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Demonstration of Efficient Aerospace Power Controller Prototyping on the DLR Core Avionic Testbed

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The design of mission specific aerospace power controllers is constrained by cost and development time, often leading to poorly adapted and less then optimal heritage solutions. We want to provide modularity on circuit level to be able to deliver truly bespoke units. This is only possible if manual labor in the development process is reduced by design automation and tailored processes. Our approach is applied to the whole development effort from architectural exploration to detailed design. In this paper we focus on the prototyping stage that aims at delivering a correct-by-design functional model of the product under time and budgetary constraints. We demonstrate the application of our Avionics Design AutoMAtioN Toolkit (ADAMANT) for aerospace power controller design. A functional model of the controller is then implemented using our Modular Breadboard prototyping system. The prototype is demonstrated on the DLR Core Avionics Testbed (CAT), a platform to perform subsystem component tests in a mission like electrical environment. The state of the overall process and toolset development, lessons learned from this first application and future activities are presented.

Key Words: Power System, Design Automation, Verification, Prototyping, HIL

Nomenclature

ADAMANT	:	Avionics Design AutoMAtioN Toolkit
CAT	:	Core Avionics Testbed
COMS	:	COMmunication Subsystem
COTS	:	Commercial Of The Shelf
DAQ	:	Data AcQuisition
DC	:	Direct Current
DHS	:	Data Handling Subsystem
ECAD	:	Electronic Computer Aided Design
EGSE	:	Electrical Ground Support Equipment
EPS	:	Electric Power Subsystem
FET	:	Field Effect Transistor
HIL	:	Hardware In the Loop
LCL	:	Latching Current Limiter
MIL	:	Model In the Loop
OBC	:	OnBoard Computer
PCB	:	Printed Circuit Board
PEBB	:	Power Electronic Building Block
TMCS	:	Test Management and Control System
TMTC	:	TeleMetry and TeleCommand
VTB	:	Virtual Test Bed

1. Introduction

Spacecraft power controller fall mainly into three categories: First are commercial of the shelf (COTS) parts that offer fast lead time and low cost, with the downside of being not optimized for the mission. Second are modular power controllers, that can be configured from pre-defined modules to fit the mission requirements. These are oftentimes much more expensive compared to the first option and time till delivery is much longer. The third option are custom designed solutions that are perfectly adapted to the mission, with the downside of high costs and long lead times. In this work we apply our power controller design process and tools to provide truly bespoke power controllers under time and budgetary constraints. We apply design automation techniques and a rapid prototyping approach to allow for modularity and reusability of functional blocks on circuit level. The focus in this paper lies on the time-efficient deployment of a functional prototype on an avionics development testbed. This ensures early verification of interfaces and behavior together with units from other avionics disciplines, especially the Data Handling Subsystem (DHS).

In the following section 2 we will present the state of the art followed by section 3 with an introduction to our efforts in the area of avionics controller design automation. After this we will introduce in section 4 our prototyping platform for power controllers and how it integrates with the overall avionics development testing facility. In section 5 we will walk through an exemplary application and demonstrate the benefits of the approach. The work is summarized in sections 6 and 7 with lessons learned, a conclusion and an outlook on future activities.

2. State of the Art

The approach to design power electronics by connecting functional building blocks for design reuse and increased modularity is already applied in the utility and industrial sector in form of Power Electronic Building Blocks (PEBBs).[1)] For

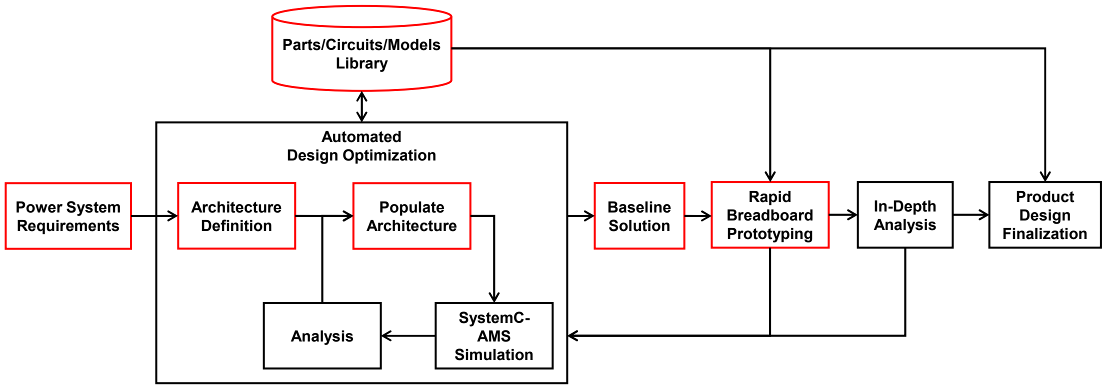


Fig. 1. The automated design process using ADAMANT. Parts relevant for this work are indicated in red.

