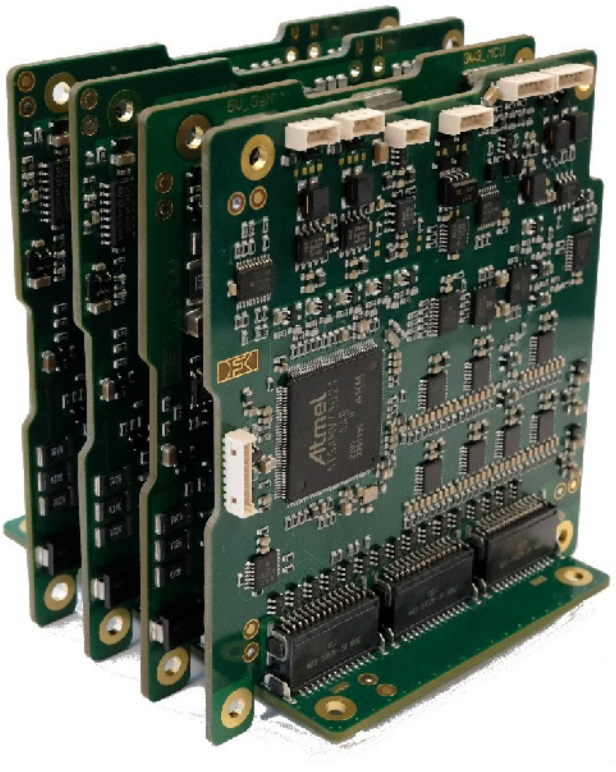
iCOTS

Intelligent COTS based Power Stages for Robotic Applications

Executive Summary Report



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Introduction

From today's perspective, a modular design of commercial computers is indispensable. This allows the simple assembly and exchange of components such as a CPU, GPU, power supply, and storage media. Considering the space domain, the development of CubeSats has shown the massive advantages of modularity and usage of COTS components to reduce the overall development cost. In the long run it is desirable to reuse these concepts in a broader range of space applications.

With the increasing interest in the exploration of celestial bodies, such as the lunar surface, or on orbit servicing the demands on robotic systems for future space missions are constantly increasing in terms of performance and compactness. In this context the actuators and the associated motor electronics play a key role in robotic systems.

The focus of the Intelligent COTS-based Power Stages (iCOTS) project is on the development of a modular demonstrator for the evaluation of power electronics of BLDC motors for robotic applications in space based on COTS GaN-FETs. The modularization of motor electronics down to the component level represents innovation potential as this significantly reduces the dimensions and complexity of monolithic electronics in space application.

The main objectives of the proposed project consist of the following aspects:

- Design and implementation of a BLDC power stage for robotic space application
- A modular design for the evaluation of power electronics in robotic space application based on COTS GaN-FETs
- Definition of the design process and the appropriate selection of COTS components
- Radiation test of selected COTS components

The initial goal of this activity was to test a new test approach. Instead of using black box tests to perform radiation tests of an entire electronic assembly we proposed to perform module tests. From our point of view this could be a good trade off between black box tests and component tests with a high amount of effort.

Within the initial phase of the project, ESA has made the recommendation to perform component test of selected critical components, instead of the proposed sub module tests and focus on heavy ion tests first. Due to the changed project goals and the associated additional effort and expense the risk was identified that not all goals could be reached within the time span of 18 months.

Design and Component Selection Process

The design process followed within the present development is described in Figure 0-1 in its individual steps. This development followed a COTS-based approach envisaged for medium acceptable risk for short and medium lunar mission duration.

