CONTROL DRIVER ELECTRONICS FOR MINIATURE PULSE TUBE COOLERS

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ABSTRACT

A novel CDE (Control Driver Electronics) design, based on integrated digital control architecture (with FPGA), for powering and control the MPTC (Miniature Pulse Tube Coolers) is presented in this paper. This CDE was developed in the frame of the ESA Technology and Research Programme in order to attend the needs for space qualified electronic devices to deal with the MPTC functional and electrical requirements.

The input and output electrical power requirements are disclosed, along with the Linear Motor's Voltage and accurate Cold-tip Temperature Control Loops performances. Besides, additional features like the input power bus current ripple reduction and the exported vibration cancellation are also presented. Then, the digital TM/TC functionalities are introduced and finally the overall performances obtained in the formal test campaign of an EM prototype are verified.

1. INTRODUCTION

MPTC are an alternative to the classical Coolers like Stirling or Gifford-McMahon. The main advantage of the MPTC is their lack of mobile parts in the cold terminal, which solves some problems of the classical Coolers such as the exported vibrations and reliability. Besides, the last generation designs of MPTC achieve better cooling efficiency than the classical coolers for the same cooler's size.

These MPTC are based on a passive Pulse Tube Cold Finger filled with gas (usually Helium), which is submitted to a variable pressure by means of a Compressor. The heat pumping process, from the hot to the cold points of the tube, is performed through the walls of the tube because of the sinusoidal movement of the gas inside of the tube.

The Compressor consists of a dual opposed pistons assembled in the same compressor chamber to optimize both compactness and vibrations reduction. Each piston is supported by a bearing made of two flexure spring packs and is driven by a linear motor. And the linear motor is made of a moving magnet attached to the piston plus a fixed stator coil external to the gas working chamber.

The movement of the linear motors has to be optimized to get the best performances of the MPTC unit in several parameters:

- The *frequency* of the sinusoidal movement should be as close to the *mechanical resonance* of the Compressor as possible to improve the electrical efficiency of the Cooler.
- The *waveform* of movement has to be adapted to correct the mechanical exported vibrations. Therefore, the pistons movement could be none sinusoidal.
- The *transients* (e.g. the MPTC cold-down from ambient) have to be treated carefully to avoid the hitting of the pistons at the end of their strokes.

1.1 Coolers qualified for space applications

Some MPTC has been lately developed for space applications (e.g. scientific and earth observational detector arrays cooling) designed to provide around 1W of cooling capacity, operating in the temperature range of 50-80 K, with an ambient temperature range of -20 to 50ºC.

The main features of these MPTC are now known and they can be outlined as follow:

- Max electrical input Power: 46W.
- Max Compressor Efficiency: 50-70%.
- Mechanical Resonance: in the range of 30-60Hz.
- Exported Vibrations by the Compressor movements are in the range of the first 15^{th} harmonics (the most significant are the 4^{th} and 9^{th})

1.2 Temperature control and CDE requirements

The main function of the CDE is driving the MPTC to carry out a very accurate control of the Cold-Tip Temperature. But it is not the only one, because the CDE is also responsible for:

- Driving the Compressor's linear motors with the right AC power and voltage profiles.
- Carrying out the appropriate regulation close loops for the compressor voltage and the cold-tip temperature.
- Conditioning the signaling feedbacks for TM; in particular, the Cold-Tip temperature sensor and vibration sensors

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- Providing means to cancel the residual vibrations generated by the compressor's pistons movement and the gas compression.
- Providing means to lock the compressor's pistons in the launching of the satellite in order to avoid hitting the end-stops.
- Interfacing with the spacecraft input power bus mitigating the noise injection, particularly the low frequency harmonics generated by the consumption of the compressor.
- Providing a series channel connection with the satellite TM/TC system to take control on the CDE (setting parameters, commanding operational modes, charging waveforms profiles, …) and to carry out the telemetries (Temp., Vibration,…)
- Protecting the Compressor and the Input Bus against failures as Over-Currents, Under/Over-Voltages, Under/Over-Temperatures,…

2 CDE DESIGN DESCRIPTION

The Control Driver Electronics Unit is intended to be the controlling function of the MPTC as well as the interface with the Satellite. Therefore, this Unit not only has to accomplish the very demanding MPTC requirements but also the typical requirements of any Unit connected to the Satellite.