these applications the PEBBs are units in itself including PCBs and structural parts. The same approach can be also applied on the circuit board itself where the blocks are reduced to electronic components including their connections, arrangement and layout information.[2,3] In these publications mostly identical blocks are replicated and connected to e.g. scale the power handling capability of multi-phase DC-DC converters. Common electronic computer aided design (ECAD) applications like Autodesk® Eagle® and Altium Designer® support the work with reusable building blocks in schematic design and PCB layout and some companies like CELUS© offer platforms for automated electronic design from functional descriptions. These tools are focused on general purpose electronics and the general concept of reusable blocks can be applied to spacecraft power controller design. Full integration in an aerospace development process with a strong emphasis on requirements tracking and design validation/verification necessitates additional effort. This is why we are implementing our own process with accompanying Avionics Design AutoMAtioN Toolkit (ADAMANT).[5]

For this design process we introduce a prototyping solution that allows for a flawless continuation of the design process into the prototyping stage. This setup for verification testing is based on the same Electrical Ground Support Equipment (EGSE) as for Electric Power Subsystem (EPS) testing on system and subsystem level.[6,7] In our case additional instrumentation needs to be foreseen for control and telemetry of the building blocks similar to the testing of PEBBs on printed circuit board (PCB) level.[8] This is necessary as the platform implements functionality related to TMTC that is normally part of the power controller itself. Our approach for the prototyping platform is based on the Modular Breadboard that connects standardized evaluation modules to form a functional model of the desired power controller.[9] Control and telemetry functionality is performed by general purpose equipment[10] and hardware functionality can be replaced by simulation models on a case by case basis combining Hardware In the Loop (HIL) and Model In the Loop (MIL) functionality. This enables to implement all configurations between a hardware prototype and Virtual Test Bed (VTB).[11]

3. Avionics Design Automation

The design of truly bespoke avionic controllers requires the ability to handle the impact of modularity on circuit level during the development time. We are using an automated design process with an accompanying toolkit ADAMANT to achieve this. The overall process is presented in Fig.1 with all parts directly related to this work indicated in red.

The power system requirements, especially the desired output configuration of the power controller, are collected and provided to the design tool. Possible controller architectures are defined that consider voltage level conversion, the capability to control the output state and protection against overcurrent. All valid architectures are then populated with DC-DC converter and Latching Current Limiter (LCL) blocks from a circuit library. Simulations with automatically generated SystemC-AMS models are performed to find the optimal configuration.[12] This performance analysis for the case of power electronic circuits is mainly a calculation of electrical efficiency for relevant operating conditions based on the spacecraft modes. This measure is important for the overall power system efficiency as well as thermal design. Right now, simple mathematical analysis is used, but advanced techniques could be implemented in the future to extract meaningful information from the time series simulation results. These results, will then be used together with other weighted metrics like reliability, mass, cost and needed board space to automatically select the optimal circuit blocks for the application. For the selected baseline solution, the needed artifacts, such as hardware and software configurations, are generated to be able to build the functional model on the prototyping platform. Results from the test-runs are later used to further refine the solution that will be manufactured in the final formfactor for the flight unit.

4. Prototyping Platform

In contrast to the traditional isolated development of the core avionics products we are in the process of combining the design

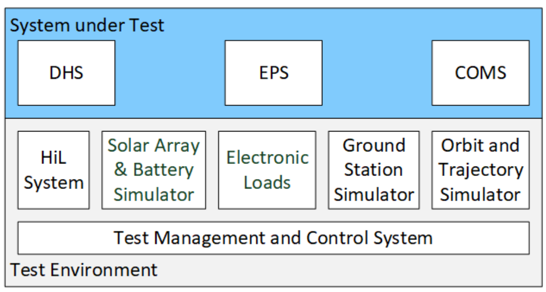


Fig. 2. Main functional blocks of the Core Avionics Testbed.

processes for units related to data handling, power control and communications. This approach reflects in the need to allow for integrated testing in early design stages. To efficiently provide representative power interfaces for avionic equipment's lead to the development of a rapid prototyping solution called the Power Controller Modular Breadboard for use in the Core Avionics Testbed (CAT).

4.1. Core avionics testbed

CAT is a facility for functional verification of space systems on system and subsystem level in DLR Bremen that is fully operational since mid-2022. The focus is on testing core avionics equipment - which includes the electrical power subsystem, onboard data handling subsystem and communication subsystem. The equipment can be verified stand-alone, or in an incrementally completed integral system. Single parts of the system under test can be emulated by the test environment. This allows to verify equipment in an approximately complete functional-relevant environment independently from the availability of all interacting components.

