EXOMARS ROVER BOGIE MOTOR CONTROLLER

Chris Gee-Yin Lee[1], **Nghiem Bao Duy Nguyen**[1], **Sebastian Ehrenreich**[1], **Sabine Klinkner**[1], **Josef Dalcolmo**[1],
Nicolas Weigel[1], **and André Schwander**[2]

[1]*von Hoerner & Sulger GmbH, Schlossplatz 8, 68723, Germany*
[2]*RUAG Space, Schaffenhauserstrasse 580. 8052 Zürich. Switzerland*

ABSTRACT

The Bogie Motor Controller (BMC) is the electronic component of the Locomotion Subsystem for ESA's ExoMars Rover. Its function is to perform low level control of the six actuators belonging to a single bogie of the Rover. The six actuators comprise of a pair of wheel drives, a pair of steering drives and a pair for leg movement to allow for deployment/wheel walking. There are 3 bogies on a single rover resulting in 3 identical BMC units.

As the BMC is mounted out side the Rover's thermally controlled environment, it is subjected to a large number of extreme thermal cycles between -125°C to +40°C. The design of the BMC not only had to minimise the volume and mass of the unit but also had to consider how to manufacture the unit in such a way as to survive this environment.

The paper describes the BMC architecture and design and discusses some of the options and trade-offs considered in order to comply with these requirements. The paper will also report on the breadboarding activity that has taken place which validates the design architecture of the proposed solution. It concludes that although manufacture of equipment to an extreme environment is expensive in price and time, the work that has been performed in an essential foundation not only for ExoMars but also other similar interplanetary missions.

The work described in this paper was performed within the ExoMars project within which vH&S (von Hoerner & Sulger GmbH) is responsible for the Motor Controller Electronics of the Rover Chassis, RUAG Space is responsible for the Locomotion Subsystem, Astrium Ltd is responsible for the Rover Vehicle and Thales Alenia Space Italy is the overall mission prime contractor to ESA. The work described in this paper was performed by vH&S.

1. INTRODUCTION

The Bogie Motor Controller (BMC) unit is the electronic component of the Locomotion Subsystem for the ESA ExoMars rover. This rover is required to travel over the Martian terrain during a mission period of 218 Martian days collecting scientific samples in order to identify evidence of past life on the planet Mars. The Locomotion Subsystem is the rover component which provides the rover with a chassis and the ability for the rover to drive over a terrain. There is a single unit for each of the three bogies of the rover chassis and each is responsible for the low level control of all the six actuators of the bogie.

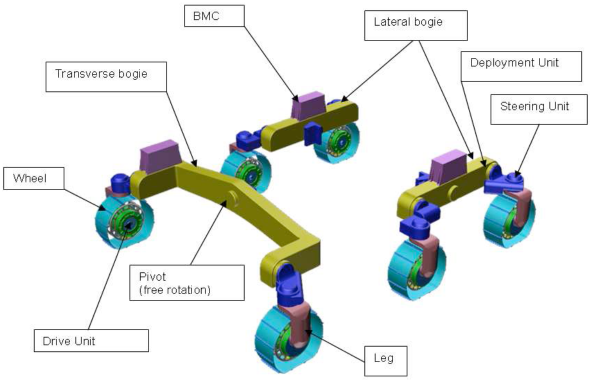

Figure 1. Diagram of ExoMars Locomotion Subsystem (Courtesy RUAG)

1.1. Basic functional requirements

The BMC manages the control of the actuators for each leg of the bogie. The BMC operates each leg independently and must provide the following functions for each leg:

- Low level speed and position control of the leg wheel.
- Low level speed and position control of a second actuator which may be selected to be either the steering or deployment actuator.
- Monitoring of absolute positions for the steering and deployment actuators.

- Monitoring of temperatures of the associated actuators.
- Communication of telemetry and telecommands via a Controller Area Network (CAN) bus interface.
- Power controlling to the actuator heaters.
- Limit checking of critical parameters.

Some functions are however shared between both legs in order to make the most efficient use of resources. These include:

- Power interface, conversion and isolation.
- CAN bus electrical interface.
- Monitoring bogie pivot absolute position and temperature sensors.

