames to mount the PCB and a recommended keep-out to allow simple adaptation to wedge-lock based cPCI-SS cartridges. The design specific keep-out area is shown with a possible minimum frame design currently under investigation. The PCB area usable for electronics is 125 cm² when using this frame and all backplane connectors, resulting in nearly 50% more board space for electronics compared to PC104.

From this PCB outline, a mechanical design for a secondary structure to accomodate the boards together with a backplane in a 2U compartment of a CubeSat is designed. For compatibility reasons the design should provide connections to the usual PC104 threaded rods present in almost all commercial CubeSat structures. Fig. 5 shows the secondary structure with three boards in place. Besides the PC104 threaded rods, the secondary structure has additional mounting holes for direct connection to the primary structure. This provides better thermal

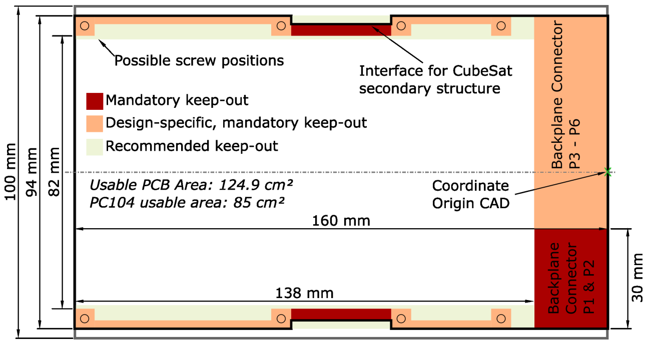

Fig. 4. Adapted PCB outline for UMF modules with keep-out areas for connectors and frames. Light gray outline indicated Eurocard standard.

connection to the primary structure as well as additional rigidity. The thermal properties and the impact on the overall thermal design of the satellite are currently under investigation for the demonstration mission described in the next section. To interface the Integrated Core Avionics (ICA) – which are described in the next section as well – with other CubeSat systems, a routing envelope for internal harness is provided at the top end assuming connectors for power and data handling or RF front-ends on the individual boards similar to a stand-alone application.

3. First In-Orbit Demostration

A first in-orbit demonstration of UMF will take place in 2024 with a rideshare opportunity on the scheduled second launch of ISAR Aerospace's Spectrum rocket.[4)] The Payload Under Test Orbiter (PLUTO) mission is a demonstration mission for a multitude of experiments from various DLR departments. Most and foremost however, PLUTO will include the first demonstration of the Integrated Core Avionics (ICA), a modular and highly scalable core avionics solution covering PCDU, communication, on-board data handling and software. All ICA components apply the UMF concept.

The PLUTO spacecraft is a satellite based on the 6U CubeSat formfactor and weights roughly 7 kilograms. A structural overview is presented in Fig. 6. A key characteristic of this satellite is that it consists of mainly new components without any prior flight heritage, making it a mission with a relatively high risk. Apart from the core avionics, this applies as well for example to the ultra-compact deployable solar array, delivering roughly 100 W of power and fitting into a 1U space when stowed, or to the battery system, that along with the PCDU, need to handle - for CubeSat measures - new magnitudes of power density and consequently also thermal challenges. This is another point whree UMF proves to be an enabler of this technology demonstration. Instead of dissipating heat through deliberate connections of the individual boards to the CubeSat structure, UMF modules aim to use of the potentially better heat dissipation properties of UMF module frames as well as potentially the cPCI's backplane connectors.

Because of the overall experimental approach of the satellite and the solar array, a selective operation of single ICA components is possible with solar panels on the surface of the satellite, in case array deployment would show to be unsuccessful. However, it is only with the more powerful solar array, that all

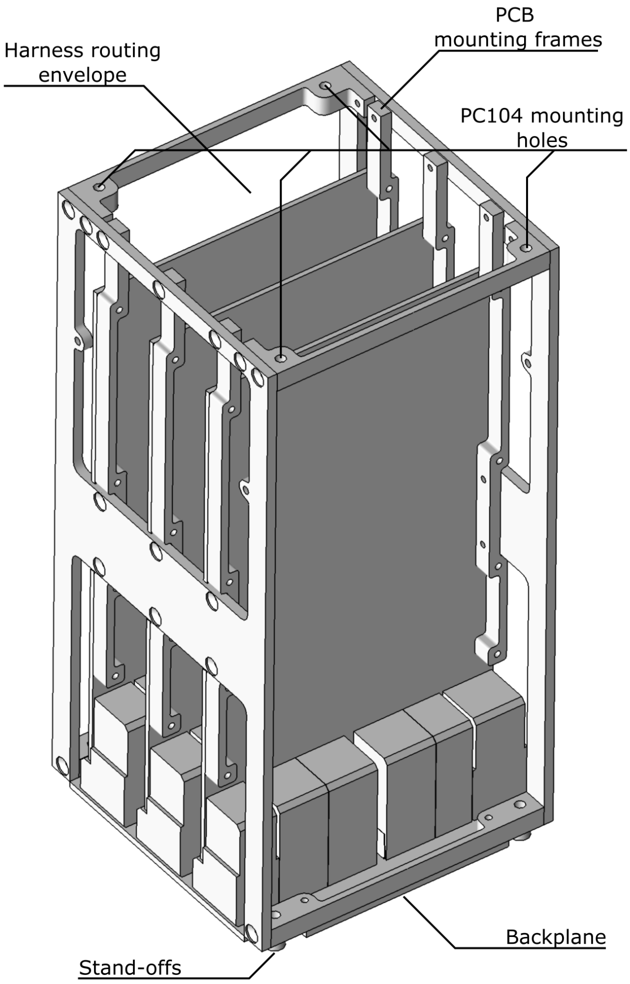

Fig. 5. Secondary structure to accomodate 3 UMF modules within 2U of a CubeSat.