The Core Avionics Testbed provides the test environment that interfaces with a system under test. The environment allows the stimulation of interfaces (generation of representative test signals), as well as test setup configuration, monitoring and control. Fig.2 shows the main functional blocks.

The test environment basically consists of a set of simulation and interface units. The core is formed by the respective counterparts to the core avionics equipment, which are, a solar array and battery simulator together with electronic loads to stimulate the interfaces of the Electrical Power Subsystem (EPS), a ground station simulator to emulate the space to ground link of the Communication System (COMS), and a hardware in the loop system to emulate sensors, actuators and further devices interfacing with the Data Handling Subsystem

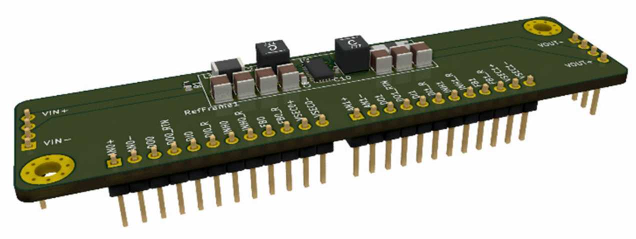


Fig. 3. Evaluation module with DC-DC converter circuit.

(DHS). The test environment is completed by an optional orbit simulator which allows to incorporate environmental conditions to the emulation, such as sun incidence angle for solar arrays and free space loss for the communication system, and to trigger events.

A test run is orchestrated by the test management and control system, which controls the test environment directly and the system under test via the test environment. Its functionality covers test configuration, monitoring and control. Furthermore, it provides the human machine interface for the test engineer.

4.2. Test process

The test infrastructure within the Core Avionics Testbed is optimized for test automation and remote operation through network access. Furthermore, all on-site operations are intended to be paper-free.

The test process is composed of six main steps:

1. Identify & specify test cases
2. Configure test environment and test setup
3. Setup (establish initial state)
4. Run test case
5. Tear down (establish final state)
6. Analyse test results

Each process step is supported by the Test Management and Control System (TMCS). It contains an information model that provides the required context-related information by defining

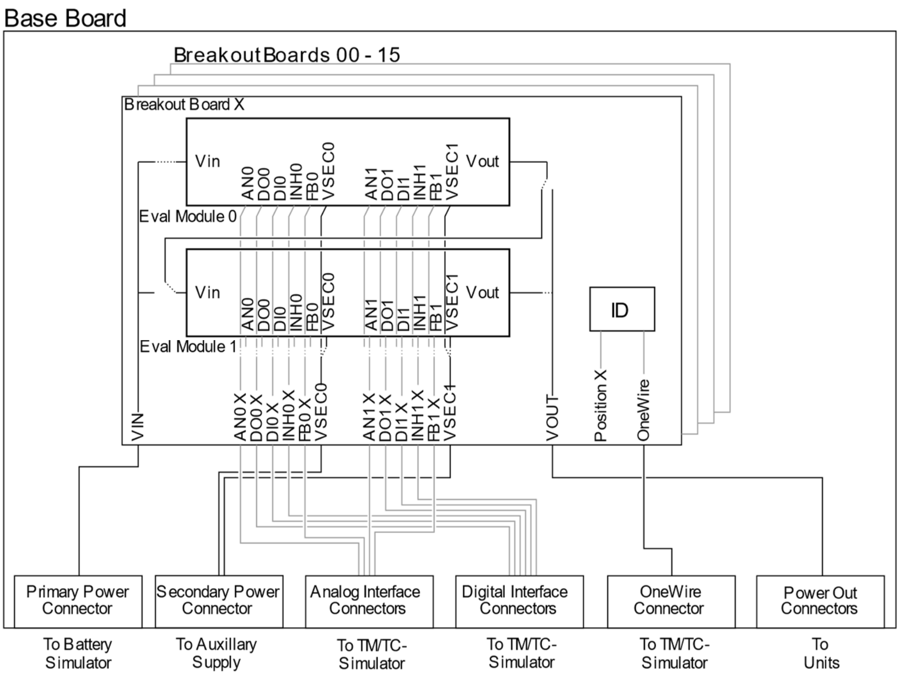


Fig. 4. Modular Breadboard connections between Base Board, Breakout Board and Evaluation Modules.

characteristics and relations of both the test environment and the system under test. This allows to compile arbitrary testcases. A test case is defined by a test configuration, a set of parameters describing the start-, end- and save-state conditions, and a sequence of test steps. A test step basically specifies a stimulus and the expected system response together with some meta data such as termination criteria.

After the physical configuration of the test setup is completed the TMCS supports software configuration and configuration verification. Before a test run is started the TMCS verifies preconditions and establishes the initial state. During a test run it monitors the test setup. In case any termination criteria are meet, e.g. by exceeding certain limit values, or entering illegal system states the test run is aborted and safe state is established. Otherwise the final state is established, after the test run is finished. During the test run all data, including telecommands, housekeeping data and events are directly written into a database. A test report for further analysis can be generated afterwards.