1.2. It is only a motor controller......

As can be seen the basic functionality is very similar to various commercial motor control units that are available on the market. Specifically they are similar to the Maxon EPOS range and the Elmo Whistle controller - which was used on the Astrium UK 'Bridget' Rover breadboard and the ESA ExoMars breadboards both of which were built by von Hoerner & Sulger GmbH in previous phases of the ExoMars project.

However there is a significant gap between commercial level electronics and those suitable for a space flight mission such as ExoMars. The equipment is expected to operate reliably in both a space and martian environment. A significant number of design and product assurance requirements are thus needed to be applied to ensure this reliability which in turn significantly affects the options that are available to the designer. Constraints imposed on the choice of components, the materials that can be used, and the electrical functionality that must be included, are generally in contradiction to the requirements to minimise not only cost but the fundamental resources of mass, volume and power.

For this application it is the thermal environment which has the biggest impact on the equipment design. Unlike the majority of rover electronic subsystems, the BMC is mounted external to the rover's thermally controlled warm box, directly onto the bogie's structure. In this way the thermal loss from the warm box via the actuator harness is minimised but at the price of the necessity to design the BMC unit to withstand the temperature extremes of the martian day and night through out the mission. Not only is the temperature range significant, with a qualification temperature between -135 and +50°C, but it must also be considered that the equipment will reach the limits every day of the mission - some 210 thermal cycles. Additionally the equipment must also be compatible to Dry Heat Microbial Reduction (DHMR) sterilisation which is typically performed at a temperature of +125°C.

Even for components and Off-The-Shelf equipment (OTS) items that are specifically designed for space, the qualification temperature are generally only in the range of -55 to +120°C and so special consideration must be made for this environment

Finally, as always, with space applications physical resources of mass, volume and power are severely restricted generally requiring an application specific solution to optimise unit function with manufacture process and overall physical size in order to achieve the requirements applied by this challenging mission.

2. BMC ARCHITECTURE

Each BMC is designed as a fully redundant system in terms of electronics and electrical interfaces to both the Rover Vehicle and the actuators. It should be noted that although all the actuator sensors are redundant, the motors themselves are not redundant: the power signals from the nominal and redundant strands are connected together at the motor terminals. Special provision is thus necessary to ensure that failures on a nominal strand are not propagated to the redundant strand and visa-versa.

Each redundant strand comprises of a Motor Control Board (MCB) and a Motor Power Board (MPB) and thus a single BMC unit will contain a total of four PCB's. The MCB is responsible for the main data processing functions of the unit whereas the MPB is responsible for the power conditioning and conversion of rover supplied power for the BMC itself, the actuator heaters and for the actuator motors in the form of Pulse Width Modulation (PWM) signals. The controller component is galvanically isolated from the rover supply in order to control common mode and ground loop interference.

2.1. Motor Control Board

The motor control board is based on a pair of large Actel Field Programable Gate Array (FPGA)'s which are referred to in this paper as the Controller FPGA. Both FPGA's are identical and represent the control of a single leg. Around the FPGA's is the circuitry which not only provide the fundamental power and clock sources but also hardware to provide the electrical interface to the data channels and sensors. With the exception of the Rover Vehicle serviced heaters and thermistors, all electronics on the MCB is galvanically isolated from the primary supply.

Each FPGA provides a Manchester encoded bidirectional serial link which are used to communicate with the MPB.