CDE design is adapted to these space requirements, accomplishing the driving of the MPTC in an easy and reliable way, by means of an integrated digital control performed with a FPGA/ASIC. The details of this implementation are presented along this section.

2.1 CDE Overview

This Unit was divided in two sub-modules implemented in two different boards:

- Pre-Regulator and APS.
- Cooler Driver Module.

The "Pre-Regulator and APS" module is responsible for interface with the input power bus as well as for generating the insulation and auxiliary power supplies required for the control electronics. And the "Cooler Driver Module" is in charge of delivering the AC power lines to driver the Compressor's Motors of the MPTC and implementing the remaining requirements. They are described in detail later on this section.

CDE performs the transformation of an input DC BUS of 28Vdc, delivered by the PCDU (Power Control Distribution Unit) of the satellite in 2 AC BUSES of 15Vac_max in opposed phase (~180º de-phased) to drive the Compressor's motors. This unit also monitors all the electrical and thermal variables of the CDE-MPTC system required to carry out the control and telemetries of the functional parameters. Moreover, a series communication channel allows the CDE to accomplish the TM/TC requirements.

2.1.1 Blocks diagram

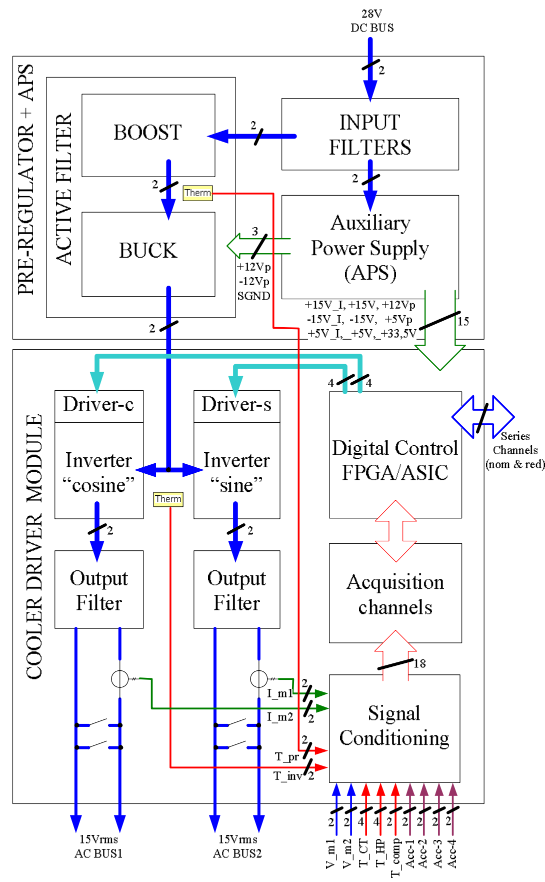
The following diagram shows the Electrical Architecture of the CDE unit, where it can be seen the main functional blocks already described, along with their sub-functions:

- Pre-Regulator and APS:
  - Input Filters.
  - Boost/Buck Active Filter.
  - APS (Auxiliary Power supply).
- Cooler Driver Module:
  - Digital controller (FPGA/ASIC)
  - Analogue Acquisition Channels.
  - Analogue Signal Conditioning.
  - Power Driving Interface.
  - Power Stage.

It can be seen as well, the Input/Output signals of each functional block.