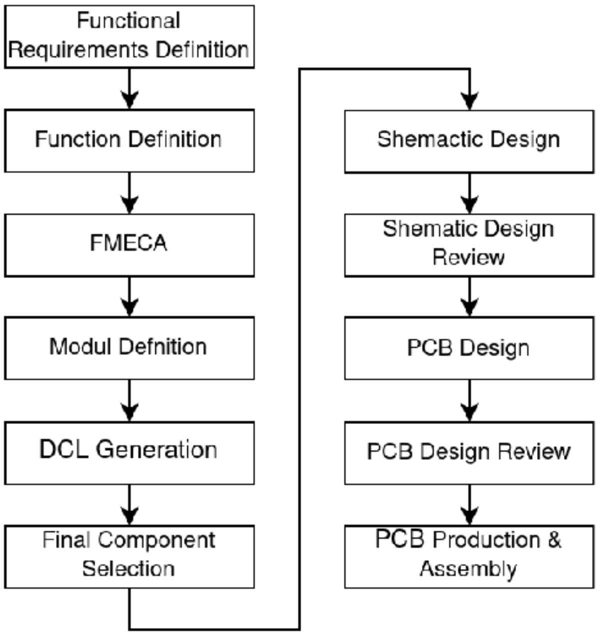

Figure 0-1 The individual steps of the component selection and design process

First of all, the functional requirements were defined followed by a function definition. We have carried out a failure mode criticality and effects analysis (FMECA) to characterize possible failure modes of the power stage and identify most critical components. Following components were identified as most critical for functioning of the power stage as all of them. could cause a fatal failure:

- GaN-FETs
- GaN-FET Half-Bridge Driver
- LCL
- MCU
- FRAM

Next the modules were defined, and the individual functions were mapped to the modules under the condition of a modular design. With the identified critical functions as basis a declared component list (DCL) was generated. The DCL was used to identify the critical components for which radiation tolerance could not be confirmed by design or test. In the case of the GaN-FETs, the half bridge drivers, and the LCLs two candidates each were selected to be foreseen for future radiation test campaign to characterize the behaviour of the selected components in heavy ion environment. We selected the COTS components to be used, as far as possible, according following selection criteria:

- Package processability,
- derating inline with ECSS-Q-ST-30-11C Rev.2 (Derating EEE components)) or higher,
- automotive rating (AEC-Q 100) preferred over industrial temperature range (−40 ◦C to +85 ◦C),
- ITAR free components

Functional Design

Functional Modules

Following a short overview of the functional modules and its functionalities. In **Fehler! Verweisquelle konnte nicht gefunden werden.** are depicted the functional units (Backplane, PSU, Power Stage, and MCU Board) and its main building blocks.

BLDC Power Stage

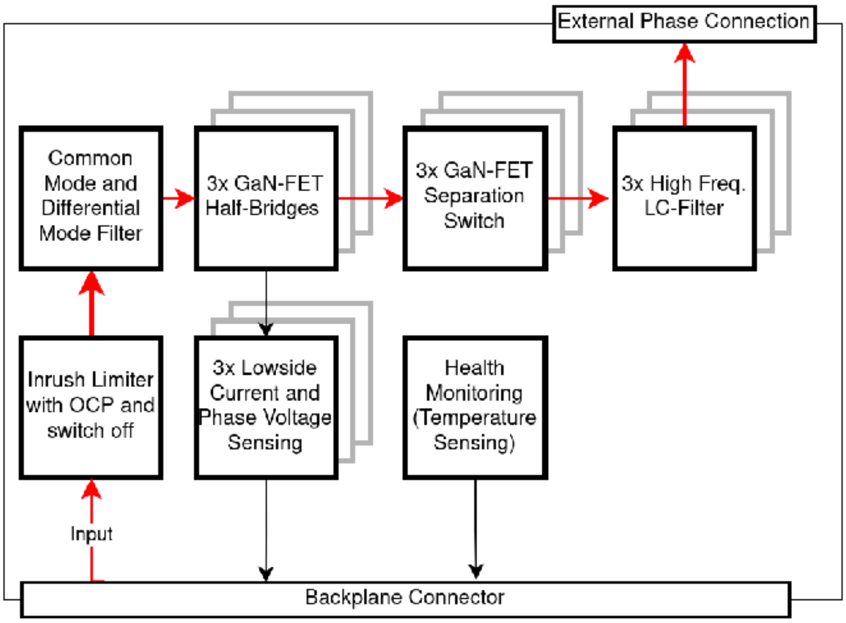

Figure 0-1 Block diagram of the BLDC power stage board

The BLDC power stage board is supplied with 28 V dc via the backplane. It has an inrush limiter with over current protection and switch off functionality. The power stage implements a common-mode and differential mode filter. Each phase can be separated and is filtered with a high frequency LC-filter. There is a low side current and phase voltage measurement for each phase. The external phase connection is on the upper side of the PCB and is not over the backplane.