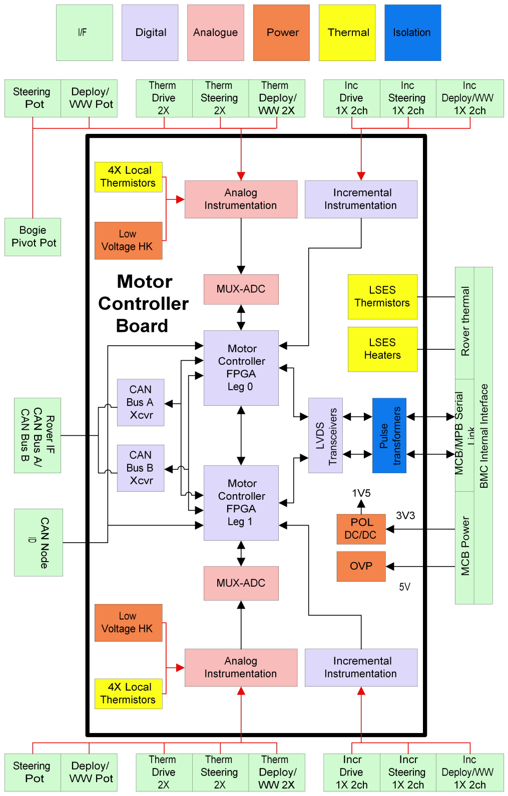

Figure 2. Functional Block Diagram of Motor Control Board

The implementation consists of LVDS transceivers in conjunction with isolation transformers located on the controller board. This solution was used to minimise the number of communication channels and thus the number of isolation transformers which are expensive in mass and PCB area. Opto-isolators were also considered but these possessed significant disadvantages including high power consumption, low bandwidth and the high risk that their construction was not compatible to this particular thermal environment of the application.

The other off-board devices serviced by the board comprise of interfaces for Rover Vehicle data (CAN-bus), the actuator incremental sensor, the absolute position sensors and the actuator thermistors. On-board sensors are restricted to isolated secondary voltages and board temperature housekeeping.

The architecture inside the FPGA, as shown in Figure 3, is based on a multi-master Wishbone SoC bus which was selected as it was significantly more resource efficient for our performance requirements than the more favoured AMBA bus. The architecture divides the functionality into a number of functional blocks which work in parallel rather than a single processor core (such as a LEON) performing all the tasks sequentially. This advantage of such an architecture is a reduction of overall complexity in comparison with a processor/software implementation plus a reduction of base clock speed for the device and thus a significant power saving. Verification is further simplified with the ability to test each functional block in a stand-alone configuration.

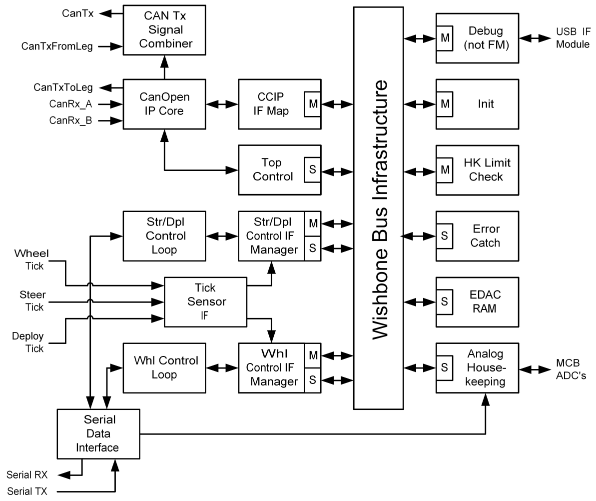

Figure 3. Simplified architecture of the Controller FPGA on the MCB (Wishbone Master/Slave interfaces are marked with M or S respectively)

The data interface is provided by a customer-supplied IP core which implements a modified version of the CANopen protocol. The protocol modifications include the implementation of a redundant CAN-bus scheme used in space applications as well as simplifications in order to reduce the overall size of the IP core. The IP core interfaces to the bus via a mapping block which converts the generic interface to a Wishbone compatible interface. The design of the address bus have been specifically selected to provide almost 1:1 mapping to the Manufacturer specific area of the CANopen object dictionary, resulting in the minimisation of gates used and removing the need for any intermediate storage - the IP core writes directly into the registers of each functional block.

Resource usage has also been minimised by ensuring that arithmetical functions are shared where ever possible. For instance limit checking of currents, thermistors and potentiometers is centralised in the HK Limit Check block which repeatedly collects actual and limit data across the bus from the Analog Housekeeping Store and the Error Detection and Correction (EDAC) RAM respectively. Additionally the speed calculation from the actuator's relative speed (tick) sensors which requires a division is centralised in the Tick Sensor block. Only the Control Loop blocks which performs the motion regulation exists in two separate instances: one for the wheel actuator and one shared by the deployment and steering actuators which are never used simultaneously.

The motion regulation performed by the Control Loop blocks has either a cascaded position and current loop control or a speed and current control scheme as seen on Figure 4. The cascaded architecture offers better dynamic performance and a higher bandwidth response. It also allows to limit the continuous motor current which provides protection for the controlled actuator.