The process described above is applied on all avionic equipment tests in the CAT and is not limited to verification activities related to the power system. The power controller specific part is introduced in the following section.

4.3. Power controller modular breadboard

The Modular Breadboard supports the design process of power controllers from functional building blocks in the prototyping stage. For this a module formfactor with standardized interface for power controller circuits is needed. This so-called Evaluation Module is depicted in Fig. 3. The small size of 90 mm x 23 mm results from the requirement of efficient packing when used for radiation testing, but is sufficient for the implementation of most single-function circuits found in power controllers. It has two four-pin headers for power in- and output, as well as two 12-pin headers for control and measurement signals. The pin assignment and signal types are well defined to allow for easy exchange of modules with the same function but different implementation. A list of the available pins with their respective function can be found in Table 1.

Differential analog output range is defined to -10V to +10V, digital in- and outputs are assumed to be in the 0V to 5V range. Thus, all signals are compatible with off the shelf data acquisition equipment.

Table 1. Evaluation Module command and telemetry pin definition. x is either 0 or 1 based on port.

Pin Name	Function
ANx+ ANx-	Differential Analog Signal
DOx	Digital Output
DOx_RTN	Digital Output Return
DIx	Digital Input
DIx_RTN	Digital Input Return
INHx	Inhibit Input
INHx_RTN	Inhibit Input Return
FBx	Analog/Digital Feedback Input
FBx_RTN	Feedback Return
VSECx+ VSECx-	Secondary Voltage Supply

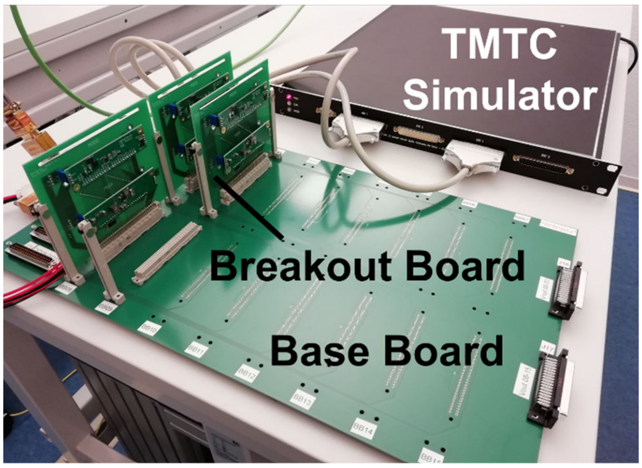


Fig. 5. Modular Breadboard Setup consisting of Base Board with three Breakout Boards and TMTC Simulator in the CAT.

To form a prototype of a complete power controller multiple Evalauation Modules need to be connected. For this the combination of Base Board and Breakout Boards is used. Each Base Board can accommodate 16 Breakout Boards and provides connectors to interface with the rest of the Modular Breadboard setup, as well as the testbe
d. One or two Evaluation Modules can be mounted on each Breakout Board either in a series or parallel configuration, depending on the power controller architecture. The set of command and telemetry signals available on a Breakout Board are the same as on a single Evaluation Module. The way the different signals are connected to the outside world can be selected via solder jumpers. This is illustrated in Fig. 4. For initial connection tests a dedicated Breakout Board is configured as loop-back module. For this the digital input lines DI0 and DI1 are connected to the analog signal lines AN0 and AN1, the inhibit inputs INH0 and INH1 are connected to the digital outputs DO0 and DO1. This module can also be used for semi-automatic platform verification, before the Modular Breadboard is configured with functional modules. With this approach the functionality of the data acquisition hardware, as well as the high number of harness connections can be tested, before configuring the setup for a test campaign.

The equipment that takes care of digital signal generation and analog and digital signal acqusition is called the TMTC Simulator. The name stems from the fact that it simulates the functions of the part of the power controller handling telecommands and telemetry, normally implemented using a microcontroller or FPGA. It is a custom 19” rack unit that houses multiple USB DAQ devices, a Raspberry Pi single-board computer, a USB-Hub and 5V power supply. The decision to custom build this unit instead of purchasing off-the-shelf equipment is based on the need to have 32 differential analog inputs and 96 digital I/O in a convenient form-factor with easy to handle connectors e.g. DSUB. Additionally there was the requirement that Python shall be used as scripting language on Linux OS through-out the setup. This is why one USB-DIO96H/50 and four USB-1608G-OEM by Measurement Computing Corporation© where purchased. These DAQ devices are providing excellent APIs for C++ and Python under Linux. The software on the single-board computer allows the control of all DAQ devices vie Ethernet in the form a clear-text protocol using a simple network socket connection. The whole hardware setup as implemented in the CAT is shown in Fig. 5.