BLDC power stage main features:

- Current Limiting P-FET separation switch for 28V input (similar to an LCL)
- Based on GaN-FETs (higher switching speed, lower losses, smaller PCB design)
- 28Vin 5Anom/12Apeak (suitable for 100W and above motor class @ 28Vdc Supply)
- 30-100kHz PWM (50 till 100kHz will be beneficial)
- Phase separation switch for redundant power stage option

PSU

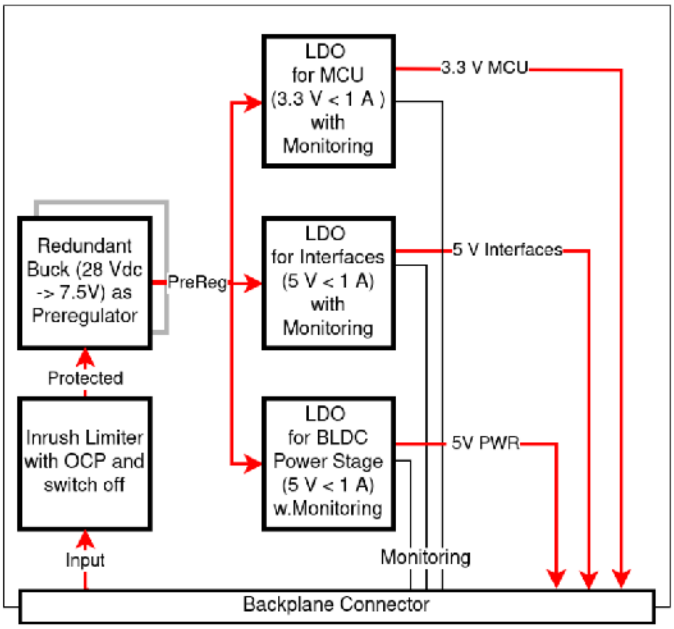

Figure 0-2 Block diagram of the PSU board

The PSU board (block diagram depicted in Figure 0-2) is directly connected to the 28 V dc. It has an inrush current limiter that can also serve as a disconnector. Two redundant switching power supplies (buck / step-down topology) in hot or cold redundancy (user-defined) serve as pre-regulators and generate approximately 7.5 V output voltage from the 28 V dc. These 7.5 V are converted via LDO to 1x 3.3 V (for the MCU) and 2x 5 V (for the interfaces such as CAN bus, and RS422 and separately for the power output stage).

Backplane

- Makes it possible to exchange individual modules
- No cable connections between the boards
- Different backplanes possible for different test setups or configurations

MCU

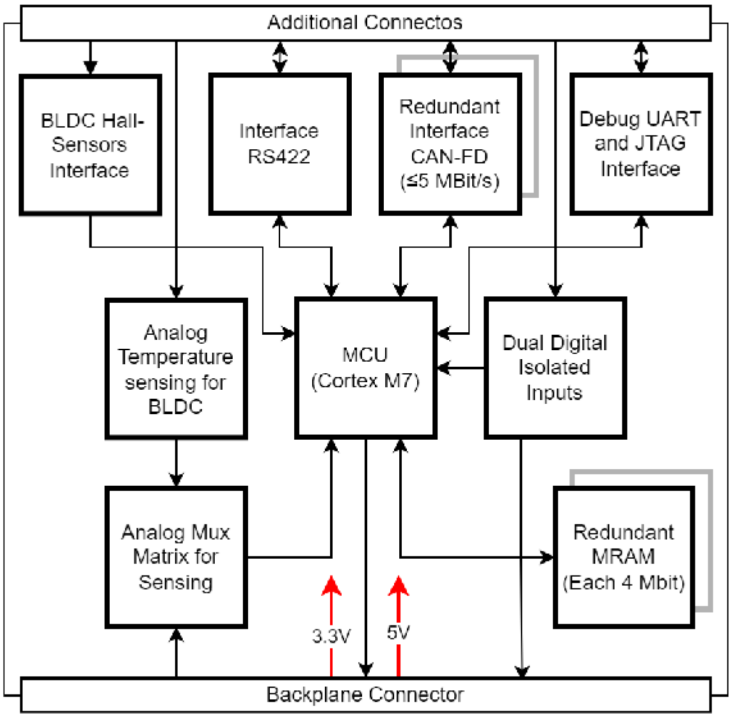

Figure 0-3 Block diagram of the MCU board

The MCU board (block diagram depicted in Figure 0-3) is the central unit for switching and control of the BLDC electronic and communication with a higher level system. It implements digital and analog interfaces for switching, control, and sensing. Furthermore, it is equipped with multiple interfaces for communication in operation and debugging. The MCU is based on a Cortex M7 with additional redundant external memory.