The control loop feedback mechanism is a Proportional Integral (PI) feedback controller widely used in industrial control systems. No derivative terms are needed to compensate for overshoot problems due to the implementation of a profile generator. The position command sent by the Locomotion Subsystem (LSS) high level control is translated into an S-curve motion profile that allows for a gradual change in acceleration. As well as minimising overshoot, this also results in less mechanical vibration seen by the system. The same approach is done with the speed control where a trapezoidal velocity profile provides smooth motion for starting and stopping the motors.

For the wheel drive units, a relative position control is implemented. The motor position variations are derived by counting the number of ticks received by the relative position encoder. For the steering and deployment units, an absolute control using the relative position encoder is implemented. Control using feedback from the potentiometer is not performed due to the uncertainty of the long term reliability of potentiometers. Instead an absolute position reference is given to the BMC by the user based on readings from the potentiometer before operation of these actuators. A relative speed control is used for all types of actuators.

All control parameters are stored in the EDAC RAM and collected by the control manager as soon as the actuator is enabled. This ensures that parameters cannot be altered during the movement as well as assurance of the parameter integrity from upset events.

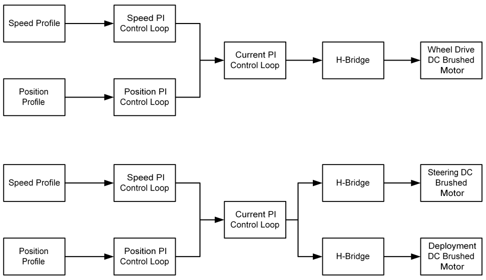

Figure 4. BMC cascaded control loop architecture

2.2. Motor Power Board

Figure 5 shows a block diagram of the MPB. Power is received as 28V from the rover and is passed to the communal PSU which filters and converts the supply to low voltages to be used by the BMC. The DC-DC component of the PSU is a multiple output, transformer coupled, current controlled flyback converter. It provides fully isolated power for the controller board and power referenced to the primary return line for the power board electronics. As the feedback is taken from isolated 3.3V supply the feedback path is modulated and passes via a small pulse transformer in order to maintain the galvanic isolation.

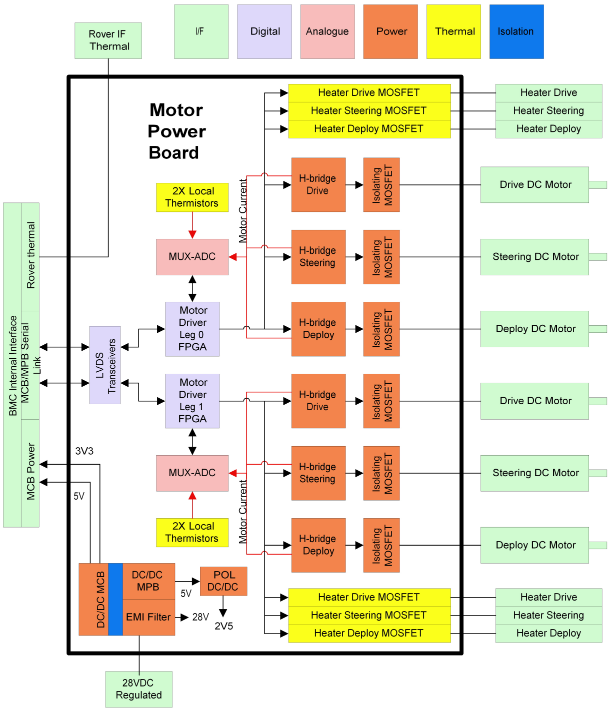

Figure 5. Functional Block Diagram of Motor Power Board

The rest of the board functionality is dedicated to providing the actuator power interface for the MCB. Data is passed between the controller and the power sections via a Manchester encoded serial link as described in the previous section. It should be noted that this solution was driven by the need to reduce mass and volume. The use of a small FPGA device on the MPB was initially to combine a number of discrete logic IC's into a smaller area. Once this decision was made, the use of a more sophisticated communication link allowed the elimination of all optocouplers reducing power, risk and real estate.

In the final design solution, the Driver FPGA on the MPB is responsible for:

- Transmission/Reception of serial data to the MCB via a Manchester-II CODEC.
- Generation of PWM and control signals for actuator H-bridges.
- Collection and averaging of current feedback data from actuator H-bridges.
- Control and state detection of actuator heater switches.
- Collection of current/voltage/temperature housekeeping data from non-galvanically isolated part of the BMC.
- Error detection, isolation and reporting.

