

Integrating a large nanosatellite from CubeSat components – Challenges and solutions

Clemens Horch^{a*}, Martin Schimmerohn^a, Frank Schäfer^a

^a Fraunhofer Institute for High-Speed-Dynamics, Ernst-Mach-Institut, EMI, Eckerstr. 4, 79104 Freiburg, Germany

* Corresponding Author, clemens.horch@emi.fraunhofer.de

Abstract

Since the first release of the CubeSat standard a diverse market for CubeSat components has developed. Recent years have also seen a trend towards larger CubeSats. Consequently, all components necessary for systems in the range of small microsattellites are now available on the CubeSat market. This also includes more advanced subsystems like ADCS with three-axis stabilization and high data rate transmitters. When combining systems from different manufacturers, several compatibility issues arise. While all subsystems share the PC/104 format, missing standardization of pin assignment as well as low flexibility of the components make integration harder than necessary. Fraunhofer EMI currently designs and builds the 12U nanosatellite ERNST (Experimental Spacecraft based on Nanosatellite Technology). The satellite contains an advanced mid-wavelength-infrared imaging payload. Most requirements of this payload exceed the capabilities of 1-3U CubeSats. Instead of realizing the mission with a commercially available microsattellite bus, we pursue the concept of building a 12U nanosatellite from components designed for smaller CubeSats. For ERNST, the subsystem compatibility issues are solved using a PC/104 backplane. The components are grouped into multiple stacks that are connected through this backplane, which then translates between the different pin assignments.

Keywords: CubeSat, compatibility, system integration, backplane, PC/104

1. Introduction

1.1. The trend towards larger CubeSats

Since the release of the first CubeSat design specification in 1999 [1], more than 750 CubeSats have been launched as of July 2017 [2, 3]. This number includes 315 3U CubeSats by Planet Labs. Fig. 2 shows the distribution of sizes of satellites launched with and without the Planet Labs satellites. Not shown in the figure is the first 12U CubeSat Aoxiang Zhixing [4], which was launched in 2016. According to forecasts, over 1000 CubeSats will launch between 2017 and 2023 [5].

CubeSats are classified by their size, which is measured in Units, referring to the approximate $10 \times 10 \times 10$ cm³ volume from the CubeSat standard. Larger CubeSats fill multiples of this 1U cube. Common sizes are 1U, 2U, 3U and 6U. The main reason for these standardized sizes is the availability of suitable launch containers. Currently, containers up to 27U are available.

There is also the traditional classification of small satellites into pico, nano, micro and mini satellites. There seems to be no commonly acknowledged source for these size classes but the most common definition is based on the decimal power of the satellite's mass. Subsequently, small CubeSats (1U) fall into the picosatellite range and most larger CubeSats (2U, 3U, 6U) are classified as nanosatellites. Strictly speaking, 12U and 27U CubeSats are then considered microsattellites.

Each of these small satellite size classes comes with a specific and distinct understanding of how such a satellite is designed and built. Microsattellites are commonly not associated with CubeSats, since they

follow different design philosophies. Microsattellites usually do not launch from a launch canister and are in general not cuboids consisting of 1U cubes.

Therefore, we propose to call small satellites that weigh just above 10kg and are designed applying the concepts of CubeSats like canisterized launch *large nanosatellites*. Fig. 1 shows how this classification fits into both the CubeSat classes and the traditional small satellite classification.

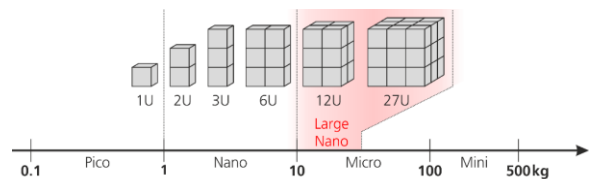


Fig. 1. Traditional small satellite size classes and CubeSats. The 12U and 27U CubeSats represent the *large nano* class.

Starting from mostly 1U CubeSats, the 3U size has become the dominant one in recent years. However, the current trend clearly goes towards large nanosatellites such as 12U or 27U. Originally, CubeSats fulfilled mostly educational purposes. While this remains one of their main uses, the commercial and military applications are increasing. This comes with a rising demand for more advanced payloads, which require more satellite mass and volume.