PCB Production and Assembly

The assembly of the printed circuits boards was performed in house at DFKI RIC. The SMD assembly was done by automatic placement machine and the SMD soldering process was done in a three-zone reflow oven. As solder we used a SN60PB40 no-clean mixture based on colophony. Conventional through-hole components such as the communication connectors on the MCU board were assembled by hand.

The printed circuit boards and SMD stencils themselves were manufactured by the industrial supplier *Multi Leiterplatten GmbH* and comply with at least IPC-A-600 Class 2 in their manufacturing quality.

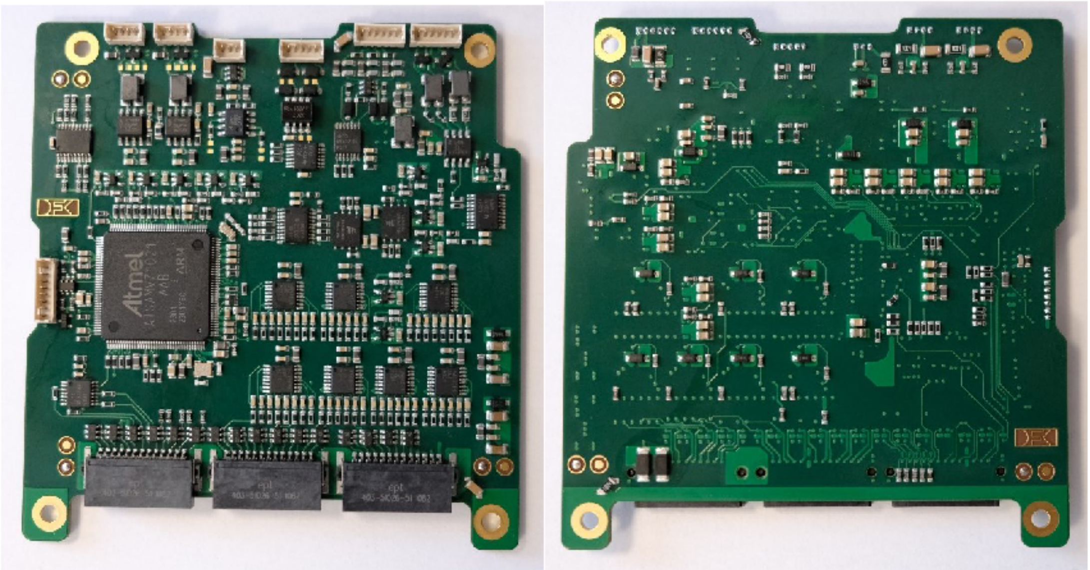

Figure 0-1 MCU board full assembled front (left), backside (right)

MCU

The upper third of the PCB contains the connectors of the interfaces and their electronic components (2x CAN bus, ext. temperature sensor, 2x isolated digital inputs, Hall sensor inputs and a full-duplex RS-422 interface). In the center is the SAMV71Q21, the two MRAM memories and the analog muxer matrix. Below this are the backplane connector contacts. To expose the sensitive highly integrated components to only one soldering reflow process, they are only located on the top side. On the bottom side of the PCB are only resistors, capacitors, and diodes.

