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Low Temperature Miniaturized Motion Control Chip - Enabled by MEMS and Microelectronics

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INTRODUCTION

ÅAC Aerospace (Ångström Aerospace Corporation, ÅAC) is leading an international consortium developing a Motion Control Chip (MCC) for the European Space Agency (ESA) under a TRP contract. The team consists of the prime ÅAC (Sweden), Aeroflex Gaisler (Sweden), Centre Suisse d'Electronique et de Microtechnique (CSEM, Switzerland), Selex Galileo (Galileo Avionica, Italy), Astrium UK, and DLR Institute of Space Systems.

The Motion Control Chip team has chosen to base the design on ÅAC's proprietary packaging technology which offers high-resolution thin-film metallization on various substrates for advanced 3D-stackaging. ÅACs packaging technology allow advanced 3D-multi-chip-modules (3D-MCM) which can incorporate all kinds of naked die. This approach was chosen in favor of special large application specific integrated circuit (ASIC) development to reduce cost and make the design more flexible. By choosing a MCM solution, the design will allow both field programmable gate arrays (FPGA) and ASICs to be used. FPGAs can be used initially to lower the prototyping cost and later be replaced with the ASICs as the packaging technology is qualified for the extreme environments of ISS, Mars, and Moon.

CSEM is providing the software for the MCC, which includes PID position, velocity, and torque control for brushed and brushless DC motors, as well as telecommand, telemetry and housekeeping through SpaceWire and CAN bus. This work is based on the experience gained during the development of the control software for the ESA Dexterous Robot Arm (Dexarm).

Astrium UK are in charge of the definition of requirements for rover locomotion applications of the MCC. Astrium UK has experience from the Beagle project and as responsible for the Exomars rover development.

Selex Galileo are in charge of the definition of requirements for three major applications of the MCC: robotic arms, complex motorized payloads (as drills and sample distribution systems) and exoskeletons. The work is based on the experience gained in programs as the Dextrous Robot Arm (as Prime Contractor) and the Exomars Drill and SPDS (as subsystem responsible). Most of these projects require the implementation of very compact servo control electronics, obtained with standard PCB technology. The technology offered by the MCC project can allow to go even further in the direction of miniaturization, increasing the possibility of fitting into smaller volumes, or to incorporate more redundancy in the same volume.

The DLR Institute of Space Systems contributes to the definition of requirements related to rover locomotion drives and is furthermore in charge of environmental testing of the MCC prototype for that application (operating an ExoMars-representative wheel drive mechanism controlled by the MCC while in simulated Mars surface environment).

BACKGROUND

The MCC development is based to a large extent on heritage from two of ÅAC's commercially available 3D-System-in-Package (3D-SiP) modules, namely the Remote Terminal Unit (RTU-100-CS) shown in Figure 1 and the Magnetic Attitude Control Module (RTU-MACS-100) add-on shown in Figure 2 [1-2]. ÅAC developed and built the RTU-100-CS and the RTU-MACS-100 on funding from the Swedish National Space Board (SNSB) and was released commercially in the fall 2008. Both devices are 34 mm x 34 mm and less than 2 mm in height, weighing between 3 and 4 grams each depending on the substrate. The RTU-100-CS is manufactured on low-temperature co-fired ceramics (LTCC) while the RTU-MACS-100 is built on stacked silicon substrates with ÅAC's XiVIA™ process.

The RTU-100-CS was developed to be a standardized miniaturized sensor and interface module with capability to act as onboard data handling system (OBDH) subsystem for a nanosatellite. A short summary of the RTU-100-CS features is given here:

- 3 SpaceWire links
- Redundant CAN busses
- 48 bit Spacecraft Elapsed time counter for distributed time synchronization
- 18 channels of analog-digital conversion
- 4 channels of digital-analog conversion
- 80 general TTL IO connected to FPGA
- 60 MIPS 8051 microcontroller
- Internal house-keeping giving status of temperature, current, and voltages.

