Modular Linear-Drive Cryocooler Electronics

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ABSTRACT

The Modular Advanced Cryocooler Electronics (MACE) system developed at Iris Technology Corporation combines configurable, high-power motor drives with precision telemetry capability in a design that is amenable to radiation hardening. A Telemetry Aggregation Unit (TAU) located near the cryocooler minimizes attenuation and contamination of sensitive cryocooler feedback by digitizing sensor data locally for transmission back to the controller, while multiple 500 W drive channels in the Main Control Unit (MCU) supply power waveforms at up to 95% efficiency. The modular design concept allows for adding drive cards in the event that additional channels are required or removing drive cards to reduce size, weight, and power. The TAU incorporates up to 14 external sensors with an aggregate data rate of up to 800,000 samples per second, dynamically allocated to any combination of telemetry by the control software. A low cost version of the electronics can be realized by populating with commercial components, or by utilizing an alternate control scheme to reduce the cost of radiation-hard controller components. A brassboard demonstration was performed at Raytheon in which the High Capacity RSP2 (HC-RSP2) cryocooler was driven, with temperature and vibration control loops closed at high power and low cryogenic temperatures. This paper discusses the MACE development, testing, and lessons learned.

PROGRAM IMPACT

Technology Impact – Raytheon Cryocooler Product Line

Raytheon has developed a patented two-stage cryocooler architecture based upon a combination of Stirling and pulse tube technologies. The Stirling / pulse tube cryocooler has the unique ability to shift capacity at nominally constant efficiency and input power by simply changing the Stirling displacer phase angle relative to the compressor drive command. The "hybrid" Raytheon Stirling / pulse tube two-stage (RSP2) has numerous and distinct advantages over Raytheon's competitors, who are implementing monolithic multistage pulse tube and Stirling approaches. RSP2 provides mission critical capability for optimization, management of transient loads, and management of environmental changes from beginning to end-of-life, etc. However, no flight electronics existed for RSP2 until the development of Iris MACE.

With the successful conclusion of the MACE brassboard test phase, the HC-RSP2 (and related RSP2 coolers) is now ready for immediate low-risk deployment on a space platform. With a flight version of the Iris MACE, customers will have the option to select Raytheon's superior thermodynamic architecture over less advanced technologies.

Producibility Impact

Present state of the art space cryocooler electronics across industry can generally be characterized as a series of point designs. This point was made in a recent paper which describes the development of a general-purpose set of tactical cooler electronics.[1] Typically, a unique set of space cryocooler electronics is developed for a specific cryocooler. In many cases, the design point is even narrower, having been specified around unique, payload-specific physical and/or electrical requirements. These point designs are not generally supportive of new program needs as they arise, resulting in a considerable nonrecurring engineering (NRE) cost and extended development times to meet each new payload's needs. In contrast, the Iris MACE has been purposefully architected for modularity and scalability. This work extends beyond the tactical cooler electronics work described by Pilvelait[1] in that the selected MACE architecture directly supports up to the highest-complexity space cryocooler applications by making accommodation for the use of advanced, processor-enabled control software.

The Iris MACE system can be configured to support a wide range of Stirling-class (including pulse tube and hybrid Stirling/pulse tube) cryocoolers. The selected H-bridge motor drive design, for example, can be readily implemented as a low power (< 20 W) drive or a high power (> 500 W) drive and configured to support from one to five motor drives. For applications that can be served with a simple control scheme, control can be implemented purely in VHDL, permitting the elimination of the expensive radiation hard SRAM and other processor-supporting components.

The result is that the general Iris MACE architecture is fully supportive of the entire range of DoD strategic cryocooler needs, from "traditional" long life strategic infrared payloads to lower cost cryocoolers for space experiments, ground-based missile defense, and Operational Responsive Space (ORS). This flexibility will provide long-term cost savings to the USG by avoiding extensive nonrecurring engineering (NRE) investment for every new cooler design that emerges in response to variations, however slight, in payload and/or mission requirements.

Mission Assurance

With MACE, Iris has enhanced Mission Assurance by implementing a simple, low part count H-bridge motor drive architecture, eliminating unnecessary complexity and the associated parts and negative reliability impact of those parts. The modularity of MACE enables further Mission Assurance improvements, particularly for ORS and other applications with reduced requirements, enabling a meaningful optimization trade between Mission Assurance and Mission Capability.