2.1.2 Operational Modes

It can be distinguished several operational modes in the CDE which can be selected by dedicated Tele-commands:



- **Init mode**: It is intended to avoid any unexpected behaviour after a power-on or reset, in order to allow a correct initialisation of the unit.
- **Standby mode**: It is a waiting mode for the start-up command of the unit when the MPTC is stopped.
- **Launch mode**: This mode is foreseen to avoid the pistons hitting of the compressor during the launching.
- **Drive mode**: It is the nominal mode of the unit when the MPTC is working correctly.
- **Calibration mode**: It is foreseen to allow the mechanical characterisation of Cooler (e.g. to find resonances,…)

The mode of the unit will depend on the command received through the series channel but also on the state of the unit itself (launch lock relays state, protections activated,…)

2.1.3 Pre-Regulator and APS Module

This module has two very well defined functions in this unit:

1. **Electrical Power Interface** with the +28Vdc input power bus coming from the batteries of the spacecraft. This module carries out the power filtering from the very low to high frequency current harmonics generated by the Cooler Driver Module, in order to release the Batteries from alternate circulating currents. This task is performed using a passive and active filters placed at the input of the Diver Module. The passive filter is a Common and Differential mode LC filter and the active filter is made of a Boost and Buck stages just in series with the input power bus. Additionally, this module also implements input and output over/under-voltage and over-current protections to avoid the failures propagation of the Cooler Driver to the input power bus.

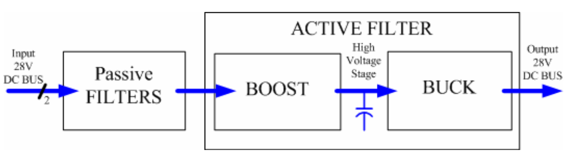


Fig. 2. Pre-Regulator Sub-module

2. **Auxiliary Power Supply** to generate all the insulated auxiliary voltages required for the CDE internal circuitry. This sub-module has reached an important role in this unit because of the amount of insulated voltages required for the internal architecture and the variability of the consumption depending on the functional mode of the unit.

2.1.4 Cooler Driver Module

This is the core of the unit where are implemented all the required functions to control the MPTC. Its most important sub-modules are described hereafter:

1. **Power Stage** is made of two identical “Inverters” for the generation of the sine and cosine voltage waveforms to supply the motors of the compressor. Each Inverter is composed by the following elements: a) One power full bridge built with power MOSFETs and the electronics needed to drive each power MOSFET, b) one symmetric output power filter to eliminate the common and differential mode high switching frequency harmonics of the power PWM generated by the full-bridge, c) one symmetric and accurate output Current Sensor, and d). two relays (nominal & redundant) to perform the passive “launch lock” function and their drivers, which are managed from the FPGA/ASIC control.
2. **Analogue Signal Conditioning** is the sub-module where the analogue signals coming from the internal or external Sensors are conditioned to an adequate signal of voltage with a right value to be interpreted by the Digital Control. The set of analogue signals to be conditioned is high because of the amount of functions involved in the control and surveillance of the MPTC: a) the output ac current demanded by the two motors of the Compressor, b) the output ac voltage supplied to the two motors of the Compressor, c) the Cold-Tip high accuracy Temperature sensing, d) the Temperature sensed in the Hot-Point of the Cooler, e) the vibrations signals measured by four accelerometers, f) the Temperature of the Compressor´s Chamber, g) the Temperature of the Power stage of the Driver’s Inverters and h) the Temperature of the Power stage of the Pre-regulator Active Filter.
3. **Analogue Acquisition Channels** in charge of converting the analogue signals conditioned in the above stage into the equivalent digital telemetry. There are two separated acquisition channels; one of them grounded to the control ground to measure the voltage and currents of the Compressor’s motors, and the other one grounded to chassis to perform temperature and vibration measurements of the external sensors. The resolution of these acquisition channels are 16 bits, although the four less significant bits are not very representative because of the noise in the signals measured.
4. **Digital Controller (FPGA/ASIC)** is the core of the Driver´s control, and implements the main functionalities of the CDE. This sub-module is comprised by a FPGA (ASIC in the flight models of CDE) and some peripherals like EEPROM memory or the insulated series TM/TC channel

transceivers. These FPGA is designed as a "System On-Chip" (SOC) where are included all the hardware block required for the current application. These blocks are split as follows:

- *Communication Block*: used to communicate the CDE with the on-board computer via a full-duplex RS-422 line.
- *Processing Block*: built with the 8051 microcontroller is in charge of processing the commands received from the communication block and controlling the CDE unit.
- *"Launch-lock" Relay Block*: used to control the contact position of the relays of the "Launch-Lock" mode.
- *Compressor's Motors Block*: controls the Voltage and Current of the two linear motors of the Compressor.
- *Analogue Acquisition Block*: used to control the analogue acquisition channel for the Temperature and Vibration Telemetries.
- *Watchdog Block*: prevents the infinite loops in the application software and controls the internal reset.
- *Memory Block*: contains all the memory modules used by the application.

The outputs of this Digital Controller sub-module are the Pulses Width Modulated (PWM) used to drive the two Inverters of the Power Stage.

2.2 Digital Control Function description

As it said above the Digital Control is the heart of the unit. It concentrates the basic functionalities:

- Temperature control loop of the MPTC "Cold-Tip".
- Drivers control loops and PWM generation for the "Compressor's Motors".
- "Launch Lock" handling.
- "Exported Vibrations" Cancellation.
- "Telemetries/Telecommands" interface management.

2.2.1 FPGA/ASIC

The SOC implemented in the FPGA/ASIC of the Digital Control sub-module includes all hardware block already defined and they are represented in the next blocks diagram:

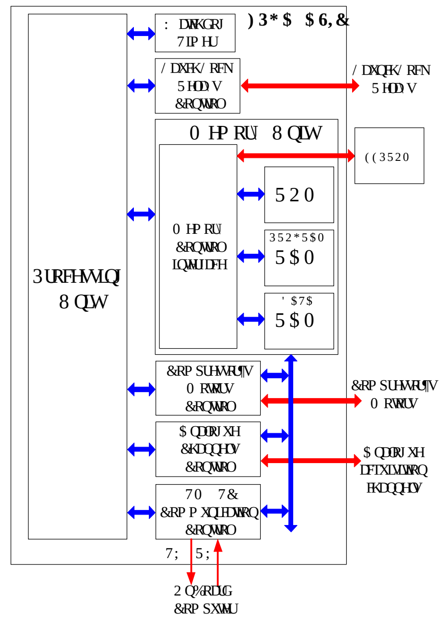


Fig. 3. FPGA/ASIC blocks diagram

The SOC receives the telemetries data required to manage the MPTC control via the interface with the "Analogue acquisition channels", and it also receives the *configuration and setting parameters* via the "TM/TC communication series channel" with the satellite onboard computer. Once the information received is processed in the SOC the results are translated to the convenient digital signals to control the Compressor's motors and the Launch Lock relays.

This novel approach enables the reduction of hardware at the same time as increasing the power of data processing and the flexibility to adapt the *configuration* to any kind of cooling device throughout the communication channel. For example, it is possible to settle the following parameters:

- "Cold-Tip Temperature" set point.
- "Vibration compensation" mode.
- "Amplitude and Frequency" of the first 10th harmonics, including the fundamental.
- Close Loop Controller "Parameters" for the Cooling Temperature and Compressor's Motors
- "Cold-down" curve.

As well as performing several *tele-commands*:

- Start/Stop the CDE unit.
- Change the operational mode (standby, drive, …)
- Reset any protection activated previously.
- Enable/Disable the supply of the Vibration Sensors.
- Memory "Patch & Dump"

Apart from delivering the *Telemetries* required by command for the onboard computer (e.g. Voltages and Currents of Compressor's Motors, Cold-Tip Temperature, Exported Vibrations measurements, etc) and the *Status* of the MPTC and its protections (e.g. ON/OFF state, Operational Mode state, Over-Current, Short-Circuit, Over-Temperature, etc) when some of those events occur or it is required.

2.2.2 Digital Algorithms

This digital control approach has been endowed with accurate and adaptable algorithms qualified to Control any MPTC, because of the "constants" used in these algorithms to perform the close loops regulation can be reprogrammed to achieve the best performances via the series communication channel. Therefore, the control loops will be able to change their behaviour to optimize the regulation of system whichever the electrical, mechanical or thermal features of the MPTC will be.