ID	Name	Description	$V_{in,min}$	$V_{in,max}$	R_s	$I_{out,max}$	
5c073c90-5fdc-11ec-b017-5c879cd02c89	ADM1270	LCL with ADM1270	4.0	60.0	0.014	10.0	Delete

ID	Name	Description	Type	$V_{in,min}$	$V_{in,max}$	$V_{out,min}$	$V_{out,max}$	V_{drop}	$I_{out,max}$	Efficiency Data Present	Delete Entry
39e4ed78-5fdd-11ec-b1c1-5c879cd02c89	LT8613	DC-DC Converter with LT8613	Buck	3.4	42.0	0.97	12.0	1.0	3.5	☑	Delete

Fig. 6. LCL and DC-DC circuits in the in the ADAMANT library.

Name	Description	$V_{out,min}$	$V_{out,max}$	$V_{out,nom}$	$I_{out,peak}$	Mode: Name	Mode: Description	Mode: Duty Cycle	Mode: I_{out}	Mode: Delete Mode	Delete Output
OBC_NOM	Secondary Supply for Onboard Computer Nominal Input	4.8	5.5	5.0	1.0	OBC_STB	Onboard Computer Standby Mode	0.5	0.2	Delete	Delete
						OBC_SCI	Onboard Computer Science Mode	0.5	0.8	Delete	
PL_NOM	Secondary Supply for Payload Nominal Input	4.8	5.5	5.0	1.0	PL_STB	Payload Standby Mode	0.1	0.1	Delete	Delete
						PL_SCI	Payload Science Mode	0.7	0.7	Delete	
						PL_OFF	Payload Supply Deactivated	0.2	0.0	Delete	

Fig. 7. Output definition in ADAMANT.

5. Demonstration

To demonstrate the process of efficient power controller prototyping in the CAT using the Modular Breadboard we will describe all steps from initial requirements to the functional prototype. A simplified configuration is picked based on circuits that are already in use for an in-house developed avionics controller.

5.1. Circuits

We use two circuits that have been utilized before and are already available in the Evaluation Module formfactor due to previous radiation tests. The first one is a DC-DC converter module based on Analog Devices LT®8613 synchronous step-down IC. On the module the enable function is present on INH0, the power good signal on DO0 and the signal from the internal current sense amplifier on AN1. There are additional signals present that have not been used for this work. The second circuit is an LCL based on Analog Devices ADM1270 input protection IC. It uses an external P-channel FET to control the power flow to following devices. The Evaluation Board for this part features the enable functional on INH1 and the fault signal output on DO1. The current is measured by a Texas Instruments INA195 current sense amplifier. It is powered by the VSEC1 pins and the output signal is present on AN1.

5.2. Design process in ADAMANT

The ADAMANT application is web-based tool developed in Python using the framework Flask. For simulations SystemC-AMS code is generated, compiled, executed and the results are