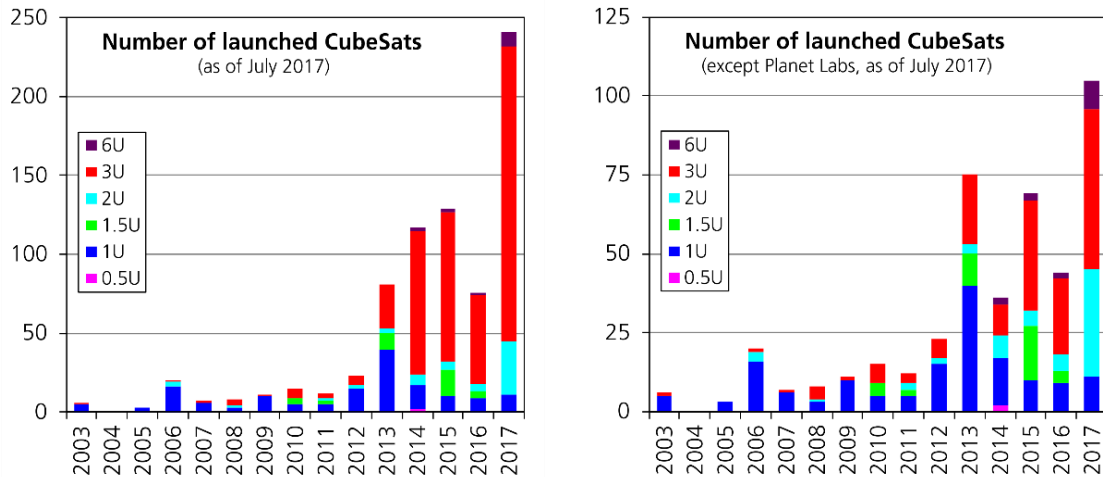


Fig. 2. CubeSat launch statistics by CubeSat size class as of July 2017 (data source: CubeSat Database [1])

1.2. CubeSat subsystem market and compatibility

According to [3] there are now over 200 companies world-wide that are active in the nanosatellite business. Many of them offer ready-to-purchase subsystems like computers, power systems or radios. The best known suppliers in Europe are Clyde Space (UK) [6], GomSpace (DK) [7] and ISIS (NL) [8].

Following the trend of larger CubeSats, many vendors have updated their portfolio to comprise also components with much higher performance. Consequently, all components necessary for a small microsatellite or large nanosatellite bus are now available on the commercial CubeSat market. This includes also more advanced subsystems like ADCS with three-axis stabilization and high data rate transmitters.

All products from the established vendors adhere to the modified PC/104 standard [9], as do almost all products on the market with only very few exceptions. While this de-facto standardization can certainly be seen as a contributing factor to the success of CubeSats, according to a survey by Bouwmeester et al. in 2014 [10] more than 50% of the CubeSat developers that use PC/104 are not satisfied with the standard. Most would prefer a smaller connector; but also mechanical reliability and pin assignment issues are quite common.

There are also other concepts for the harness besides PC/104. One example of many is the LMPC CubeSat by the Aerospace Corporation, which uses a highly customized interconnect system with custom stacked subsystems [11]. The recently founded Danish company Space Inventor sells CubeSat subsystems without any electrical stacking. They rely solely on cable harness, which may have its advantages over board-to-board connectors [12].

Several university projects have chosen to develop their own interconnect system using a backplane with orthogonal daughterboards. One example is the NUTS

CubeSat from the Norwegian University of Science and Technology (NTNU) as described by Birkeland et al. [13]. A second example is the UWE-3 satellite from the University of Würzburg, Germany [14, 15]. The latter even goes one step further and proposes the system used in UWE-3 as a standard [16]. Regarding the use of backplanes in CubeSats, there is also at least one relevant US patent by Spire Global, Inc. [17] that describes a concept very similar to NUTS and UWE-3. All these alternative concepts are only viable for missions that can afford to build all subsystems by themselves.