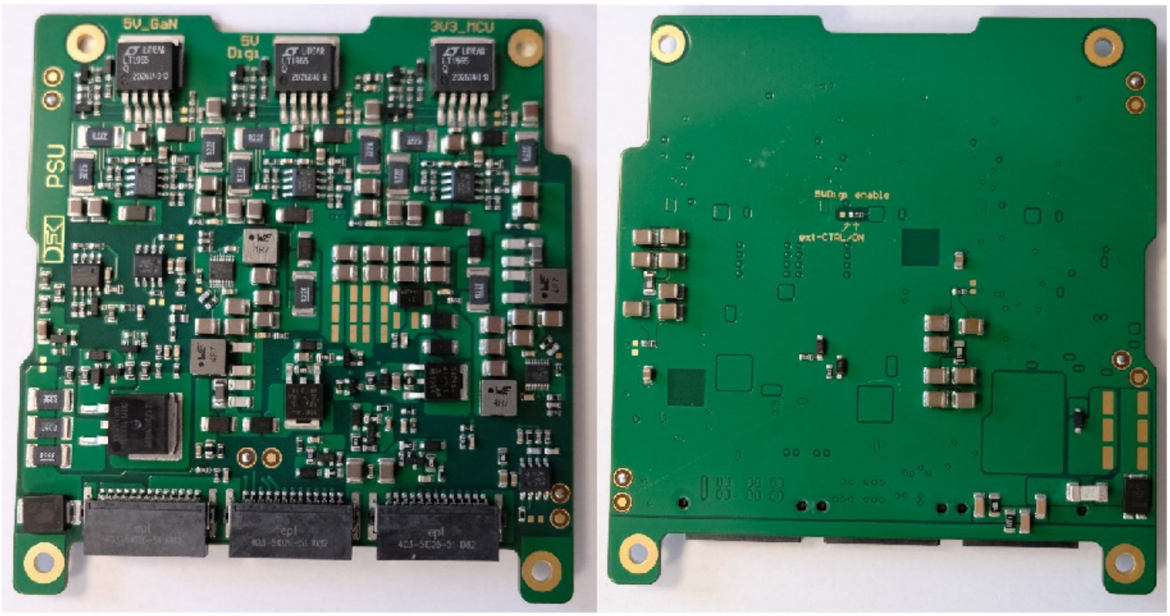

Figure 2 PSU board full assembled front (left), backside (right)

PSU

The three LDOs and their circuitry are provided in the upper third. In the middle the redundant step-down switching regulators and their filters are provided. The P-FET and the current measuring resistors of the inrush limiter can be seen at the lower left. On the bottom edge are the backplane connector contacts. As on the MCU board, highly integrated semiconductors are placed only on the top side to expose them to only one soldering process.

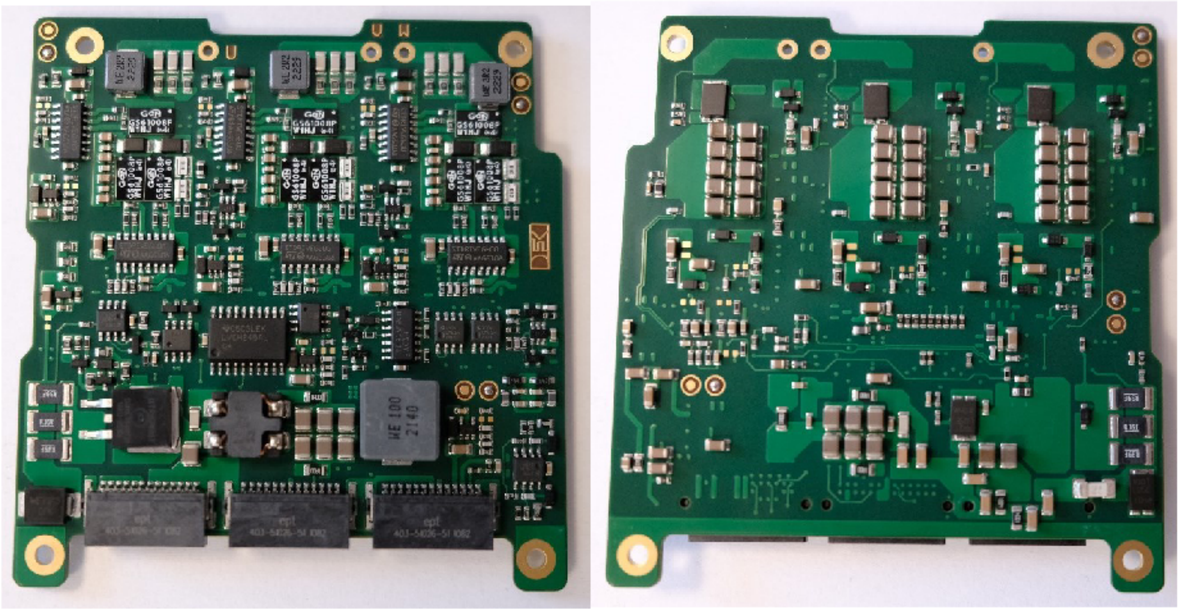

Figure 3BLDC power stage board full assembled front (left), backside (right)