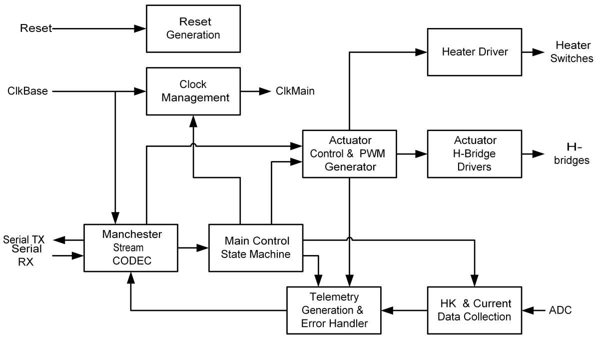

Figure 6. Simplified architecture of the Driver FPGA on the MPB

To reduce the number of components, the Driver FPGA generates a PWM signal that drives only the low side H-bridge MOSFET's directly with the use of rad-hard logic level MOSFET's from International Rectifier. As the actuator gear ratios are high the BMC does not need to provide any electrical breaking function to the actuators allowing the removal of any requirement of fast switching of the high side devices. The state of these devices need only be changed at the start and end of each movement in order to either enable or disable the drive and to select its direction. It is thus possible to control these devices from a special voltage generated by a ladder pump-up circuit above the 28V supply. In this manner it has been possible to remove large and power hungry H-Bridge driver IC's and eliminate an additional power rail from the PSU.

Similarly the blocking MOSFET at the outputs of each H-Bridge terminal is controlled in the same manner. These devices ensure that the redundant strand of the BMC provides a high impedance when powered off even if there is an internal failure within the H-Bridge, thus making the BMC single point failure free.

2.3. Mechanical enclosure and planetary protection

The mechanical enclosure contains both the nominal and redundant card sets of the BMC (see Figure 7). The enclosure supports all the electrical interface connectors which are attached to their respective PCB with a strip of flexible polyimide PCB.

The enclosure also forms a vital component of the Planetary Protection (PP) measures incorporated into the BMC design. The principle is that the BMC is a sealed unit vented only via a pair of Highly Efficient Particulate Air (HEPA) filters incorporated into the enclosure. In this way the costly and labour intensive precautions required for PP is minimised as it is expected that the microbes are trapped within the enclosure.

Sealing of the enclosure is accomplished by using a soft Indium wire gasket around all mating edges. To minimise the number of mating edges each half of the enclosure is machined out of a single piece of aluminium with a simple flat flange around mating faces.

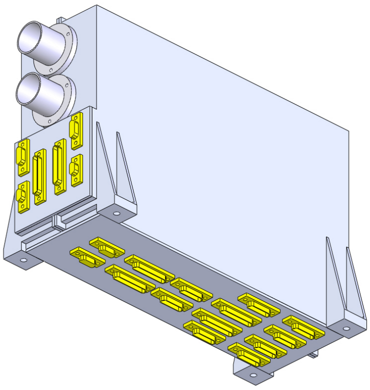

Figure 7. View of the preliminary enclosure design (detailing of connector plates and seals not full performed)

The two boards of a single redundant strand are first mounted on an internal frame (see Figure 8), which is integrated and tested before placing within the enclosure half. Connectors are first mounted and sealed onto two flat connector plates so that their seals may be inspected. When the internal frame is finally integrated into the enclosure half, the connector plates themselves are sealed against a cutout in the enclosure half. Due to the complexity of this procedure, the connectors are limited to only two faces of the box.

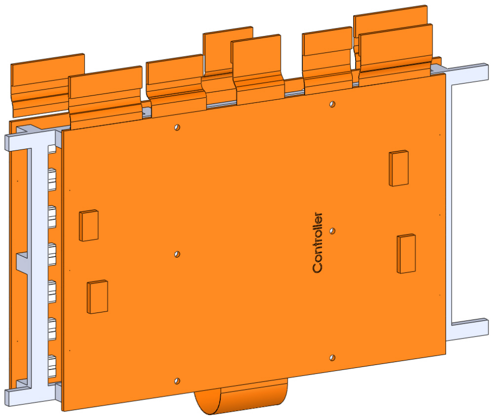

Figure 8. View of the internal frame

2.4. Resource Budgets

The latest mass and volume values for a BMC unit are:

- Volume: 231 x 151 x 67 mm

- Mass: 2.55kg including 20% margin.