The following Control Algorithms are implemented:

a) *Compressor's Motors output voltage control*: This output voltage is required to follow a reference-voltage signal consisting of a fundamental frequency plus its first 10th harmonics. This means that the close loop has to reproduce frequencies up to 600 Hz.

   The control algorithm implemented is of the PI type (no differential action) with anti-windup to avoid problems of saturation. Additionally, a separate input for motors current compensation has also been used to improve the transient response of the output voltage close loop. The controller "parameters" can be modified via the series communication channel to configure the CDE unit for the requirements of the specific MPTC in order to achieve the best regulation performances in each particular case.

b) *"Cold-Tip" Temperature control*: The Cold-tip steady state Temperature is required to follow a reference-temperature signal, which will be fixed via the series communication channel with the onboard computer, and it will be in the range of 50 to 90K.

   The structure of the temperature control algorithm is also a PI type (no differential action) with anti-windup to avoid problems of saturation. And its controller "parameters" can also be configured via the series communication channel to adapt the controller to the MPTC's features.

   The resulting output signal of this Temperature control algorithm is used as the input reference-voltage signal for the Compressor's Motors voltage control algorithm. In other words, the Temperature control loop manages the internal Compressor's Motors voltage control loop.

c) *Active "Launch-Lock" control*: This control algorithm can be implemented as an alternative to the "passive" "Launch-Lock" Relays use to protect the pistons of the compressor's motors against hitting the end-stops.

   This algorithm is intended to emulate the effect of short-circuiting the terminals of the compressor's motors as the relay's contact does.

2.3 Protections

The CDE unit has been designed with the needed protections to avoid the single failures propagation to the power interfaces (input power bus and compressor's motors), as well as the "Launch-Lock" relays to protect the MPTC during launching.

a) *Input Under-Voltage protection*: The CDE unit remains stopped as long as the input voltage will be lower than a minimum voltage threshold. This protection prevents the unit to have high input currents during the power on and it allows starting up softly in a known condition.
b) *"Pre-Regulator" Active Filter self-protections*: The Pre-Regulator is protected against internal failures which deal to Under/Over-Voltages. Thereby these internal failures are not propagated to the CDE unit interfaces.
c) *"Pre-Regulator" Output Over-Voltage*: This protection stops the Pre-Regulator when the output Voltage rises above the over-voltage threshold, but a transient voltage suppressor (TVS) device is also use to protect the CDE unit against this failure.
d) *"Pre-Regulator" Output Over-Current*: If the "Cooler Driver Module" demands an over-current from the "Pre-Regulator Module" then the Pre-regulator will limit the current delivered. This way, the CDE unit and the Compressor's Motors will be protected against any short-circuit or unexpected current transient downstream from the Pre-Regulator avoiding the failure propagation to the input power bus.
e) *"Cooler Driver" Output Over-Current(RMS)*: The "Cooler Driver Module" is protected against over-current demands in steady state from the Compressor's Motors.
f) *"Cooler Driver" Output Short-Circuit*: The "Cooler Driver Module" is protected against any short-circuit in the terminals of the Compressor's Motors.

g) *"Coolers Driver" Output Currents Mismatching*: The "Cooler Driver Module" is protected against mismatching between the currents delivered to the Compressor's Motors.
h) *"Compressor" Over-Temperature*: If the Temperature of the Compressor Chamber is higher than the Over-Temperature threshold then the "Cooler Driver Module" will be stopped.
i) *"Pre-Regulator Module" Over-Temperture:* If the Temperature of the Pre-Regulator Module is higher than the Over-Temperature threshold then the "Cooler Driver Module" will be stopped.
j) *"Cooler Driver Module" Over-Temperture:* If the Temperature of the Cooler Driver Module is higher than the Over-Temperature threshold then the "Cooler Driver Module" will be stopped.
k) *"Launch-Lock" Compressor's Pistons Protection:* The Compressor's Motors terminals will be short-circuited during launching with two relay's contacts in redundancy to prevent the hitting of the pistons with the end-stops of the compressor. The states of these relays are checked by the "Cooler Driver Module" to manage them according with the Operating mode of the CDE unit and to detect any possible failures of those relays

NOTE: This CDE unit can also implement the "Launch-Lock" protection in an ACTIVE form. That is, The CDE unit would remain started during the launch, and the Driver Control module would carry out the task of the above relays only controlling the current and voltage applied in the terminals of the compressor's motors.