SUMMARY OF TECHNICAL EFFORT

The Iris MACE is a two-box distributed system consisting of a Main Control Unit (MCU) and a Telemetry Aggregation Unit (TAU) to provide accurate command and control of a 1000 W class cryocooler. Iris MACE advances the state of the art in space cryocooler electronics by every important measure, in particular radiation hardness, power capacity, preciseness of the servo control, motor drive efficiency, reliability, and overhead (tare) efficiency. A brassboard version of MACE has been successfully tested with a Raytheon HC-RSP2 Cryocooler. Details of the development and test results are presented below.

MACE System Level Development

Approach

Because the architecture is modular, the design team had the option at the outset to select the cryocooler for which the initial brassboard MACE configuration was to be matched. Iris and Raytheon, in conjunction with the Missile Defense Agency, decided to target the largest, most complex space cryocooler Raytheon manufactures, the High Capacity Stirling/Pulse Tube Two-Stage (HC-RSP2) Cryocooler.[2] Raytheon's HC-RSP2 requires five motor drives (2 main compressor, 1 compressor trim, and 2 expander), draws over 500 W input power at maximum stroke and, because of its complex thermodynamics, has inherently challenging temperature control needs. Taking on such a challenge at this stage will make implementations in Phase III (Commercialization) comparably simple.

The Requirements and Architecture described in the paragraphs to follow are specific to the HC-RSP2. However, Iris MACE can readily be adapted for lower power (down to <10 W), single-stage, and/or simple pulse tube cryocoolers.

Requirements

The Iris MACE requirements were determined in consultation with Raytheon and MDA with the result being a requirements set, shown in Table 1, that fully supports the HC-RSP2 for projected MDA applications.

System Architecture

For increased performance and a more flexible configuration, the Iris MACE system consists of two separate electronics packages. A Telemetry Aggregation Unit (TAU), mounted near the cryocooler, minimizes sensor signal attenuation and cable weight. The transmission of all digital data also reduces the opportunity for noise pickup through long sections of cable. This small, low-power (<3 W) unit performs all necessary signal conditioning and A/D conversion for communication back to the controller, as well as allocating its sampling bandwidth between sensors as instructed. The Main Control Unit (MCU) contains the control logic, power circuitry, and a configurable number of high-power drive cards. A block diagram of the brassboard setup is shown in Figure 1.

Table 1: MACE Requirements Summary

Description	Requirement/Goal
Main Control Unit (MCU)	
Output Power	2 Ch @ 500W; 2 Ch @ 100W; 1 Ch @ 10W
Motor Drive Efficiency	>95% at peak power
Telemetry Aggregation Unit (TAU)	
Four precision Cernox channels	+/- 0.100 K
Two PRT channels	+/- 1 K
Four LVDT channels	+/- 0.01 mm peak
Six programmable gain charge amplifiers	Resolve 1mN at most sensitive. Read up to 40 N at least sensitive scale.
Four piston contact detectors	<.05 sec response time