BLDC power stage

The upper half contains the three phases including GaN FETs, GaN FET driver, current measurement including phase output filter. The lower half contains the current measurement resistors and the P-FET of the inrush limiter, as well as the common mode and differential mode filter to suppress electrical interference. The backplane connectors are located at the bottom edge. On the backside there are again no highly integrated semiconductors. Among other resistors, capacitors and diodes, the bulk-capacitors are placed closed to the GaN-FETs in the form of multiple MLCC capacitors.

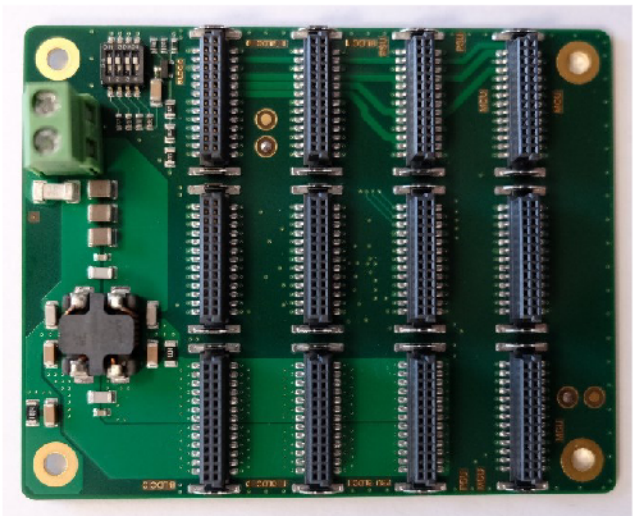

Figure 4 Assembled Backplane

Backplane

The backplane is equipped on one side. Besides a simple HF common mode filter and a 28Vdc input, it contains only the backplane connectors and the routing of the electrical signals for the individual boards among each other, in addition to a DIP switch for configuration of the PSU.

Commissioning and Test of Electronic Boards

The PSU module was plugged separately onto the backplane for commissioning. The backplane was supplied with 28V via a laboratory power supply. On the backplane there are DIP switches to select the redundancy path of the pre-regulators. Thus, both pre-regulators can be selected individually, together, or none of them (both deactivated).

For the first activation we deactivated both pre-regulators.

When the 28V was switched on at the lab power supply, it could first be seen how the inrush limiter with the foldback circuit slowly increased the current. No critical inrush current could be seen.

For the second short test, we activated one of the two pre-regulators and switched on the lab power supply again. We could again see a slowly increasing current flow. In addition, the previously selected pre-regulator activated after some time after its undervoltage threshold was exceeded. Shortly after that, the 3.3 V LDO also activated. We repeated this process for the second pre-regulator with the same result.

It should be noted here that the foldback circuit could be modified, since it allows the current to rise very slowly. Also, the undervoltage threshold of the pre-regulator, which is about 3V according to the data sheet, should be adjusted. Here, a threshold of at least equal to the output voltage would be preferred. These steps could be done without adapting the layouts, because it is simply a case of re-calculate and re-equipping already existing resistors. However, these measures could not be implemented for time reasons.

Because of the missing MCU software, no electrical commissioning could be performed on the MCU-PCB as well as on the BLDC Power stage at this time.

Radiation Test Plan and Heavy Ion Test Electronic Description

Within the activity radiation tests of selected components were planned. For this purpose, a radiation test plan was developed. Furthermore, a modular test electronic for heavy ion test compatible with the mechanical conditions at RADEF, Jyväskylä, Finnland, and UCL, Louvain-la-Neuve, Belgium was designed and implemented.

DUT & test configuration / conditions

Description of the DUTs

Before planning the radiation test campaign, a risk assessment of the iCOTS electronic has taken place to identify the most critical components. In Table 1 the selected parts to be tested.