2.4 Packaging

The housing concept of the box proposed is an assembly of two modules stacked over the base-plate and enclosed by the top cover, by means of assembly screws. The PCB's are installed horizontally, parallel to mounting plane.

I/O connectors selection and layout of module have been optimised in order to minimise the height of the box.

Module stiffener serves as box vertical outer walls. External section of the ribs has a thickness of 3 and 4 mm and the internal ribs have a thickness of 1.5 mm.

The Base Plate will be a machined 2 mm thick plate having a flat contact surface to the platform without internal ribs and external ribs of 4 and 3 mm. This item will have a pattern of mounting feet, total 6 (M4), located along the housing perimeter and machined from a single block providing a continuous flat bottom surface.

The Top Cover is an aluminium sheet 2 mm thick that alloys enclosing the box and provides fixing points for the assembly bolts.

The box is assembled by means of screws, passing through the Top Cover and through the stiffener to the base-plate threaded inserts. The items of the housing are machined parts made of aluminium alloy, having through holes or threaded inserts along their edges to allow an easy assembly, minimising the number of mechanical parts

Fig. 4. CDE (EM model)

The overall dimensions and mass of this box are summarized in the next table:

Length	**206**	mm
Width	**226**	mm
Height	**80**	mm
Mass	**2,75**	Kgr

Table 1. CDE (EM model)

2.4.1 Connectors Assembly

The quantity and type of connectors for the CDE unit is summarised on table below.

Reference	Type	Function	Module
CDEC/R4-J01	*DBM25P*	*28V, 4A Bus Input Power*	Pre-Regulator
CDEC/R4-J02	DEM9P	RS-422 I/F	Cooler Driver
CDEC/R4-J03	DAMA15S	AC Bus Output Power	Cooler Driver
CDEC/R4-J04	DCM21WA4S	Sensors I/F	Cooler Driver

Table 2. External Connectors

Internal interconnections between both modules are performed by means of direct plugging while stacking the assembly two antagonists.

3 SUMMARY OF CDE PERFORMANCES

This unit implements five operational working modes:

- **INIT mode**: to avoid any unexpected behaviour of CDE after the power-on or reset events.
- **STAND-BY mode**: to leave the CDE in a known state when it is stopped or is waiting for a start-up command.

- **DRIVE mode**: CDE nominal mode when the MPTC is running correctly.
- **LAUNCH-LOCK mode**: to prevent the pistons hitting in the compressor during the launching.
- **CALIBRATION mode**: to characterise the cooler mechanical behaviour.

The CDE unit selects the adequate operational mode depending on the MPTC state and the commands received from the series communication channels.

3.1 Control of Cooling Temperature

Temperature range	50K to 90K
Temperature Setting Resolution	10mK
Temperature Control Stability	±20mK (60sec) ±100mK (100min) ±300mK mission

Table 3. Control of Cooling Temperature

It is also important to highlight that the "cold down" curve from ambient to cryogen temperature is programmable via the series communication channels, by means of an internal lookup table of 256 steps. This "cold down" curve prevents the compressor's pistons from hitting their end-stops.

3.2 Attenuation of exported Vibrations

This CDE unit can integrate two different methods of attenuating the exported vibrations:

1. Automatic vibrations cancellation performed in real time with an algorithm embedded into the SOC.
2. Pre-programmed vibration cancellation consisting of using a voltage waveform profiles, programmed via the series communication channels, to cancel the vibration harmonics generated in the compressor. The CDE unit is also able to measure the vibrations with 4 accelerometers sending these telemetries through the series channels. Once the telemetries have been analysed by the user, the CDE unit could be re-programmed with new voltage waveform profiles.