Nohka et al. [18] present a concept for their AISat/Clavis-1 microsatellite that is based on CubeSat components while not adhering to the mechanical CubeSat specification. Consequently, the satellite was not launched from a CubeSat canister. They connect PC/104 components from different vendors through a backplane. The subsystems are grouped in four PC/104 stacks that are arranged in a 2-by-2 grid on the backplane.

1.3. The ERNST mission

Fraunhofer EMI currently designs and builds a 12U nanosatellite with an advanced mid-wavelength-infrared (MWIR) imaging payload. The mission is called ERNST (Experimental Spacecraft based on Nanosatellite Technology) and its main goal is to evaluate the utility of a nanosatellite mission for scientific and military purposes. Fig. 3 shows a rendered image of the current engineering status.

The satellite's primary payload is a high-resolution MWIR camera that is actively cooled by a Stirling cryocooler. The system performs background monitoring in spectral bands with low atmospheric transmission, which have not been extensively characterized yet.

The payload consists of a commercially available infrared lens, a filter wheel for switching between multiple spectral bands and the infrared detector unit.

The image data is passed to the so-called Data Processing Unit (DPU), which handles the processing and storage of the captured image data as well as the controlling of the payload's subsystems. This system can be seen as a successor to the DPU currently flying on the Kent Ridge 1 microsatellite [19]. The MWIR payload of ERNST is described in more detail by Horch et al. [20].

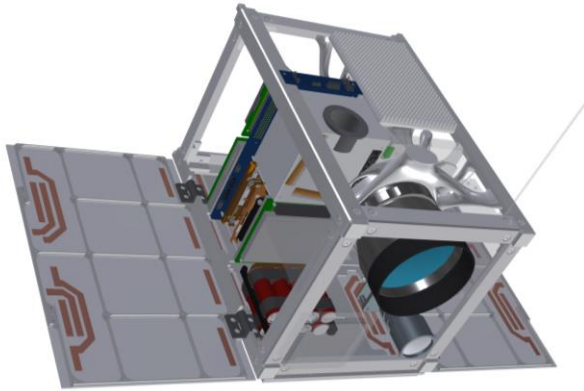


Fig. 3. The ERNST nanosatellite

A simpler optical camera and a radiation detector serve as secondary payload. Parts of the satellite structure make use of additive design and manufacturing methods in order to optimize its behavior for both thermal and vibrational loads from the cryocooler [21]. Gulde et al. [22] describe the thermal design of the satellite and especially the 3D-structured radiator design. For de-orbiting, a drag sail as presented by Sinn et al. [23] will be unfolded.

Most requirements of the MWIR payload (dimensions, mass, power budget) exceed the capabilities of 1-3U CubeSats. Instead of realizing the mission with a commercially available microsatellite bus, we pursue the concept of building a 12U nanosatellite from components designed for smaller CubeSats. As stated above, the 12U format exceeds the definition for nanosatellites and ERNST indeed has a mass above 10kg. Nevertheless, the design philosophy of this project is much closer to CubeSats than to much larger microsatellites, which leads us to classify ERNST as a large nanosatellite (cf. Fig. 1).

The satellite is currently being integrated at Fraunhofer EMI and will be available as an engineering model by the end of 2017. Subsequently, thermal vacuum, vibration, and radiation testing will be performed, further pursuing space qualification.

The purpose of the ERNST project is the evaluation of the utility of a 12U platform in comparison to both smaller CubeSats and larger microsatellites. The question is whether it is possible to integrate a sophisticated payload that would usually require a larger platform into a satellite that is built from existing CubeSat subsystems as much as possible. In order to answer this question we

have evaluated the solutions currently on the market and have chosen suitable components that fulfil our requirements. Where suitable components are not available, we develop our own solutions. In particular, ERNST uses an On-Board-Computer (OBC), electrical power subsystem (EPS), and a UHF transceiver (COM) from GomSpace, an integrated attitude determination and control system (ADCS) from Berlin Space Technologies (BST), which is a larger version of the one described by Segert et al. [24], and an X-Band transmitter from Syrlinks [25].

Combining subsystems from different vendors together with the requirements of a very demanding main and two secondary payloads lead to some specific challenges that will be discussed in what follows.