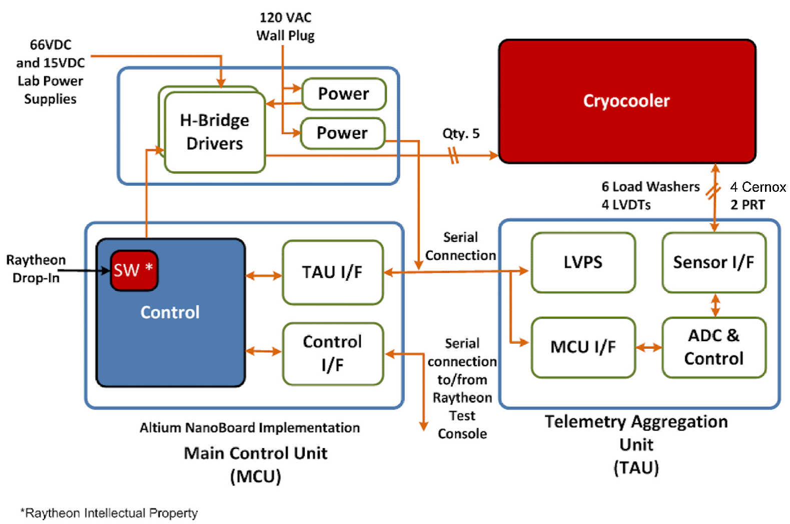


Figure 1: Brassboard MACE Block Diagram

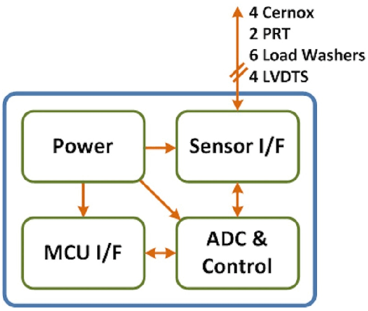
Telemetry Aggregation Unit (TAU)

The Telemetry Aggregation Unit (TAU), shown in Figure 2, is responsible for local signal conditioning and A/D conversion of cryocooler telemetry. The primary components of the TAU are a linear regulator to derive clean power from the MCU supplied input, an A/D to digitize the telemetry stream, all necessary signal conditioning hardware, and a digital communication interface to transfer control and telemetry information. The heart of the unit is a 20MSPS true 12-bit A/D converter fed by a series of analog multiplexors that are configured remotely with the serial data stream from the MCU.

Main Control Unit (MCU)

The physical design of the brassboard MCU, shown in Figure 3a, includes a lab-top card cage to hold the drive-board assembly and a COTS FPGA platform (Altium NanoBoard) to implement the control logic. Implementing the control firmware and software on a COTS FPGA platform reduced cost and sped development of the brassboard system. The brassboard's low voltage power supplies are regulated down from a 120V A/C source with COTS converters, and the H-Bridge drive inputs are applied from lab supplies. For a flight system, the control logic will be implemented on a custom board containing the FPGA and all necessary interfaces.

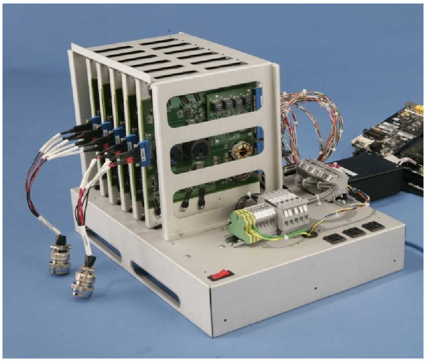
In its final packaged form for flight, a single box will contain the H-Bridge drives, control board, low voltage power supplies (LVPS), and an active line filter (ALF), as shown in Figure 3b. The optional ALF reduces the conducted emissions impact of the high power drives on the spacecraft bus, as discussed in an earlier paper.[3]



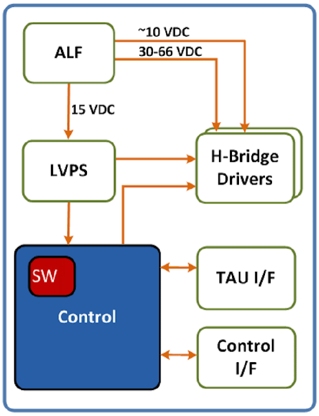
(a)

(b)

Figure 2: (a) Telemetry Aggregation Unit Block Diagram and (b) TAU Photo.



(a)



(b)

Figure 3: MACE MCU Brassboard. (a) Motor drives in card cage. Altium NanoBoard shown partially at the right edge of the photo. (b) Block diagram for a flight version of the MCU.

NanoBoard

The Altium NanoBoard is a general-purpose development platform used to implement the control logic for the Iris MACE system. An attached Spartan 3 FPGA implements a TSK3000 soft-core microprocessor with operating code held in 512 kb of external SRAM. Custom software provides hooks into the VHDL hardware drive and telemetry control code, allowing Raytheon's proprietary control code to operate independently and without the VxWorks OS typically required. The NanoBoard is a low-risk simulation of the custom control-board to be implemented in a flight design. A radiation-hard alternative to the Spartan 3 FPGA remains to be selected. That is expected to be as much a programmatic decision (driven by a customer's Approved Parts and Materials List) as a technical decision.

