A MINIATURIZED MOTION CONTROLLER CUSTOMIZATION FOR EXPLORATION

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ABSTRACT

The European Space Agency ESA has awarded ÅAC Microtec AB (Sweden) a GSTP contract to develop an advanced miniaturized motion controller for future robotic exploration missions (MCC-X). The consortium includes CSEM SA (Switzerland) and Maxon Motor AG (Switzerland).

A motion control device has many electrical connections to the robotic joint and fewer to the central control system. Therefore, savings in harness length and complexity can be achieved by placing the controller physically as close as possible to the motors, thus enabling a distributed motion control architecture. This approach can improve performance of rovers and robotic arms as well as achieve a substantial reduction in harness weight. The challenges with this approach are that the space around a joint often is limited and that the controller needs to withstand environmental extremes. For a Mars rover application for instance, the controller must survive many temperature cycles in a very wide temperature range as well as vibrations and possibly dust. At the same time it should be as small and light as possible.

Hybrid electronic technology allows manufacturing of miniaturized and robust electronics for harsh environments. The performance of ÅACs 3D MEMS hybrid technology, based on bare die assembly and ceramic substrate stacking technology, was demonstrated successfully in the former MCC ESA TRP project completed in 2011 [1].

The MCC-X product to be developed in the current project is a miniaturized motion control device, designed to withstand the environmental requirements of several different space applications, including the Martian environment and GEO orbit. The targeted non-operational temperature range is -130°C to +100°C. The MCC-X shall have low power consumption and a small size (< 120cm^3).

The controller is a stand-alone hybrid component that includes a power drive module, control and sensor modules for operation of up to two brushed motors or one brushless motor in torque, position or velocity control mode. For each motor, a switch for supplying current to a brake solenoid or a motor heater may also be implemented to allow the use of motors with solenoid brakes or heating the motor if necessary in cold environments. The MCC-X will also have an internal heater, which will be controlled autonomously when the unit is powered on and within its operational temperature range. On this hardware platform, an FPGA will perform digital closed-loop motor control as well as communication with the user platform. The design is modular in terms of the available subsystems: power electronics for driving the motors, on-board logic for implementing the control algorithms, telecommand/telemetry functionality and sensor data acquisition. This allows customization of the design according to the needs of various applications.

The project started in June 2016 with ÅAC Microtec being responsible for electronics, analysis and hardware manufacturing. CSEM is in charge of development of the firmware implementation and user interface. Maxon Motor contributes to the definition of requirements, review of the electrical design and is responsible for functional and environmental testing. The Systems Requirements Review was successfully completed in November 2017.

The project is currently in the preliminary design stage. A first prototype, the Development Breadboard (DBB) has been manufactured and is being used for early verification of both hardware and firmware solutions.

Within the scope of the project, an engineering qualification model (EQM) of the MCC-X will be designed. A series of EQM units will be manufactured. These units will be subjected to an environmental test campaign which includes thermal cycling over the full non-operational range, among other tests. The tests are planned to be finalized by the end of 2019.