2. Challenges

2.1. Power supply and distribution

There are several strategies when it comes to power distribution in CubeSats. There is no doubt that separate overcurrent protection per subsystem can help mitigate latch-up effects. Nevertheless, different missions follow different philosophies regarding the implementation of the protection: it can be done centrally at the electrical power subsystem (EPS) or locally at each subsystem.

A similar design question arises about power distribution. The two main options are either one or few shared power busses that are used by multiple subsystems or individual power lines per subsystem.

For the ERNST mission, we implement individual power lines with central overcurrent protection at the EPS. This is one of the most common options with current CubeSats [10] and, as we believe, also the most reasonable one from an operational point of view. To have a single entity that does all power switching and measuring eases the collection of telemetry data and the commanding of the satellite.

In view of the fact that ERNST combines subsystems from many different vendors, it is also the cleanest solution. Central overcurrent protection is required for all systems that do not have local protection, while it is redundant for those systems that have it. The same is true for power switching and measurements. Some subsystems can be switched on and off via the data bus or with dedicated signals, others not. The viable solution is to have all switchable output channels at the EPS.

Another important topic is voltages and voltage regulation. ERNST needs 3.3V, 5V, 12V and 18V power rails. 18V are required for the cryocooler in the MWIR payload. Due to this relatively high voltage, ERNST has a nominal battery voltage of 29.6V instead of the more common 14.8V. Some subsystems come with their own voltage regulators and are intended to be supplied directly from the battery voltage rail on the stack connector. For most of our subsystems, this is not feasible, as they cannot handle such high battery voltages.

The solution is to use a regulated 12V output from the EPS for those systems. This leads to unnecessary and inefficient doubled voltage regulation, but it is the only option without modifying the third-party subsystems.

Taking all this into account leads to a quite complex EPS for ERNST. We chose the P60 EPS from GomSpace since it fulfils all requirements mentioned above. First, it provides 23 switchable and individually protected output channels at five different voltage levels. Second, all power channels are available at the stack connector. Third, GomSpace even allows customizing the pin assignment (within certain boundaries) during ordering.

2.2. Data busses

Traditionally, most CubeSats use I²C [26] as their main communication bus. At the same time, this bus is one of the most unreliable options and seems to cause problems during many CubeSat missions [10]. While more robust data busses like CAN [27] or RS-422/485 [28, 29] seem to become more popular, I²C is still the common denominator that almost every subsystem from every vendor supports.

For ERNST, we chose CAN as our main data bus since all systems from GomSpace and the systems we develop in house support it. Nevertheless, we still have to implement I²C for those systems that do not support CAN. While having multiple masters on an I²C bus is an option, this is only possible if all masters on the bus support the multi-master mode. This is not the case for all subsystems. Especially with Linux-based systems, this is difficult since the Linux kernel does not support multi-master I²C. This consequently requires having multiple I²C busses in the satellite for different masters.

2.3. Stack connector compatibility

Having 23 power channels, CAN, multiple I²C busses and a few other signals on the PC/104 stack connector poses some compatibility challenges. Although not actually standardized, the most common pin assignment provides three power rails (3.3V, 5V and battery voltage) as well as one I²C connection.

Unfortunately, not all vendors allow the customization of the pin assignment in the stack connector and the options for customization that GomSpace offers for their systems have their limits; they mostly focus on the compatibility within their own product family. This is understandable since customizations are costly and interfere with batch production. Nevertheless, the implicit promise of the CubeSat philosophy of plug-and-play compatibility comes to an end very soon when trying to combining different vendors. Even the most basic things like power supply create significant challenges, not even taking into account more high-level compatibility such as communication protocols.

3. Solutions

3.1. The ERNST backplane

As mentioned above, most alternative harness concepts to the common stack of PC/104 boards are only possible if all subsystems are either heavily customized or designed by the satellite integrator themselves. Similar to AISat [18] but for a 12U large nanosatellite instead of a custom-shaped microsatellite, we opted for a backplane concept for ERNST.