Firmware

The main purpose of the control logic is to enable precision temperature control while modifying the drive waveform to reduce exported vibration. The FPGA contains a soft-core processor running Raytheon's proprietary control algorithm, with an Iris-designed and implemented wrapper to tie in to the VHDL telemetry and drive interfaces – seamlessly tying together the telemetry feedback, control logic, and outgoing drive waveforms. Figure 4 shows a block diagram of the controller FPGA contents.

The primary challenge in integrating the Raytheon control software lay in mapping the previous control and data registers to their new locations and functions. To that end, a new layer of code was added providing translation needed to talk to the new control firmware in the FPGA.

MCU Testing

MCU-level testing was performed prior to full system testing to independently measure and assess motor drive efficiency as a stand-alone parameter. The MCU was connected to a load resistor bank for this test. Peak performance of 95% was measured while driving a resistive load at 100 W with a 66V supply, as shown in Figure 5.

Drive boards were also inspected for variations in performance and were seen to operate with a better than 1% tolerance for efficiency across 6 boards (see Figure 6). For a 200 W sinusoidal drive wave, efficiency peaks at 95%. Both the motor drive efficiency and repeatability measurements met Requirements, clearing a key hurdle prior to fully-integrated testing with a cryocooler.

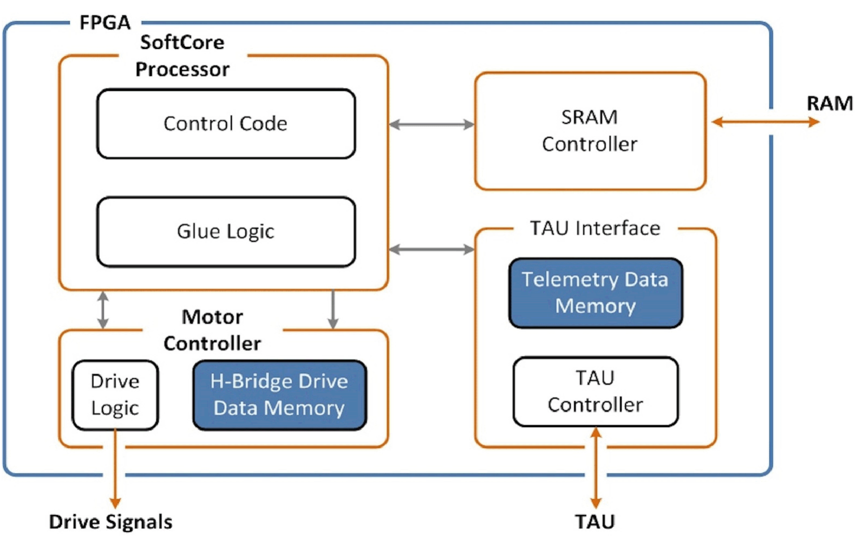


Figure 4: Block Diagram

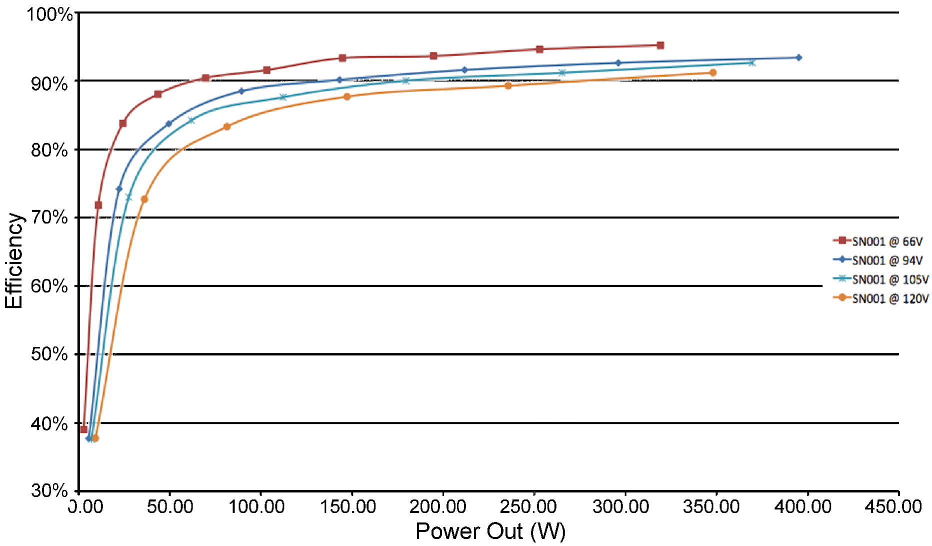


Figure 5: Drive Card Efficiency. The nominal operating output power for these motor drives is 250 W, a power level at which >90% efficiency was achieved for a wide range of input supply voltages.