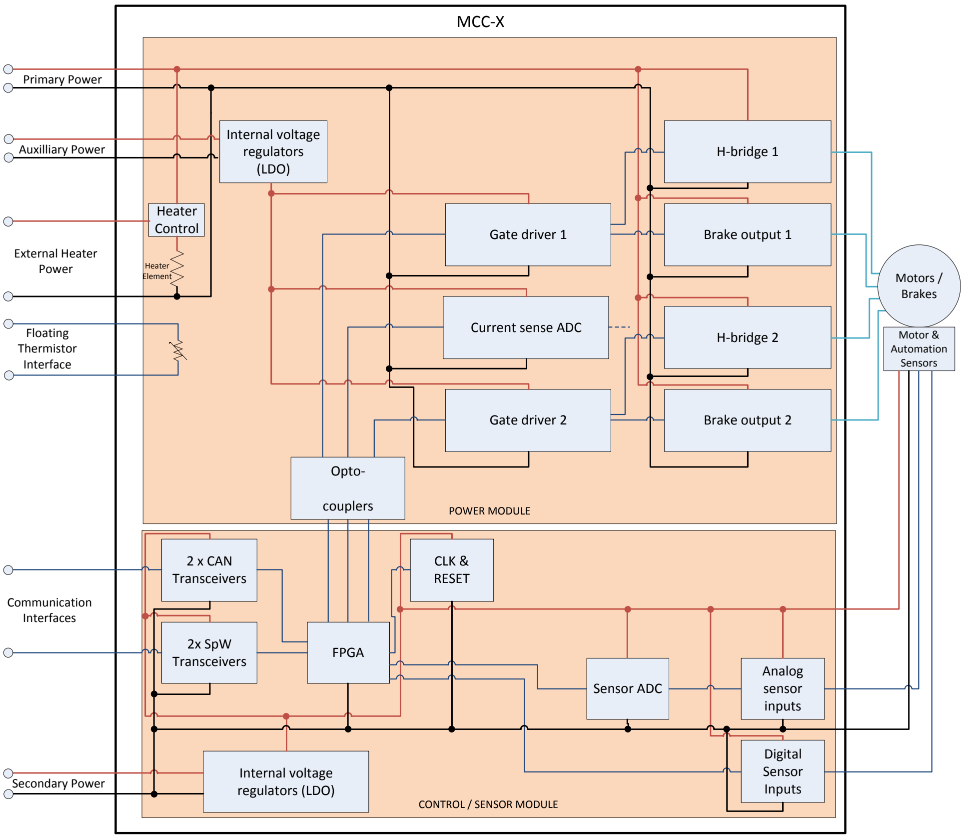

Figure 1. MCC-X Block Diagram

1. SYSTEM DESCRIPTION

The MCC-X is designed to be a closed-loop motor control unit with a simple interface, consisting of only connectors for power and standardized communication buses, towards the user platform in order to enable distributed motor control. It is intended to be very compact (< 120cm^3) and to withstand the extreme thermal environment of exploration missions – the targeted non-operational temperature range is -130°C to +100°C. Due to these requirements it will be realized using hybrid mounting technology, where several hybrid modules are mounted on a carrier which is placed in an enclosure with connectors. Figure 2 shows the initial conceptual MCC-X unit design.

Figure 2. Conceptual view of the MCC-X exterior

The main functions of the MCC-X are summarized as follows:

- Motor driving (2 brushed motors or 1 brushless motors) in 4-quadrant mode for a motor power of up to 200W.
- Driving of brakes/solenoids or motor heaters
- Sensor interfaces for motor and automation sensors
- Dual CAN interfaces
- Dual SpaceWire interfaces
- Integrated logic for closed loop motor control
- Isolated temperature measurement
- Autonomous thermal control

A large part of the specifications are similar to those of the previous MCC development [1], but there are also significant differences:

- No soft processor is implemented in the FPGA. Instead, the communication interface and motor control logic is implemented directly as FPGA firmware. This simplifies the control hardware significantly as no external memories are needed, whereas the previous MCC development contained both SRAM and FLASH chips.
- The hybrid models built within this project will use the same components as the flight model, potentially with a lower screening grade, while the previous MCC used commercial components only. This ensures that the electrical performance, the physical design and the build quality are equivalent to that of the flight model.
- The MCC-X features autonomous thermal control when the internal electronics are within its operational temperature range. The previous MCC development only featured a thermistor and external heater power interfaces.

Another important feature of the MCC-X is the modularity of the design, where the power electronics in the power module are separated from the logic in the control module. The latter is, for example, unaffected by a redesign for a different bus voltage or power level. The control module features a basic set of sensor interfaces as well as an expansion module where any custom sensor interfaces can be implemented without changing the design of the control or power modules. The modularity also has the benefit of simplifying the manufacturing and enabling functional tests of each individual module, thereby increasing the overall production yield.

2. ELECTRONICS DESIGN

The electronics design of the MCC-X is divided into three modules, shown in the block diagram in Figure 1:

- Power Module. This module contains the power switches for driving the motors and brakes/heaters including gate drivers, local power conditioning and current measurement electronics. Its interface towards the control module is isolated using opto-couplers.
- Control Module. This module contains the FPGA, where the control logic is implemented, the communication transceivers as well as local power conditioning and other supporting circuitry.
- Sensor Module. This module contains the electronics used to interface the motor and automation sensors. A basic set of sensor interfaces are integrated into the control module and an expansion sensor module can be added for custom interfaces.