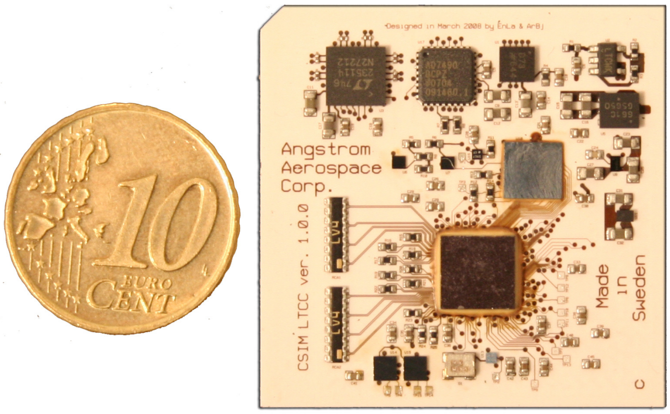

Fig. 1. Picture of the commercially available ÅAC Aerospace Remote Terminal Unit (RTU-100-CS) built on LTCC substrate with high resolution thin-film metallization.

For the RTU-MACS-100 the goal was to develop a miniature H-bridge power output module supporting 100 W per channel for three channels. The module can be used to drive three brushed dc motors, heaters, or magnetic torquers. The prototype power module is enabled on silicon substrate has three commercial H-bridges from National Semiconductor (LM18200) which can drive 57 V and 3 A each for a total of 171 W per channel. However, these H-bridges have not been space qualified but serve to demonstrate the capabilities of the packaging technology. Another interesting feature of the LM18200 is that the component can be flip-chip mounted compared to n- and p-mos field emission transistors (FET) that typically has to be wire bonded.

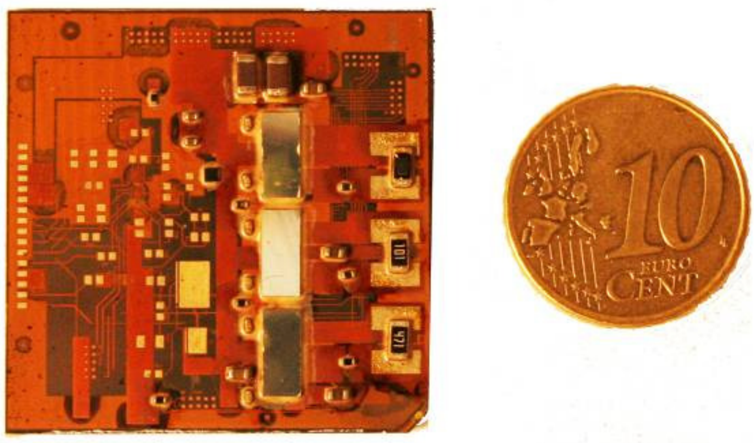

Fig. 2. Picture of the commercially available ÅAC Aerospace Magnetic Attitude Control Module (RTU-MACS-100) addon for the RTU.

One area which has been a problem for many years is related to adhesion of the thin-film metallization on various substrates. ÅAC has solved these issues and tested the metallization in several ways. First, a test silicon substrate with Cu thin-film metallization was used to test the adhesion. Running the sample through ± 30 g at 50 Hz didn't cause any measureable defects with perfect behavior of the oscillator before and after operation. Figure 3 shows the test setup with the applied motion in the figure to the right. The oscillator was intentionally selected carefully to have less than one mm in height, making it compatible with 3D packaging.

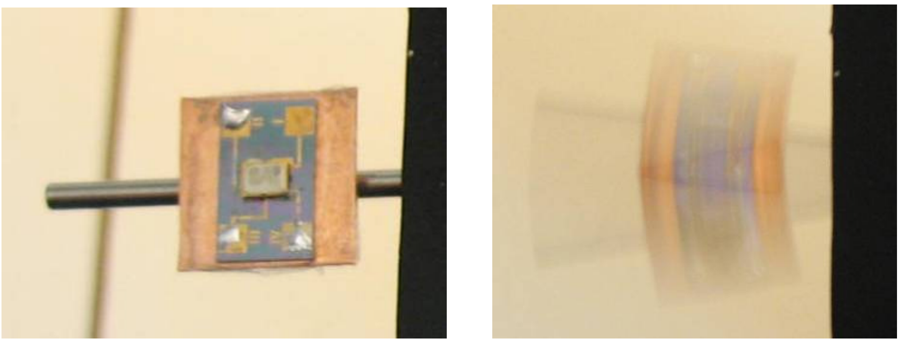

Fig. 3. Left: Picture of a silicon substrate deposited with Cu thin-film metallization. An oscillator is used as a test chip. Right: Silicon substrate exposed to ± 30 g at 50 Hz.