These figures are exclusive of the enclosure feet whose location is not yet specified and the latest HEPA filter specification which has yet to be fully considered.

The current end-of-life/worse case power estimates excluding margin are 4.4W Idle and 5.7W during peak operation. These figures do not include the power dissipated by the motors themselves.

3. MANUFACTURING TECHNOLOGY

The expected environment of the BMC mentioned at the start of the paper has big implications for the actual manufacturing process of the equipment. On a practical level the miss match of Coefficient of Thermal Expansion (CTE) at the interface between of the PCB/substrate and the electronic component applies a significant thermal stress. The wide temperature range of almost 200°C as well as over 200 cycles means that this thermal stress is major driver of the reliability and must be carefully considered as part of the design.

Formally the result is that there is no space-qualification for this environment of any process that is needed to build the equipment and thus any process used needs to undergo at least a delta qualification if not a full qualification before being acceptable for as subsystem equipment[1].

This problem is being addressed in a two stage approach:

- Firstly, a Risk Reduction excerise is being undertaken to identify, select and test a suitable suite of technologies.
- Followed by a qualification of the selected processes for the specific electronic equipment.

A detailled account of the first item is given in the same proceeding by Klinkner [1]. During this activity it was identified that a theoretically greater tolerance to the thermal cycling could be achieved by using a ceramic substrate instead of a standard PCB. The ceramic substrate which would improve the matching of CTE between itself and the largest electronic components which are all packaged in a similar ceramic material. Additionally the use of an alloy solder would provide some flexibility in the joint to absorb expansion difference over temperature. These two major items in conjunction with a selection of staking compounds and conformal coating was thus tested against more standard material such as polyimide PCB substrate in a thermal cycle test.

The exact details of the qualification stage is still uncertain but it is expected that it will involve the qualification by thermal cycling of the empty PCB/substrate followed by a similar qualification of fully populated flight representative assembled electronic boards. For both items in order to achieve statistical significance it is necessary to test more than a single unit. As the latter are expensive in terms of components it is expected that only three test items will be used. The thermal cycling test itself will undertake 510 cycles to the equipments non-operational temperature limits. These tests do not replace the standard equipment qualification of a complete unit including enclosure which is kept at 8 cycles of the qualification temperature.

4. BMC BREADBOARD

A breadboard based on the BMC flight design was manufactured by vH&S to validate the feasibility of the proposed implementation of the motor control and power boards with representative actuator hardware. The implementation was investigated with relative (tick) position sensors with the nominal 32 ticks per motor rotation as well as 16 and 8 ticks.

4.1. The Breadboard Hardware

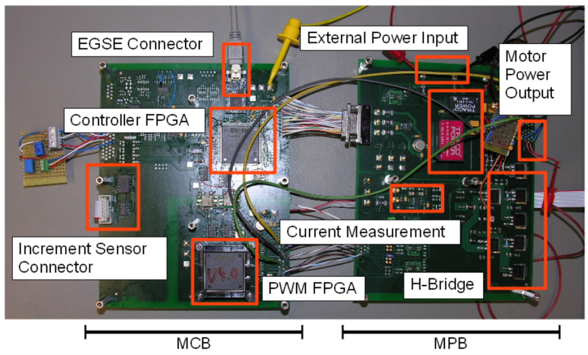

Figure 9. BMC Breadboard (the Driver FPGA is identified as PWM FPGA in the photograph)

The breadboard is not a full implementation of the BMC but a reduced subset of functions in order to achieve the validation goal at minimal cost and time. The major difference is that it only implements in hardware a single interface to an actuator of a single leg rather than the full set. Despite this, the FPGA code was written as if all actuators were present and for the Driver FPGA is a full implementation of the flight device.

Other differences between the breadboard and the flight design are as follows:

- All the components are commercial grade electronics components.