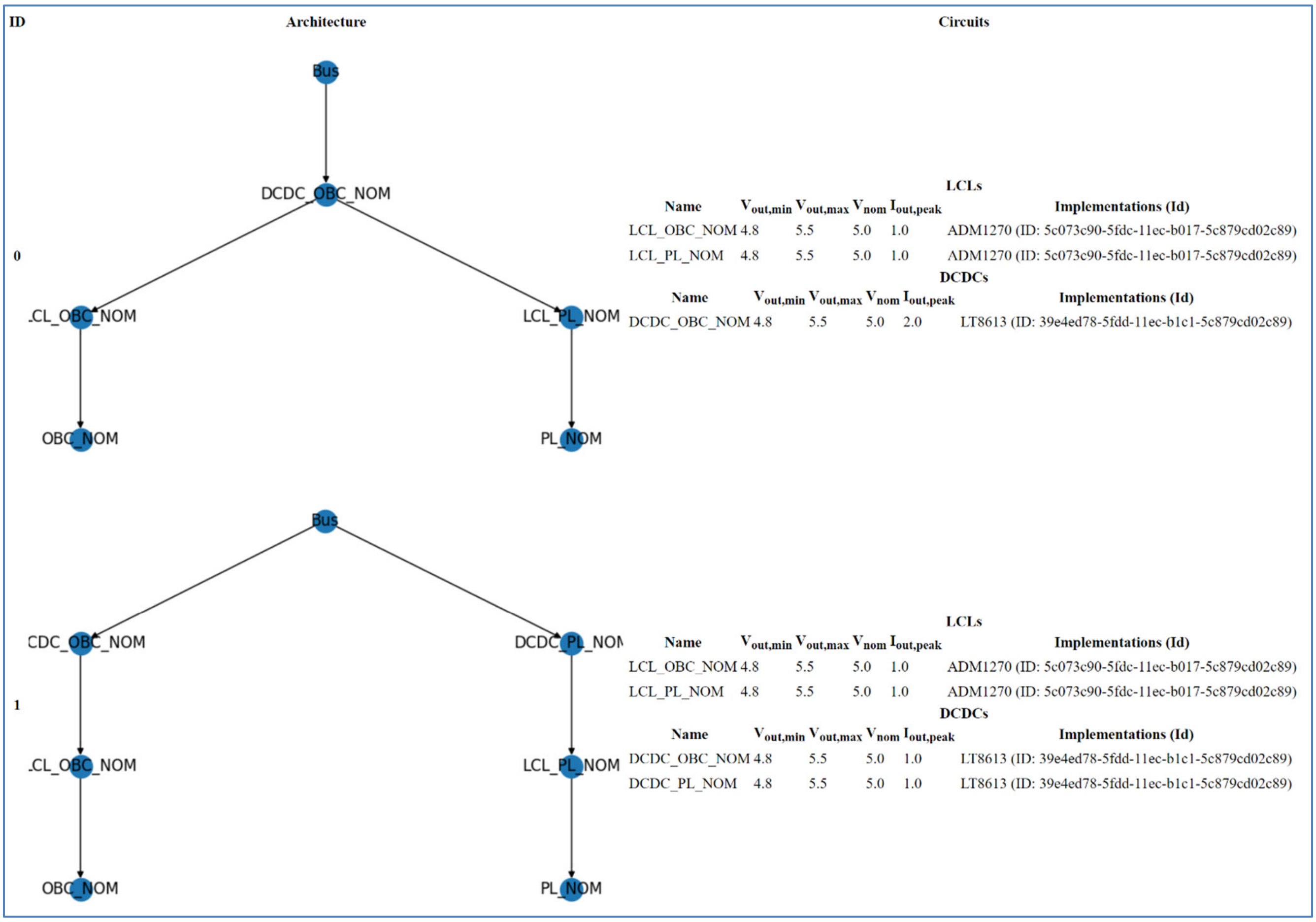
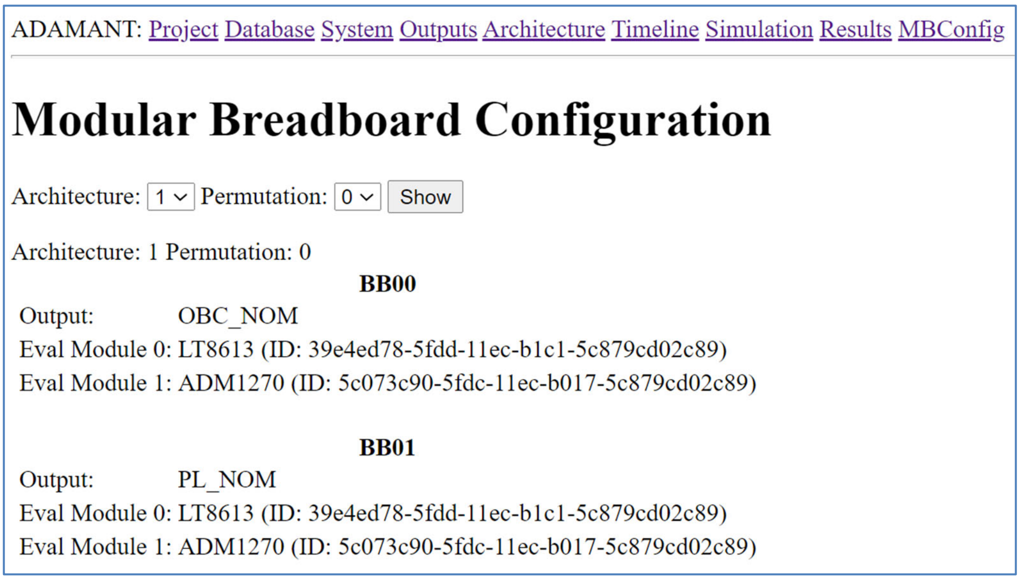


Fig. 8. Resulting architectures in ADAMANT.



ADAMANT: Project Database System Outputs Architecture Timeline Simulation Results MBConfig

Modular Breadboard Configuration

Architecture: 1 Permutation: 0 Show

Architecture: 1 Permutation: 0

BB00

Output:	OBC_NOM
Eval Module 0:	LT8613 (ID: 39e4ed78-5fdd-11ec-b1c1-5c879cd02c89)
Eval Module 1:	ADM1270 (ID: 5c073c90-5fdc-11ec-b017-5c879cd02c89)

BB01

Output:	PL_NOM
Eval Module 0:	LT8613 (ID: 39e4ed78-5fdd-11ec-b1c1-5c879cd02c89)
Eval Module 1:	ADM1270 (ID: 5c073c90-5fdc-11ec-b017-5c879cd02c89)

Fig. 9. Modular Breadboard configuration as presented in ADAMANT.

read back for analysis and visualization in the browser. Right now, the tool uses plain HTML and is therefore quite sparse from the user interface point of view.