Second, the test vehicle was subjected to massive thermal cycling. Figure 4 show a picture of the test vehicle setup for thermal cycling experiments setup by ÅAC. A Pt-1000 temperature sensor can be seen just below the test substrate for reference.

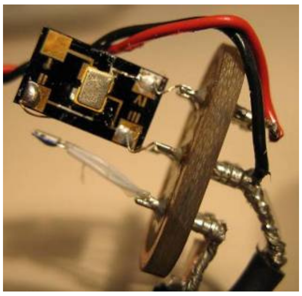

Fig. 4. Picture of the test silicon substrate setup of for thermal cycling test.

The lowest temperature that was possible to be controlled was -72°C. Thus temperature cycling was performed in the range -72°C to +128°C covering, thus, a temperature range of 200°C. The test was stopped after 72 cycles with no measurable degradation of the performance or function. The oscillator frequency was altered with 820 Hz (of a default 16.0000 MHz) during the thermal cycling test. This corresponds to 51 ppm. Further testing has shown no defects after 500 cycles.

Engineering samples of the MACS-100 has been tested with thermal shock to -160 º C without any measureable defects.

It is clear that the RTU-100-CS and the MACS-100 show that naked die FPGAs, ASICs, H-bridges, ADC, DAC, etc. can be used in space applications with very good robustness using ÅAC's packaging technology.

PRELIMINARY DESIGN OF THE MOTION CONTROL CHIP

The Motion Control Chip development is approaching system requirement review (SRR) so the design is very preliminary. It is important to stress that the focus for the MCC development is miniaturization which require some waivers from standards and qualification of new processes. The temperature interval is given to -120 ºC but will likely be extended to -143 ºC which corresponds to requirements derived by JPL. Based on previous studies conducted by ÅAC the MCC is expected to be tested to -143 ºC to 125 ºC.

Figure 5 shows the preliminary block diagram of the miniaturized Motion Control Chip (MCC). The design is based around a 3 M gate Actel ProAsic flash based (RT3PE3000L) FPGA as the core. This allows flexibility and re-programmability in flight. The MCC is designed as single-string with only partial redundancy inside. Redundancy is made on system level with parallel MCC units. The MCC is designed not to cause a load effect if redundant windings are used on a motor where redundant MCCs are connected. This approach allow the size of each MCC to be minimal.

A short summary of the features is given here:

- The MCC is built around a FPGA in which are implemented communication layers, a memory manager, a LEON-3 32bit processor and various interface to control ADC and PWM controller.

- 3 H-bridges are made of MOSFET in N type in order to decrease losses when controlling either 3 brushed motors or one 3 phase brushless motor. Each H-Bridge is able to drive at least 3Amps.

- Communications are made through redundant CAN and Space Wire. For common mode rejection, the communication part of the MCC is galvanically isolated from the power part.

- Sensors like resolvers, potentiometers, digital encoders or end switches are directly interfaced by the MCC. A torque sensor based on strain gage can also be connected to the MCC.

- The MCC generates all the necessary voltage supplies thanks to buck converters and linear regulators.

- It is also possible to control 4 simple power loads like brakes, heaters, etc up to 3Amps

- From user point of view, the MCC can be preheated after long period at low temperature and an access is available to a triplet temperature sensor to monitor the temperature inside the MCC

- Various internal parameters can be monitored directly by the MCC like currents, voltages and temperatures

- Motor control is based on PID algorithms running in various threads in the embedded RTOS.

In the scope of the TRP, the MCC is not being built on rad-hard components but on commercial bare dies only. However, commercial components are chosen keeping in mind existing equivalent rad-hard components, making the design shift to space qualified version of the MCC straight forward.