The main part of the power module are the two H-bridges, built using four N-channel MOSFETs in each bridge, which are used to drive the motors. As the MOSFETs are relatively large and costly components and brushless motors are considered the main use case for the MCC-X, the amount of H-bridges was adjusted compared to the previous MCC development by reducing the simultaneous amount of controlled brushed motors from 3 to 2. This allowed a reduction from 12 to 8 N-channel MOSFETs in the H-bridges, which is a significant improvement regarding both area and cost as well as a reduction of the hardware overhead in the case of driving a brushless motor.

To allow the use of the MCC-X in systems with different grounding schemes, and to protect the control and sensor unit electronics, galvanic isolation is provided in the interface between the control module and the power module. By placing ADCs on both sides of the isolation barrier, the problem of isolating analog signals has been avoided as only the digital interface towards the ADC needs to cross the barrier. The isolation is implemented using hybrid mountable high-speed opto-couplers in a very small form factor.

The control module is designed around a FLASH-based FPGA, allowing the logic to be reprogrammed for different applications, if needed. The control module also features redundant CAN and SpaceWire interfaces for communication. The SpaceWire interface can also use an internal router, implemented in the FPGA, to allow daisy-chaining of MCC-X units on a SpaceWire network.

The default sensor interfaces on the MCC-X are generic analog inputs, generic digital inputs, a torque sensor interface and an SPI sensor interface. The generic analog inputs have a bandwidth of up to 1kHz and an input voltage range of -5V to 5V. A number of amplifiers with different gain levels are available to allow the connection of different sensor types such as for instance potentiometers or thermistors. The generic digital inputs have a logic voltage level of 5V and feature pull-up resistors to allow the use with open collector sensors. This interface type can be used with hall sensors, quadrature encoders or end switches. The torque sensor interface is a high-gain differential interface intended to be connected to a strain gauge. The SPI interface uses 3.3V logic and can be connected to any SPI-compatible digital sensor. Additional sensor interface types that can be implemented in the expansion sensor module for specific applications include electrical encoders and resolvers.

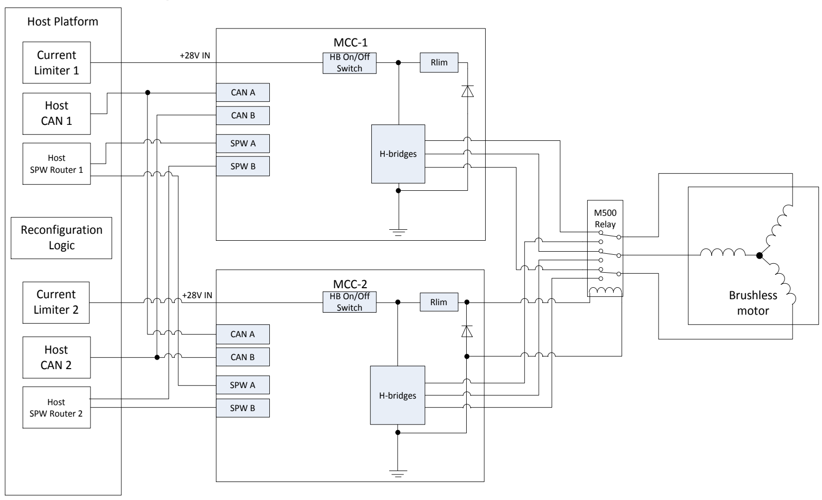

Figure 3. MCC-X Redundant Configuration

In addition to the sensor interfaces mention above, electronics for sensorless control of brushless motors are being evaluated on the current MCC-X prototype and may be included in the final model.

The MCC-X is designed to allow redundant operation, with two MCC-X units connected to the same motor using an external relay for isolation, see Figure 3. The reconfiguration logic is not included inside the MCC-X and the redundancy is managed by the host platform supplying power only to the unit which is currently active. All communication transceivers which are used have cold spare functionality to ensure that the unit which is powered down does not interfere with the operation of the active unit.

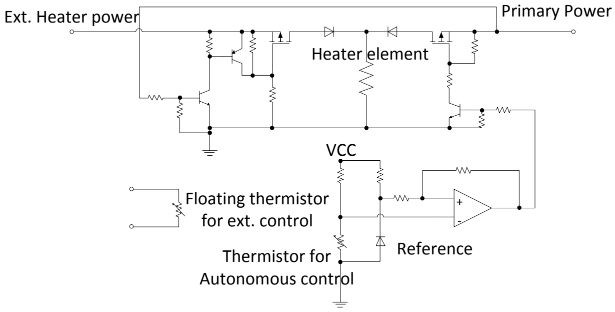

Figure 4. MCC-X Thermal Control simplified schematic

A simplified schematic of the MCC-X thermal control is shown in Figure 4. The unit temperature is monitored by the user platform using the floating thermistor interface. If the MCC-X internal electronics are outside their operational temperature range, heater power is provided externally. Once the operational temperature is reached, the unit can be powered up. From this point on the thermal control is autonomous, implemented using a hardware hysteresis control.