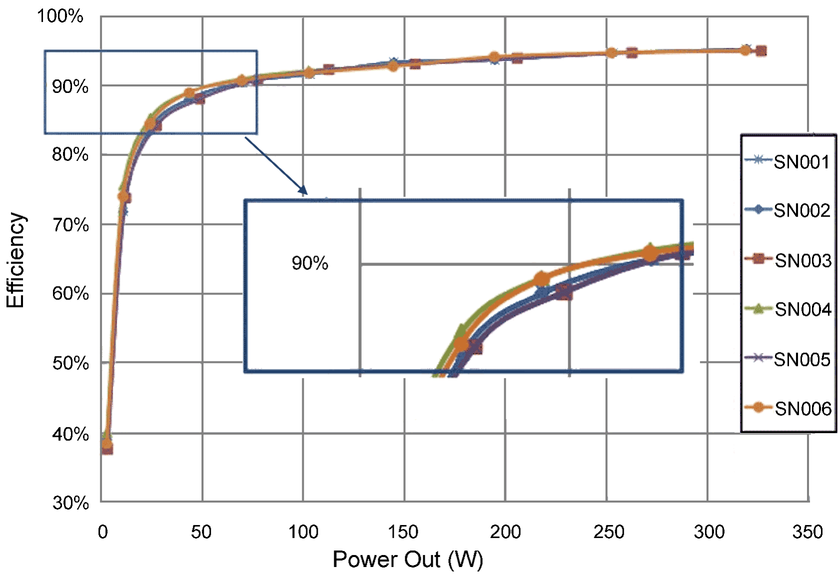


Figure 6: Drive Board Efficiency by serial number for six different motor drive cards. Even at high magnification, as shown in the inset, the motor drive efficiency variation is nearly undetectable. 66 VDC supply for all cases shown in this figure.

MACE Test Results with Cryocooler

Delivery of the MACE brassboard from Iris to Raytheon occurred in September of 2009. As shown in Figure 7, the MACE was integrated with the High Capacity RSP2 cryocooler and a computer (with the user interface software) in the Cryocooler Development Laboratory.

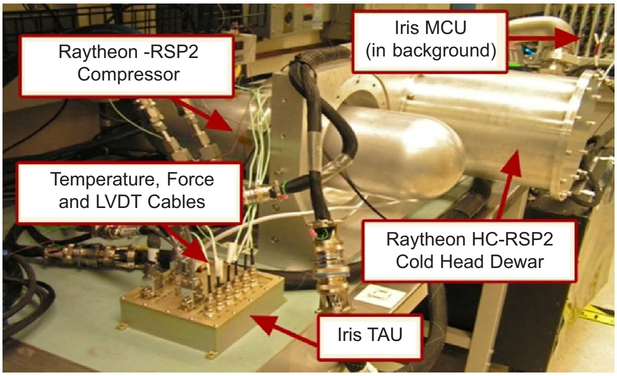


Figure 7: Brassboard MCU and TAU Integrated with the HC-RSP2.

Integration

The first step in integrating the system was to calibrate the piston position sensors so that the cryocooler could be started and operated with full knowledge of piston location. This is critical for hardware safety.

Several software and EMI issues were overcome to enable capture of clean LVDT signals sufficient for safe, closed-loop operation. For example, initial operation of the Raytheon HC-RSP2 with Iris MACE under high power conditions revealed that the piston stroke control code, originally designed for use with the smaller RS1 style cryocoolers, was not properly set up

to deal with the dynamics of the higher power machine. The control code was modified accordingly and shown to be adequate for immediate testing needs.

In the future, use of the code to drive RSP2 machines will likely require further refinement of the control algorithm. Of specific interest is the reduction of steady-state stroke amplitude drifts to increase temperature control and exported vibration control effectiveness. Transient control algorithm behavior, of interest during initial cool-down and other transient operational scenarios, is also a candidate for optimization.