First of all, it must be ensured that the circuit library for LCL and DC-DC blocks is up-to-date. The library tables for both kinds of circuits are shown in Fig. 6. For illustration purposes only a single circuit is present in each library.

The second step is to define the output configuration of the power controller. Fig. 7 shows the resulting table in ADAMANT. Next to the strictly necessary information for the prototype, like nominal voltages and peak current there is also information about the equipment modes. In this case for the imaginary equipment OBC_NOM (Onboard Computer Nominal) and PL_NOM (Payload Nominal) there are multiple mode definitions that would be used for finding the optimal power controller architecture and circuit selection. For this example, this is not necessary. Both equipment expect a 5 volt power supply, with each unit consuming a maximum current of 1A peak defined in the values for $V_{out,nom}$ and $I_{out,peak}$.

The resulting possible architectures are shown in Fig. 8. As expected with only this limited number of circuits, the design process results in two possible solutions: ID 0 using a single DC-DC converter block with two LCLs providing the power to the two equipment and ID 1 using separate converters followed by an LCL. If the library would be filled with more circuits, this would result in multiple implementations for each node in the architecture graph.

For the demonstration we choose the architecture with ID 1 to implemented in hardware. The configuration of the Modular Breadboard is presented in ADAMANT as a table shown in Fig. 9. For this two Breakout Boards need to be configured each with one LT8613 module in slot 0 and one ADM1270 module in slot 1.

5.3. Modular breadboard hardware configuration

Finally, the Modular Breadboard can be assembled resulting in the overall hardware configuration illustrated in Fig. 10. The main bus of the Base Board is connected to a battery simulator inside the Power EGSE Rack. In this scenario it applies 28V to all of the Breakout Boards. Commands and telemetry are handled by the TMTC Simulator via multiple digital and analog

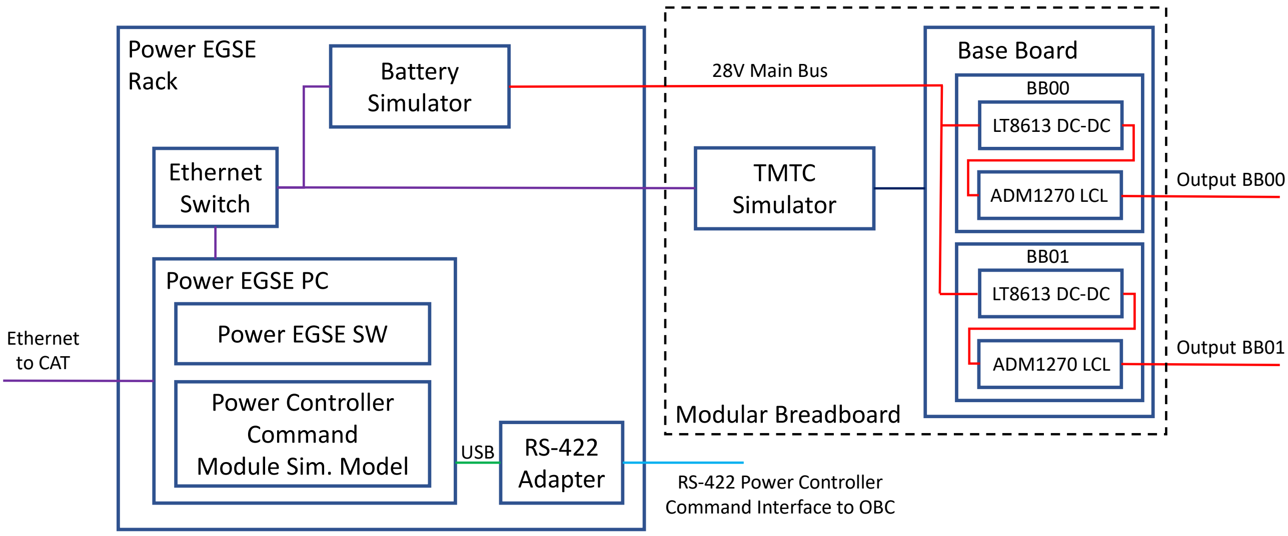


Fig. 10. Modular Breadboard Configuration as implemented in the CAT.

signal harness connections. The battery simulator, TMTC simulator and Power EGSE PC are present on the local ethernet network for common control by the CAT TMCS. An additional USB to RS-422 adapter is used to provide a data interface to the OBC, acting as flight representative interface to the power controller.