The following hardware models will be built during the MCC-X project:

- Development Breadboard (DBB). An initial prototype, built before the preliminary design review, used for functional testing of the main concepts in the MCC-X design.
- Engineering Breadboard 1 (EBB1). The first complete breadboard of the MCC-X, including all functionality but built on a PCB using commercial components. This model will be used for electrical and functional testing.
- Engineering Breadboard 2 (EBB2). This is an elaboration of EBB1 which also includes the final packaging (i.e. bare die or similar) for certain critical components. The EBB2 will be verified in full temperature and it will also be used to evaluate parts of the thermal modelling.

- Proto-Qualification Model (PQM). The first hybrid version of the MCC-X, built in such a way that it allows for more electrical testing than the final design, including test points and potentially a less dense design. This model will be used for electrical testing in the full operational temperature range, verification of thermal models and verification of the packaging processes.
- Engineering Qualification Model (EQM). This model is intended to be equivalent to a flight model of the MCC-X and will be used in the environmental test campaign described in section 5 of this paper.

At the current stage, the DBB has been built and initial testing has been performed. In Figure 5, the DBB is shown together with the MCC-C board, stemming from the previous MCC project and hosting the FPGA. The DBB implements the critical parts of the power module, control module and sensor module in a first iteration. It can be used as a platform for hardware and firmware development as well as evaluation. It also includes optional versions of some parts of the design so that these can be benchmarked against the baseline implementations as input to design trade-offs.

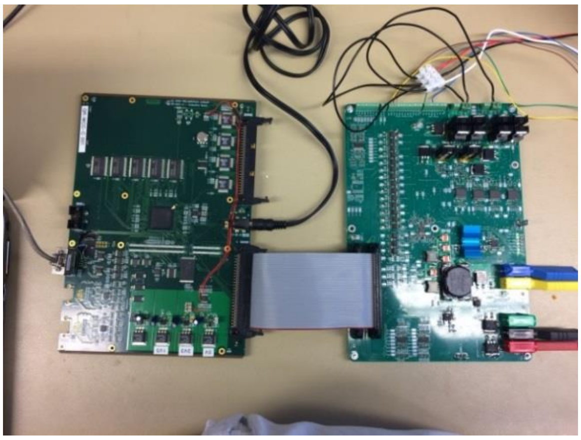

Figure 5. MCC-X DBB with MCC-C FPGA board

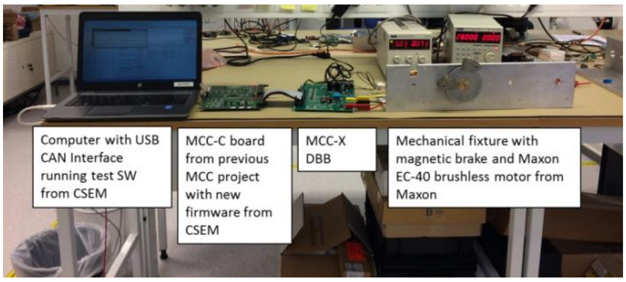

Figure 6. MCC-X DBB initial test setup

Figure 6 shows the basic setup used for the DBB tests. A laptop computer runs a preliminary user interface software developed by CSEM, which communicates with the prototype setup using the CAN interface. The MCC-C board is used for the CAN transceivers and the

FPGA. This board then connects to the DBB, which implements all power electronics, the sensor interface electronics, galvanic isolation and all supporting circuitry.

The test setup includes a fixture for a variety of motors. A load is applied to the motors using an eddy-current magnetic brake. In the test case shown, an EC-40 brushless motor from Maxon motors is mounted in the fixture. With this setup, the full verification of the DBB will be performed and the results will be used as inputs to the development of EBB1.

3. FIRMWARE AND CONTROL

The preliminary MCC-X FPGA firmware design is shown in Figure 7.