---

[1] The same issues also apply to EEE components. However the responsibility for selection, testing and up-screening of the component was handled by the Common Part Procurement Agency Tesat-Spacecom GmbH

- The CANopen interface which was not implemented as the customer supplied IP component was not available at the time.
- A USB based debug port was implemented on the breadboard .
- The controller FPGA is a Flash-based FPGA instead of an anti-fuse FPGA.
- The driver FPGA is on the MCB .
- The DC-DC converters are commercial off-the-shelf units.
- Failure Detection, Isolation and Recovery (FDIR) functions have not been implemented on the breadboard.

Both the MCB and MPB were implemented as separate boards although as mentioned previously the partitioning of components between them has slightly changed following a later design iteration. The MCB board also contains the USB debug port to the controller FPGA. The port and associated FPGA design block provides high speed direct access to the internal Wishbone bus allowing all activity with in the controller to be monitored. As the internal architecture already implements the CANopen object dictionary address map, the debug protocol uses the CANopen Index/Sub-index addressing scheme to access any of the registers. It should be noted that all the manufacture specific Object registers relating to the actuator control has been implemented as they would be in the flight model.

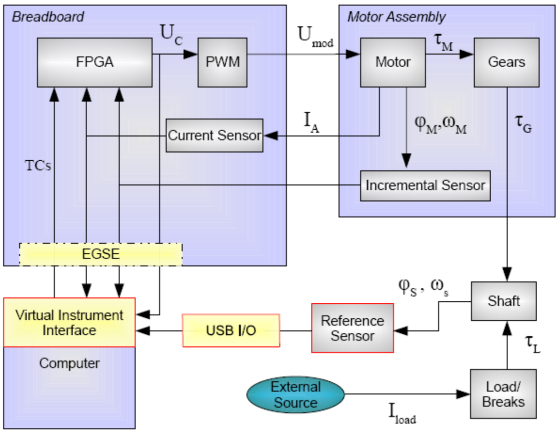

Figure 10. BMC Breadboard testbed block diagram

Figure 10 and Figure 11 shows the block diagram and photograph of the breadboard testbed with a single actuator motor. The actuator hardware consisting of a single motor with incremental sensor, reduction gear and hysteresis break inertia were supplied by RUAG Space. The reduction gear was not the full flight model gear train but sufficient to provide representative loads from the inertial brake to the motor.

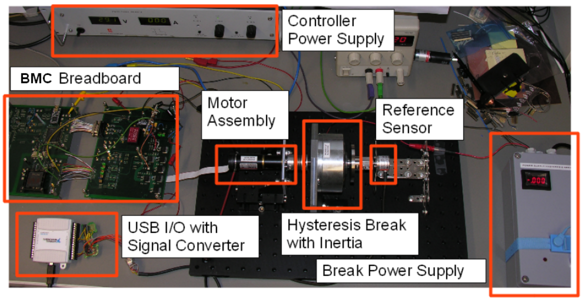

Figure 11. BMC Breadboard testbed

The data acquisition Electrical Ground Support Equipment (EGSE) was built by vH&S and provided the ability collect telemetry and send telecommands by reading and writing the appropriate CANopen objects as controlled by a GUI front end. The EGSE also collected data from a complimentary external incremental sensor installed on the test stand. Its purpose is to give an independant measurement of the output shaft movements and to validate the results given by the internal sensor and processing.

4.2. BB Results

The functional testing of the breadboard was divided in 3 parts:

1. testing of the actuator speed mode
2. testing of the actuator position mode

The speed mode control tests consisted of sending a variety of speed commands to the breadboard with a different testbed parameters for velocity, direction of rotation and load to characterise the performance of the system. These tests were performed for each different resolution of the relative encoder (8, 16 and 32 pulses per motor rotation). Some of the tests also included update of control parameters before the movement was completed in order to ensure a smooth and continuous movement was achieved to reach the final target. The tests were limited to a duration of 30 seconds to avoid motor damage as some of the loads required motor operation outside the continuous operation region of the motor. Example of speed responses can be seen on Figure 12.

The position mode control tests consist of sending a variety of position commands with two different maximum velocities with a similar set of testbed paremeters. Example of position responses can be seen on Figure 13.