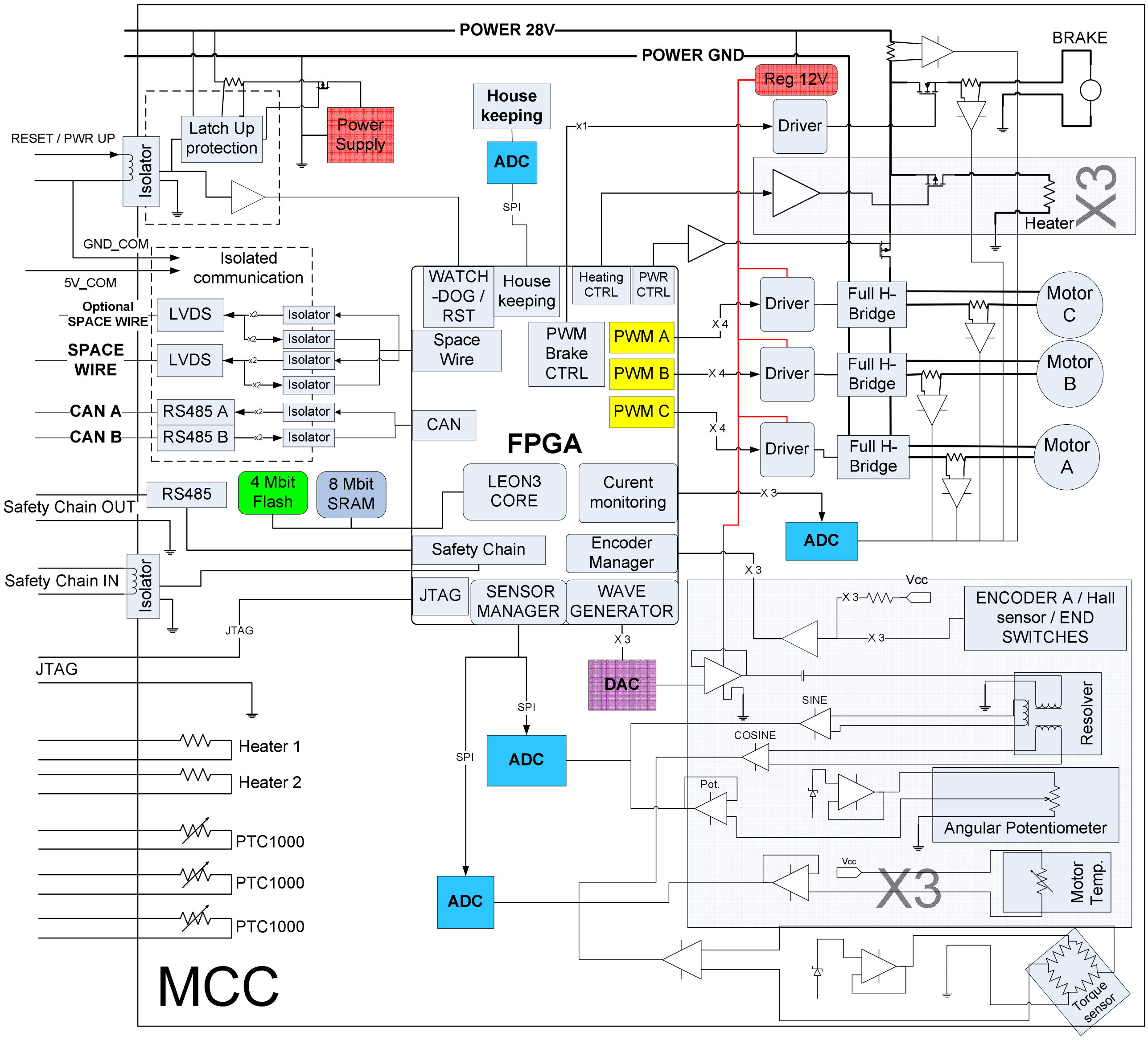

Fig. 5. Preliminary block diagram of the miniaturized Motion Control Chip (MCC).

DISCUSSION

The packaging technology applied to the Motion Control Chip is not limited to only this application. It is general in nature and can enable extremely miniaturized modules for harsh environments. For the MCC it enables a design that can easily be upgraded with ASICs in the future since the technology is not limited. The current design offer a great deal of flexibility by employing a large flash based FPGA and flexible design. Using an FPGA as baseline allow users to either use the IP cores provided by Aeroflex Gaisler and the software provided by CSEM or to use their own.

The FPGA based design takes the edge from any discussion whether to use a state-machine, an 8 bit processor or a 32 bit processor. Any of the mention methods is applicable to the MCC since the hardware is designed flexible and can be altered by re-programming.

An alternative would be to go forward using ASICs but the economy of scale benefits the multi-chip-module approach with lower cost in small to medium series.

During the MCC development, a focus will be on rover locomotion, however, the MCC is not limited to this in any sense and will have the performance to control applications such as Exoskeletons, robotic arms, masts, solar panels, etc.

ACKNOWLEDGMENT

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