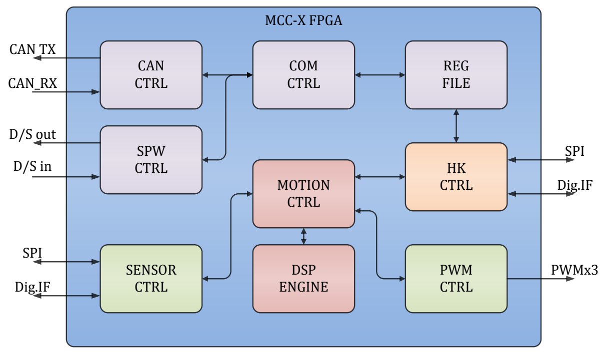

Figure 7. Preliminary FGPA firmware design

The firmware design consists of the following blocks:

- A communication controller, which provides access to the register file for configuration and status of the MCC-X FPGA. The CAN (or optionally SpaceWire) controller implement the protocol of the related communication interface.
- A housekeeping controller for operational state and error handling.
- A motion controller, which uses a dedicated Digital-Signal-Processing engine (DSP) to implement Proportional-Integral-Derivative controllers, filters and interpolators. The motor H-bridges are controlled using the PWM module. For closed-loop control, the motion controller uses the sensor controller.

The firmware control implements a state machine, shown in Figure 8.

Figure 9 shows the block diagram of the motion control scheme, where the variable *p* stands for position, velocity or torque, depending on the high-level controller; *i* stands for current, and *v* for voltage.

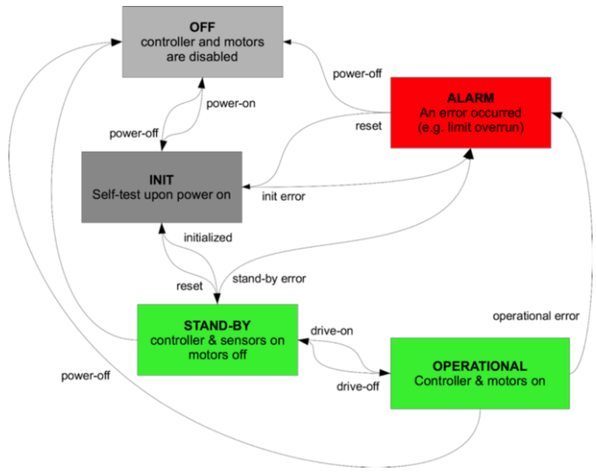

Figure 8. Preliminary state machine & state transitions

The control blocks will be implemented in 32-bit fixed-point arithmetic. The motion controller acts as a sequencer to the DSP engine, which implements a 32-bit fractional multiply-and-accumulate data path. The PID controller is evaluated in time-multiplex with a single multiply-and-accumulate instance. In every step, the intermediate result is fed to a 64-bit accumulator, correctly shifted and sign/zero extended. This results in a very compact control implementation that still satisfies the control performance requirements.

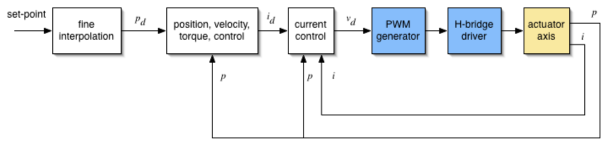

Figure 9. Motion control block diagram

4. MINIATURIZATION AND ASSEMBLY TECHNIQUES

The hybrid modules are realized using qualified hybrid assembly techniques of bare active dies and passive components on ceramic substrates. Each hybrid is encapsulated in a flat-pack or plug-in Kovar package for assembly on a double sided carrier PCB. Other options (e.g. CuW base + Kovar frame) for power hybrid will be considered if supported by thermal analysis.
The PCB carrier is defined with solders pads, vias and routing layers for electrical connection. To ensure high reliability for the intended environment, the carrier material is based on a low CTE organic laminate that can maintain its physical and chemical properties in the MCC-X non-operational temperature range. The FPGA (CCGA package), connectors and large passives are assembled directly on the carrier board. The complete assembly is screw-mounted in an Al casing for a fully integrated unit as shown in Figure 10.

The identified critical package/assembly technologies will be verified in the development phase by means of implementing a sub-set of parts and components into a number of test vehicles that will be exposed to environmental tests. Thermal cycling will be conducted to demonstrate the integrity of the assembly in the full temperature range. Also thermal dissipation characteristics using critical components operating at the full operational range will be evaluated.