The EM model of CDE shown above was tested with the second method of attenuation, and the first one is in progress at the moment of writing this paper. The performances achieved with the first method are summarised in the following table:

Vibration Telemetries exes	Axial & Radial
Channels of Vibration Sensors	4
Number of harmonics compensated (phase and amplitude)	first 10th harmonics
Resolution of the exported vibration cancellation for each harmonic	< 150 mNrms [(1)]
ON/OFF vibration compensation TC	YES

Table 4. Attenuation of exported vibrations

[(1)] *for a MPTC's compressor with a mass of 2,1 Kgrs.*

3.3 Electrical Interfaces

The main electrical performances of this unit are summarised in the table 5.

Input Voltage Range	22... 37 V_{DC}
Max Input Current	< 3,5 A_{DC}
Low frequency input current ripple	< 200 mApp
Output Voltage Range	0.. 15 V_{AC}
Output Voltage 1st harmonic distortion	< 5%
Output Frequency Range	30.. 60 Hz
Long Term frequency stability	< ±0,5Hz
Max Output Power	50 Wrms
Max Output Current	2,5 Arms
Control circuitry consumption	< 7W
Pre-Regulator Efficiency	> 85%
Power Inverters Efficiency	> 90%

Table 5. Electrical performances

It is remarkable the very low input current ripple (less than 200mApp) for the low frequency AC currents generated by the motor drivers of the compressor achieved because of the use of an input Pre-Regulator stage.

Additionally, the current design of this CDE unit foresees the ability of synchronising the switching frequency of its internal power devices with an external clock to improve the EMC features.

3.4 TM/TC Interfaces

CDE tele-command and telemetry interfaces are performed via a standard series link (RS-422), and their protocol has been approved by ESA. However, this series interface can be adapted easily to another standard (e.g. MIL-1553) in future flight models.

3.5 Temperature and Vibration Transducers

This unit is endowed with conditioning electronics for the following transducers:

- Two channels of four wires for accurate Temperature measurements with Probes like PT1000 or PT100 placed in the Hot-Point and Cold-Tip of the Cold-Finger. The temperature **monitoring accuracy** achieved with this measurement acquisition channels is better than **10 mK**.

- Four channels of coax wire for the Accelerometers used in the measurements of the exported vibrations. The main performances achieved in these acquisition channels are summarised in the table 6.

Measurement acceleration Range	± 150 mg
Frequency Range	1.. 7000 Hz
Resolution	± 2,5 mg
Temperature Range	-55.. 120 ºC
Accelerometer shock limit	± 5000 g_{pk}

Table 6. Acceleration measurement performances

3.6 Reliability and Radiation Tolerance

The design of this CDE unit has been performed for a lifetime of 5 years in flight plus 2 years on ground.

The selection of EEE components for an intended CDE flight design has been taken into account. Radiation hardened parts by process or devices less sensitive to SEE have taken preference. All the components selected are latch-up free, and the design of the CDE unit includes countermeasures against SEU effect if any.

4 CONCLUSIONS

The design of a space qualified CDE for Cryocoolers has been successfully ended and its performances have been verified with an EM model.

Its flexible and modular hardware configuration offers multiple possibilities to modify this CDE unit for the particular Cryocooler requirements or calibrate it. This versatile design based on a SOC can be adapted easily via a series TM/TC link.

The very high accurate analogue acquisition channels allow the CDE unit to accomplish the very demanding performances in terms of Temperature accuracy and exported vibration cancellation.

The very low input current ripple enables this unit to be used in a satellite with a non regulated Power Bus.

The very good ratio between mass and performances provided by this unit is even better if it is taken into account that its modular design (Pre-Regulator & Control Driver) can be disassemble to get a Control Driver Module working in a stand alone configuration without the Pre-Regulator Module.

This hardware is already prepared to support advanced CDE features as the “Automatic exported vibration cancellation” and the “Active Launch Lock” because of the programmability of the SOC architecture.