5.4. Modular breadboard software

There are multiple software components involved in the operation of the setup. The TMTC simulator software provides a clear text network socket interface for controlling the Modular Breadboard and to acquire measurement data. In case of direct control by the TMCS, the Power EGSE Software handles the translation between the CAT-wide protocol and the specific protocols for the battery simulator or TMTC Simulator. In the case that the Modular Breadboard shall embody a flight-like power controller behavior the Power Controller Command Module Simulation Model is employed to translate between the onboard protocol of the OBC on a serial RS-422 or RS-485 connection, and the protocol spoken by the TMTC-Simulator.

5.5. Initial operation

For the verification of the Modular Breadboard setup first the aforementioned Breakout Board with loop-back connections was used. During this step an assembly error of the DSUB connector gender on the Base Board was discovered, leading to some hardware modifications. In the same way all problems with the DAQ channel assignments in the TMTC software were solved. For the time being the TMTC Simulator was not commanded by the platforms TMCS or the OBC but manually by a command line software developed for this purpose.

The Breakout Boards were configured with the Evaluation Modules as shown in the ADAMANT output in Fig. 9. After setting the INH0 line high the output voltage of the DC-DC converters was measured. For both modules this value was in specification, therefore it was continued by activating the LCLs by setting INH1 high for both Breakout Boards. The Outputs were confirmed to be switched on so that the 5V where present. After applying 5V to the VSEC1 secondary voltage rail on the Modular Breadboard the analog and digital telemetry signals could be checked. The current sense amplifier outputs and power good signals acquired by the TMTC Simulator measured as expected. At this point the setup would be ready for an operational campaign in the CAT.

Further verification activities including control of the Modular Breadboard by the TMCS or OBC, as well as connecting real equipment as power users could not yet be performed. These activities are planned in the near future for the first overall CAT demonstration campaign.

6. Lessons Learned

The Evaluation Module formfactor with its well-defined interfaces has demonstrated its benefits not only for use in the Modular Breadboard setup, but also for numerous radiation tests. DC-DC and LCL modules based on it have also been used for initial prototyping of a deployment controller used in a launcher demonstrator and for building specialized EGSE equipment. Especially the availability of pre-defined PCB templates and clear interfaces reduces the likelihood of errors in test setups. Tests performed on Evaluation Module level are also comparably time and cost efficient, leading to less design errors in more complex PCBs that contain a high number of these building blocks and would be expensive to re-spin.

During development of the Modular Breadboard a trade-off was made between purchasing COTS DAQ hardware or designing it in-house. The decision toward a unit assembled from commercially available parts was taken to reduce the number of work hours. In retrospect the effort for internal cabling inside the TMTC Simulator and harness to connect to the modular breadboard might offset the initial assumptions. A custom solution with integration of the DAQ hardware on the Base Board itself might have a lot of benefits. A downside of this option would have been the development effort for the embedded software running on the microcontrollers that take care of data acquisition and communication. Apart from the cabling we are very satisfied with the chosen DAQ solution specifically with respect to the available software.

Especially during the initial operation, the quite fundamental self-test function of a loop-back module helped immensely for identifying some errors. It is planned to further improve these kinds of capabilities. For example, the Breakout Boards already contain an ID chip, so that the full hardware configuration on the Modular Breadboard can be determined automatically. Right now, we are limited by the state of the software development. For future developments related to test platforms the software development should be better synchronized to the hardware integration activities. This could result in saving time by using already developed self-test routines compared to manual debugging.

7. Conclusion and Future Activities

In this work we presented the current state of the Modular Breadboard prototyping setup in the Core Avionics Testbed with its initial operation. The configuration of the prototype was generated by ADAMANT, illustrating the connection between electronics design automation and prototyping for avionics power controllers. The ideas behind the setup and its implementation were described. The platform was used for implementing a simple power controller prototype. During the first operation some shortcomings were identified that can serve as input for the implementation of similar platforms.

For the near future our activities will focus on the use of the Modular Breadboard for end-to-end avionics testing in the CAT. This will include the demonstration of control of the power controller prototype by the testbed during campaign preparation and the Onboard Computer during the test runs. One goal is also to fully implement the co-simulation of power circuits that are not present in hardware. This capability would allow to have a full set of telemetry, even with a reduced hardware setup. This function will be based on the SystemC-AMS simulation capability already used for system level power system simulation. Additional effort will be spent on the improvement of self-test and configuration checking functionality. Overall the link between ADAMANT and the Modular Breadboard needs to be strengthened by allowing the auto-generation of the configuration for the power controller control logic models.

To enable the more wide-spread application of this technology we plan to design a more cost-efficient version of the setup based on custom data acquisition hardware. This approach could strongly reduce the amount of work necessary for building a setup as the amount of cabling would be reduced significantly. Publication of the hardware design and software as open source would also allow for adoption outside of DLR.

Further information related to this work including design files for some hardware components can be found on the following DLR GitHub page: https://github.com/DLR-RY/power-controller-prototyping-example.

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