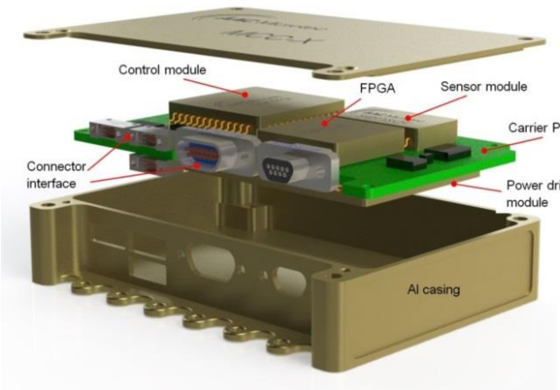

Figure 10. Conceptual view of the MCC-X assembly

5. ENVIRONMENTAL TEST CAMPAIGN

As part of this project, the MCC-X EQM units will be subjected to a test campaign intended to verify its functionality in the targeted environment. This campaign includes the following tests:

- Thermal cycling, -135°C to +100°C, 200 cycles
- Thermal vacuum
- Vibration and mechanical shock
- Sterilization/Dry Heat Microbial Reduction (DHMR), 1h at 125°C, 3 cycles
- Life test

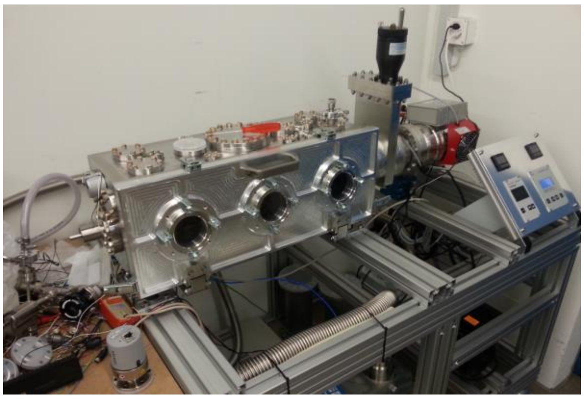

Figure 11. Vacuum chamber with rotary feed-through

The main part of the test campaign will be performed at Maxon Motors. Due to long-term collaborations in space projects Maxon has a broad variety of brushed and brushless motors including gearboxes and encoders suitable for Lunar and Mars conditions. This work has resulted in Maxon making a strategic investment to be able not only to build drives systems but also to validate them for harsh environments. In particular, this includes high and low temperature environmental chambers, vibration and shock test facilities, and vacuum and CO_2 chambers with integrated cooling and heating plates.
Rotary feed-throughs with magnetic brakes allows putting realistic loads onto the drive systems, continuously monitored by automatic data acquisition and analysis systems.

6. CONCLUSIONS AND FUTURE WORK

The preliminary design of the MCC-X has been performed and after the finalisation of the upcoming Preliminary Design Review (PDR), the detailed design phase will start. In parallel with the design activities, process tests will be performed to verify the suitability of the hybrid technology for the intended environment. Two PCB prototypes of the system (EBB1 and EBB2) will be designed, manufactured and tested to ensure that the electrical functionality is complete and well tested before starting the hybrid manufacturing. Two models of the final hybrid design will also be built: PQM and EQM. The PQM will be used for comprehensive tests of the assembly and internal electrical performance. The EQM will be used to test the MCC-X subsystem behaviour in the environmental test campaign.

While the MCC-X primarily targets exploration missions, requiring it to withstand a large temperature range, it is also intended to be a suitable unit for use in other missions where an integrated and distributed motor control solution is required. This will be taken into account during the detailed design work: the interfaces will be designed in such a way that as many applications as possible can be supported.

At the conclusion of this project, a product shall be available that is as close as possible to qualification, using qualified parts and processes, while satisfying the very demanding environmental requirements. The goal is to, with minimal delta qualification for the exact application, arrive at a market-ready product.

7. ACKNOWLEDGEMENTS

The MCC-X activities are performed in the frame of an ESA GSTP contract which we gratefully acknowledge.

8. REFERENCES

1. Lofgren, H. Bruhn, F., Gunnarsson, M., Hagström, M., Ljunggren, A., Häll, K., Lindegren, R. (2012) Miniaturized Motor Controller for Space Robotic and Rover Applications. In *Proc. i-SAIRAS 2012, 4-6 September, Turin, Italy*