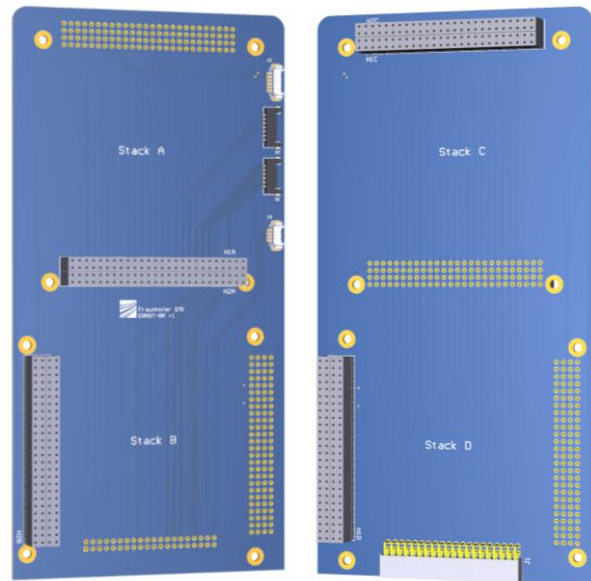


Fig. 4. ERNST backplane (front view and back view) with four PC/104 compatible stacks and a side connector for EGSE.

The backplane itself is a custom PCB with four PC/104 connectors on both sides. Fig. 4 shows a front and a back view of the board. On one side there is also an orthogonal connector where the so-called Flight Preparation Panel (FPP) is connected. This board provides the necessary connectors to the electrical ground support equipment (EGSE) and contains remove-before-flight pins.

The subsystems are arranged in four different stacks that connect to the backplane. Fig. 6 shows the complete arrangement including the FPP. The backplane then maps the different pin assignments for each stack. As mentioned above, this mainly applies to the many different power lines and to the different I²C busses as well as some other signals.

The stacks are composed mainly according to the different vendors. Stack A comprises all bus components from GomSpace and a custom payload board by Fraunhofer, Stack B the ADCS from BST, Stack C contains only custom systems by Fraunhofer EMI and Stack D holds only the X-Band transmitter by Syrlinks. This allows for a pin assignment specifically tailored to each vendor.

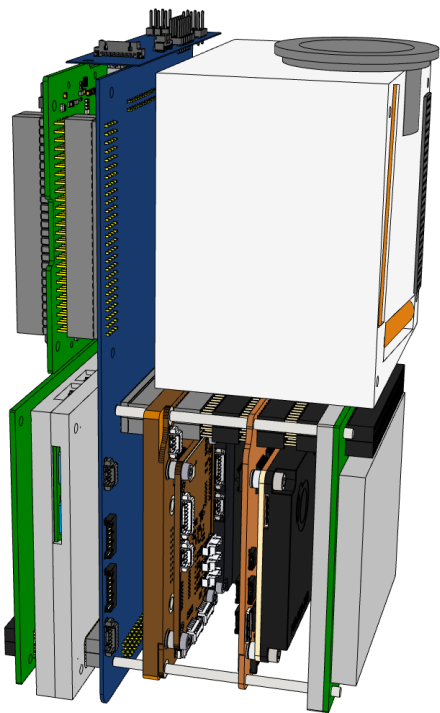


Fig. 5. ERNST backplane (blue) with all subsystems attached.

The backplane is mission specific and cannot be reused. This is not a desired property but it is unavoidable with this concept. Yet, the design of the backplane PCB is not overly complicated after all and can quickly be adapted to other components and pin assignments.

The PC/104 standard leads to some difficulties that have to be addressed in the backplane design. First, the

stack connectors are only available in through-hole technology (THT) and not as Surface Mount Devices (SMD). As a consequence, the front (A+B) and the back (C+D) stacks have to be rotated against each other (cf. Fig. 4). This is unfortunate, because this makes it difficult to arrange all systems in a way that all auxiliary connectors on the side of the subsystems' PCBs remain accessible during satellite assembly.

Secondly, the PC/104 mounting hole configuration is asymmetric. This means that the holes of stacks A and C (B and D) do not fit together. We solve this issue with an additional aluminium frame that will be attached to the backplane and adapts the mounting hole positions between the front and the back stacks.