Table 1 List of selected DUTs

Part Type	EPC2029	LM5113-Q1	STDRIVEG600	FPF2006	FPF2106
Manufacturer	EPC	TI	ST	ON Semi	ON Semi
Part Function	Enhanced Power Mode Transistor	Half Bridge GaN Driver	Half Bridge GaN Driver	Latching Current Limiter	Latching Current Limiter
Technology	GaN-FET	Power BICMOS	Unknown	P-FET / CMOS	P-FET / CMOS
Sample Size	5	5	5	5	5
Ordered Quantity	100	50	100	100	100

For each of the DUTs a break out board was designed for simplified handling and modular design of the test electronic. The DUTs will be mounted on a specific test motherboard. For each part function a different motherboard will be used. Each of the motherboards can mount 5 DUTs. The motherboard is depicted in Figure 0-1.

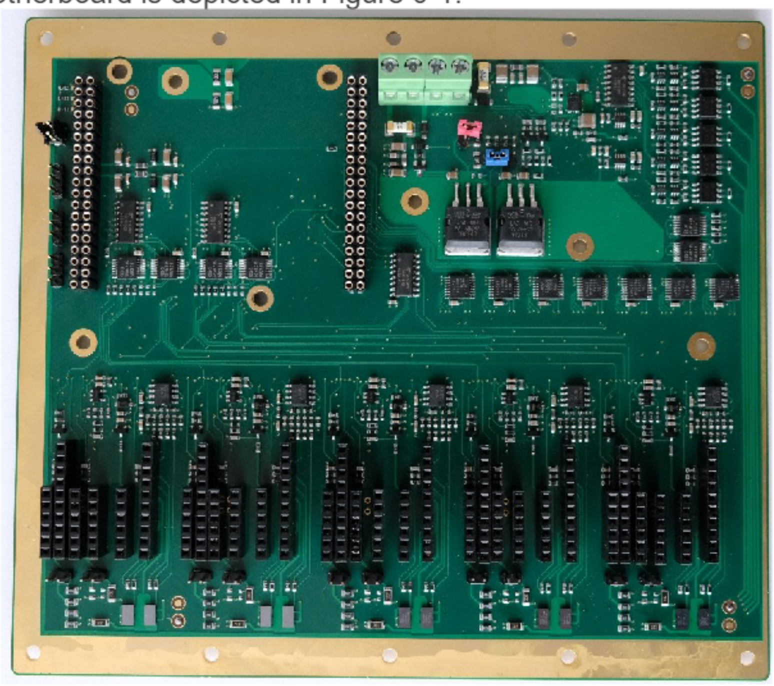

Figure 0-1Modular HIF electronic with five sockets to plug possible DUT modules

Summary and Outlook

Within the iCOTS activity a modular GaN-FET BLDC power stage for robotic space application was designed and manufactured based on selected COTS components. Envisaged missions are high risk missions with short duration in the lunar environment. The power stage is designed for a nominal continuous power of 80 W at 28 V dc bus voltage. Due derating of the critical components it is expected that the power electronic is capable of handling five to ten times higher peak performances. The mechanical dimension of the electronic assembly is compliant with CubeSat standard.

Aside from the design, implementation, and manufacturing of the BLDC power stage a test plan for a heavy ion test campaign was prepared, with the goal to test COTS components which were identified as critical for the design. The selection consists of GaN-FETs, GaN-FET driver and latching current limiter. One alternative was selected for each component type.
For the planned radiation tests a modular test adapter was developed. The test adapter is capable of handling 5 identical component probes. Each of the probes is placed on a separate socket using a small carrier. Due to the modular design, we were able to reduce the complexity and it allows to reuse the adapter board. The opening of the components was contracted to an external company. Unfortunately, the components were destroyed during the decapping.

The decision to perform components test was a deviation from the initial goal of this activity and was not reflected in the initial project planning. Instead of using black box tests to perform radiation tests of an entire electronic assembly we proposed to perform sub module tests.

Within the initial phase of the project, ESA has made the recommendation to perform component test of selected critical components, instead of the proposed sub module test approach and focus on heavy ion tests first instead of TID tests as heavy ions were identified as the dominant factor in lunar environment. The change of the test strategy introduced additional efforts. Consequently, the design and assembly of the electronics was delay as we put our focus on the preparation for heavy ion testing of selected components.
Furthermore, we were not able to perform a full commissioning of the developed electronic within the project schedule.

The next steps are:

- Full commissioning of the assembled BLDC power stage and performance characterization
- Carry out foreseen irradiation tests of identified critical COTS components
- Environmental and EMC test of electronic assembly