components of the spacecraft, especially the full core avionics experiments, can be conducted as a full system at the same time. While in this ICA configuration, only 20 watts will effectively be used and produce heat, even larger configirations and more components using the full capapbilities of the 100 W solar array are possible.

UMF is also an enabler for technology demonstrations of DLR technologies that are intended originally for the use on SmallSats, larger satellites or other spacecraft such as landers and deep space probes. One of such examples is the Generic Software Defined Radio (GSDR), an integrated multi-channel, multi-band communicatiosn module, which will have it's first demonstration flight aboard PLUTO[5)] on a UMF module.

Figure 7 shows the core avionics UMF modules integrated into the 6U cubeSat structure. Directly visible are the individual UMF module frames (blue) as well as the auxiliary support structure (purple), placing the modules in the lower end of one half of the satellite; with the remaining 1U containing the deployable solar array and the other 3U half housing the batteries and other PLUTO experiments.

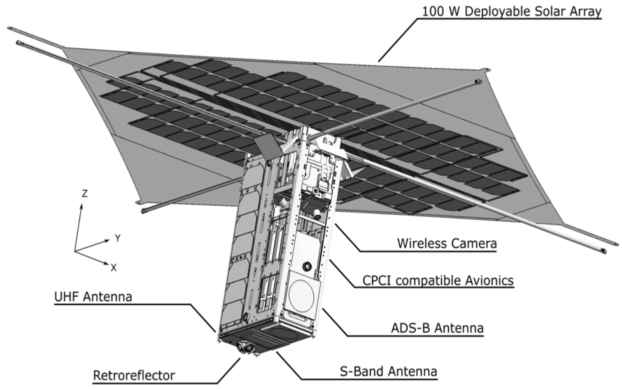

Fig. 6. PLUTO spacecraft structural overview with deployed 100 W solar array

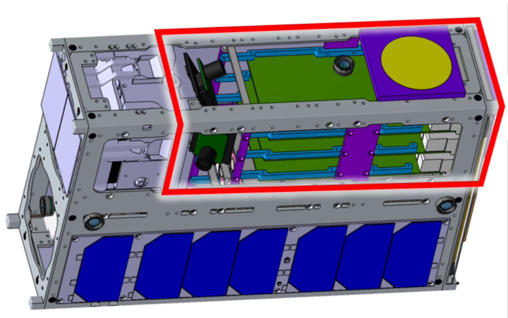

Fig. 7. PLUTO spacecraft prototype design with UMF and auxiliary support structure (purple) containing Integrated Core Avionics (ICA) components

4. Conclusion

In this paper, we presented an approach for a modular satellite framework that is designed to simplify technology demonstrations of (specifically, but not exclusively) avionics components. The approach aimed at bringing the cPCI-SS backplane architecture into a module design suitable to be integrated into a CubeSat formfactor. To keep the necessary modifications to a minimum and guarantee full compatibility to the final design, the basic Eurocard design could only be modified mechanically without requiring any electrical modifications of the components that designers want to demonstrate. Because the cPCI Serial standard deliberately leaves some freedom in the design of its connections, the UMF modules could also be tailored specifically to the required and most common interfaces for their applications in space.

On the electrical side, it was necessary to make desicions on which data interfaces to use for the high speed and management interface. This was based on the interfaces that are most practical for application in space domain with respect to coverage by available (space grade or space qualified) components and especially with respect to the ease of implementation. CAN was chosen for management interface and SpaceWire for high speed interfaces (dual star architecture). The decisions were made always with the condition that UMF modules could still be used in standard cPCI-SS systems and are compatible with commercial equipment for prototyping and electrical ground support equipment (EGSE). That influenced specifically how certain user I/O pins were used for control signals in a way that was feasible for CubeSat applications and yet still compliant with the cPCI-SS standard.

Finally, in the power supply definition, the specific requirements had to be condisered for the integration into a formfactor smaller than originally intended by cPCI standard. This was particularly important with respect to power consumption and thermal properties, as cPCI was not originally designed for the relatively small CubeSat dimensions with (originally) limited power consumption and heat dissipation capabilities.

The presented UMF formfactor already finds application in an upcoming demonstration mission, including multiple avionics components. This will be the first opportunity to demonstrate the porposed benefits of UMF and provides the chance to further solidify the design with the results achieved in this mission. If the demonstration through the PLUTO mission and the co-working of the designed components inside the core avionics and UMF proves successful, DLR can even build on a fully integrated system that can work stand-alone, including batteries, power handling and core avionics, unifying all core features of a satellite platform.

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