The BMC Breadboard successfully completed all tests after some minor design modifications made to both the hardware and the FPGA code. The performance of the control loops was shown to reach the customer performance requirements once some adjustment of the control

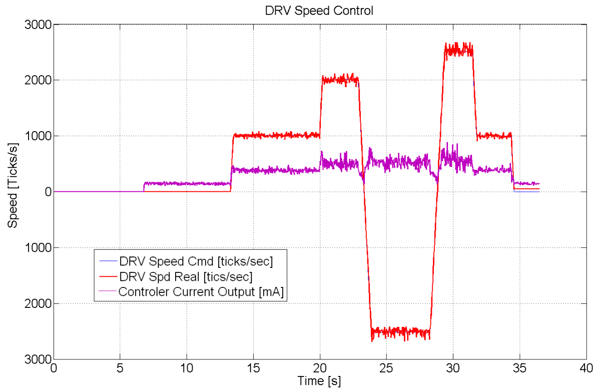

Figure 12. Example of different speed test results

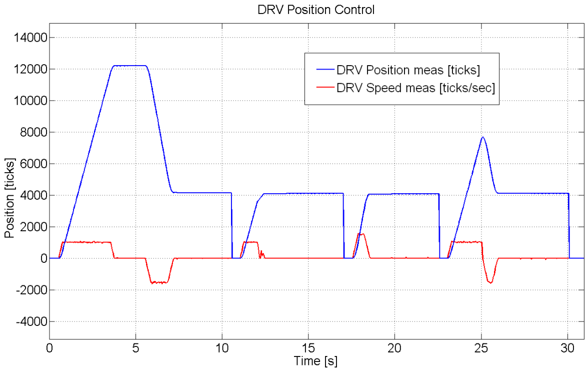

Figure 13. Example of different position test results

loop parameters were undertaken. The breadboard successfully proved the BMC design as a feasible solution to the application. The breadboard also showed that the FPGA code implemented by vH&S required the expected amount of resource for both devices. The CANopen IP core which was not available and thus not implemented is still a significant unknown and for this reason additional work on the breadboard was conducted that allowed various resource reduction techniques to be implementation in order to regain resource margin for the controller FPGA design.

5. CONCLUSION

This paper presents the Bogie Motor Controller - the low level motor controller of the ExoMars Rover. The unit is responsible for receiving commands over a CAN bus and controlling the 6 actuators of a single bogie. Although this function is very common especially commercially, this specific application is extremely challenging due to the small size and mass required of the unit and most importantly the extreme thermal environment consisting of 218 cycles between -125°C and 40°C during the mission lifetime.

The design of the equioment is now at a mature level and a breadboard that drives a single actuator has been manufactured and successfully tested. The testing demonstrated that the electronic design is valid and that the control loop algorithm can meet all the performance requirements. In parallel to the breadboard activity a study and test of possible manufacturing process was conducted using alternative materials such as ceramic substrate and Indium alloy solder in conjunction with the more traditional space level manufacturing materials and technologies.

Despite this testing, the selection and qualification of manufacturing technology remains a significant work item which has yet to be completed along with the delivery and integration of the CANopen IP core for the main controller FPGA.

It can be seen that for such an application which requires not only qualification to a non-standard environment but also to be physically light and compact, the use of any off-the-shelf equipment or even technologies designed for space applications is excluded. Thus it is necessary to consider and undertake a customised solution for both the equipment and the way it is manufactured. This unfortunately has significant impact on both the cost and schedule for the development from the initial concept to final delivery of the flight unit. The work that has been performed by von Hoerner & Sulger GmbH so far in addressing this issue provides a critical foundation in knowledge and experience that may be readily applied not only to the current ExoMars mission but also other destinations and applications that are required to survive an extreme environment.

ACKNOWLEDGEMENTS

The work described in this paper was performed within the ExoMars project within which von Hoerner & Sulger GmbH is responsible for the Motor Controller Electronics of the Rover Chassis, RUAG Space is responsible for the Locomotion Subsystem, Astrium Ltd is responsible for the Rover Vehicle and Thales Alenia Space Italy is the overall mission prime contractor to ESA.

The author would also like to thank the support and co-operation with TESAT-Spacecom GmbH who role as Common Parts Procurement Agency greatly assisted vh&S during the selection of components.

REFERENCES

[1] Sabine Klinkner et al., Comparative tests on electronic technologies to be compatible with thermal cycling over extreme temperature range, Astra Conference, April 2011.