3.2. Recommendations to the CubeSat industry

Following up on the study by Bouwmeester et al. [10] we would like to round up our contribution with some recommendations to the CubeSat community and especially the subsystem vendors:

- The pin assignment of the stack connector is underspecified. While it is important to have enough room for mission-specific assignments, a higher level of standardization would be helpful. Especially more power channels and more data buses like CAN and multiple I²C busses should be standardized.
- We would like to see more vendors of CubeSat subsystems offer the possibility of customizing the pin assignment on the stack connector. Increasing system complexity and larger satellites require more flexibility in this area. The backplane presented above is a way around, but it would be the cleaner solution if the (mission-specific) backplane were not necessary in the first place.

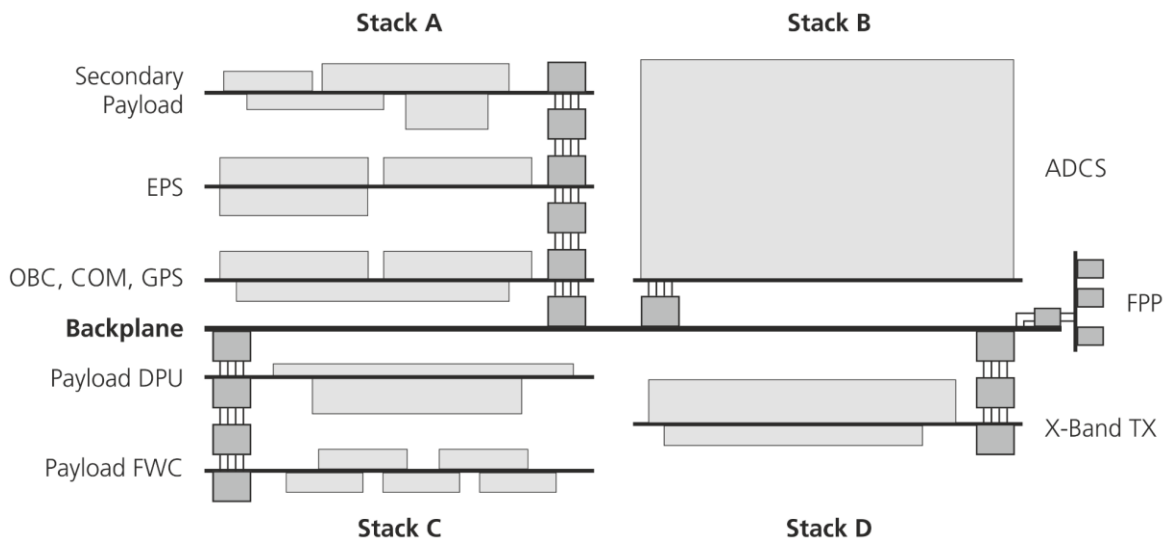


Fig. 6. The four stacks and the ERNST backplane. Each stack is dedicated to a specific vendor of components. On the right, the Flight Preparation Panel providing the EGSE connectivity is shown.

- We recommend against developing proprietary CubeSat hardware that does not implement the common standards. The standardization, as incomplete as it may be, is still one of the core strengths of the CubeSat market and community.
- The PC/104 connector is not an ideal choice. We would prefer a smaller and mechanically more reliable connector that is available as SMD part.

The last recommendation is the most difficult in implementation and is in part contradictory to the second to last. As we pointed out, a maturing market has formed around the PC/104-sized components. Any new developments there would automatically suffer from lacking compatibility with the rest of the market. Nevertheless, we think the additional effort could, in the end, lead to an overall improvement for the market.

4. Conclusions

In this paper, we have discussed the challenges that arise while integrating a large nanosatellite from components on the CubeSat market. As nanosatellites tend to become larger and more complex, the number of components increases and the lack of standardization of the electrical interfaces become more and more obvious. The market already offers many components that do fulfil the requirements of larger systems, but their compatibility is often more problematic than necessary.

We have described the large nanosatellite ERNST, which is the attempt to combine an advanced MWIR imaging payload with bus components from the CubeSat market. For this satellite, we have presented a solution for these compatibility problems: the PC/104 backplane. A backplane board that adapts between different pin assignments allows to combine subsystems from many different vendors.

Finally, we have formulated some recommendations and wishes to the CubeSat industry. More standardization and probably a movement away from the PC/104 standard may lead to improved interoperability and compatibility in the market.

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