Controlled Low Temperature Operation

With the integration steps successfully completed, high power operation could commence. Automatic cool downs with the compressor drive circuit input power approaching 600 W were demonstrated with the Iris MACE driving the Raytheon HC-RSP2 in temperature control mode. The system was allowed to stabilize under first-stage temperature control at various temperatures in the vicinity of 100 K. Second stage temperatures (uncontrolled) were typically below 25 K, and as low as 17.25 K. Heat loads in the range of 2 W to greater than 12 W were applied to the first stage of the HC-RSP2, and Iris MACE was shown to successfully maintain the temperature setpoint by automatically varying the compressor stroke commands.

While temperature control was demonstrated, the stability achieved (+/- 0.5 K) likely requires refinement for an actual operational scenario. It is believed that two factors are presently impacting the stability. The first is noise in the temperature and piston stroke amplitude telemetry, to which the various control algorithms react. This source of this noise was identified and corrected in a post-integration Iris-funded R&D project. The second factor concerns the fact that the control algorithms, temperature control in particular, have not been thoroughly tuned for use with the HC-RSP2. These algorithms were originally intended for use with the much smaller RS1 cryocooler. Raytheon's HC-RSP2 is significantly more powerful than the RS1 and has a much higher heat capacity at the cold tip(s). It appears that the RS1-tuned control algorithm is only semi-stable when used with Iris MACE and HC-RSP2 such that small perturbations in telemetry and performance result in larger oscillations of the strokes, temperatures and exported disturbances.

Given the vast differences in thermodynamic function and size between Raytheon's HC-RSP2 and the RS1, the degree of success achieved is remarkable and very encouraging for a smooth transition to fully functioning flight-level temperature control.

Vibration Compensated Operation

The HC-RSP2 was allowed to stabilize at a first stage temperature of 100 K with a heat load of 12.44 W. The Adaptive Feed Forward (AFF) vibration reduction algorithm was activated with only the compressor 2nd harmonic enabled, and it was confirmed to be effective. The balancer drive, disabled for previous testing, was enabled by reinserting the fuse into the circuit. The system was restarted and it was found that the polarity of the balancer piston-centering algorithm was inverted. Aside from this small issue - easily addressed via a software change - the balancer operated as expected.

The system was allowed to re-stabilize at a 100K first stage temperature, and AFF was activated one harmonic at a time until the largest forces (occurring on Compressor harmonics 1, 2, and 4, and Expander harmonics 1, 2, and 3) were being controlled. As previously mentioned, factors relating to telemetry noise and control algorithm tuning prevented true stabilization of the system, which in-turn prevented extremely fine vibration control. Despite the non-ideal operational conditions, the system was able to reduce vibration output to a small fraction of the normal values with very minimal tuning of control coefficients. For example, the uncompensated expander vibration at the drive frequency, which is by far the largest uncompensated vibration signal, was reduced by 14.8 dB.

It is also worth noting that the compressor vibration control was performed via the HC-RSP2 trim coil and the MACE dedicated trim coil drive. This Raytheon-patented trim coil enables a dedicated, precision servo for compressor vibration mitigation. This capability is particularly important for high power coolers, like the HC-RSP2, in which the main compressor motors are putting out nominally 250 W each, while the vibration correction power is only on the order of one Watt. Using the trim coil provides a means by which to achieve fine digital command precision on the vibration compensation waveform while providing a coarser but higher bandwidth, distinct main drive waveform.

This was the first test of the trim coil system at high power and a significant step forward in terms of cryocooler vibration control technology.

CONCLUSION

Iris MACE electronics were first integrated with the HC-RSP2 Cryocooler in September 2009. This was the first integration of a non-Raytheon designed and built set of cryocooler electronics with a Raytheon space cryocooler, and it was the first complete set of cryocooler electronics built by Iris. In two short months after the start of integration, high power, closed-loop operation of Raytheon's largest, most complex space cryocooler was achieved. The demonstrated success of the brassboard MACE, and the relative ease with which success was achieved post-integration, bodes very well for the near-term implementation of MACE in a flight-design configuration.

ACKNOWLEDGMENTS

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