Power Systems for Avionics and Motor Control in Deep Space Missions

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Jet Propulsion Laboratory
California Institute of Technology

Agenda

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10. COLD CAPABLE ELECTRONICS
11. CRYOGENIC DAISY CHAIN SOLDER TESTING WITH COTS COMPONENTS
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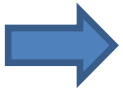
13. CRYOGENIC TESTING OF STANDARD POLYIMIDE SUBSTRATES
14. Cryogenic testing of standard Polyimide Substrates with ENEPIG finish and Au and Aluminum 1mil wire bonds
15. Summary

PROJECT GOAL

- The project's goal is to allow a potential Europa Lander to last longer on the surface or allow more room for additional science by reducing the volume, mass and power of its avionics and the amount of energy required to keep the avionics warm.
- This goal would be achieved through the use of advanced electronic packaging, low power computing and cold capable electronics
-

Baseline Lander Avionics		
Mass	14.13	Kg
Volume	11250	cc
Power	26	W



Tech Lander Avionics		
Mass	3.58	Kg
Volume	1159	cc
Power	13.44	W

Compact Ultra Low Temperature Electronics Goal

Baseline Lander Avionics		
Surviaval	-55C to	+70C

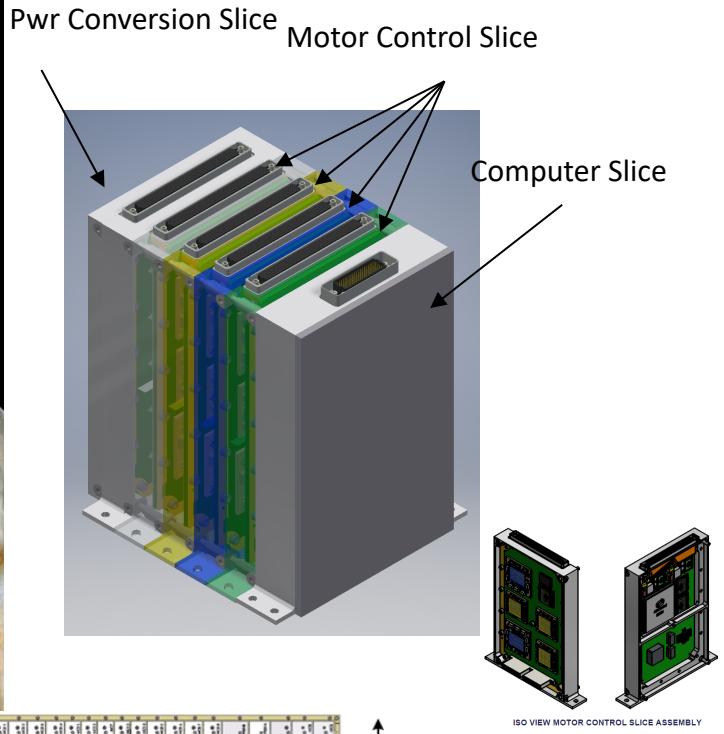
Tech Lander Avionics		
Surviaval	-200C to	+70C

Survival Temperature Goal

Where We Are Headed

Centralized Design

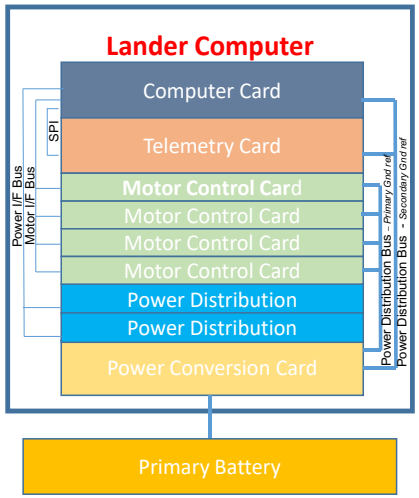
(Europa Lander Baseline)



- Controls 3A & 10A Brushless DC Motors
- Up to 1 motor can be run simultaneously per Motor Controller Card
- 2 Resolver channels per motor
- On board EMI Filter
- 1 Brake Driver per motor channel
- Supports resolver, hall sensor or encoder for commutation
- 28 Volt power bus
- On board commutation and control logic
- Simple transformer isolated interface
- Compact 10cm x 16cm x 2cm/Slice design
- CMC Mass CBE = 3.05Kg; Vol CBE = 3386cm^3
- Slice based packaging approach
- Survival temperature: -184C to +85C
- Operational temperature: -55C to +50C

The Europa Lander has accepted the 10x volume, 2x power and 4x mass reductions that our modules enable.

System Design



Stand Alone Motor Controller

Mass (CBE: 3.05 kg, w/Uncertainty: 3.97 kg)

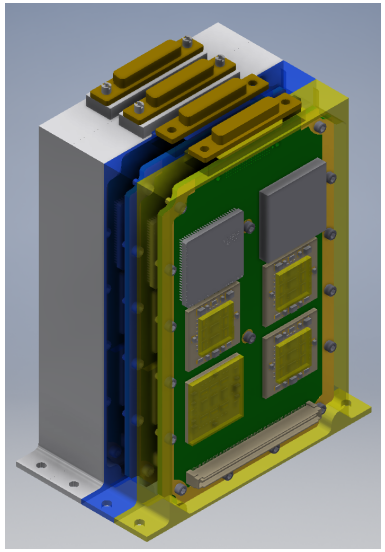
Sub-sys.	Component	Type	# of Units	Each, kg	CBE Total, kg	Uncertainty, %	CBE + Contingency, kg
Stand Alone Motor Controller				**Total**	**3.05**	**30%**	**3.97**
	Computer Card HMC	Computer Card 3U	1	0.50	0.50	30%	0.65
	Motor Control Card HMC	Motor Card 3U	4	0.40	1.60	30%	2.08
	Power Conversion Card HMC	Power Conversion 3U	1	0.75	0.75	30%	0.98
	End Plate HMC	HMC End Plate 3U	2	0.10	0.20	30%	0.26

Volume (CBE: 2604.8 cc, w/Uncertainty: 3386.24 cc)

Lander Computer			**X**	**Y**	**Z**	**Total cc**
	Computer Card HMC	Computer Card 3U	100.00	160.00	26.40	422
	Motor Control Card HMC #1	Motor Card 3U	100.00	160.00	25.00	400
	Motor Control Card HMC #2	Motor Card 3U	100.00	160.00	25.00	400
	Motor Control Card HMC #3	Motor Card 3U	100.00	160.00	25.00	400
	Motor Control Card HMC #4	Motor Card 3U	100.00	160.00	25.00	400
	Power Conversion Card HMC	Power Conversion 3U	100.00	160.00	26.40	422
	End Plate HMC #1	HMC End Plate 3U	100.00	160.00	5.00	80
	End Plate HMC #2	HMC End Plate 3U	100.00	160.00	5.00	80

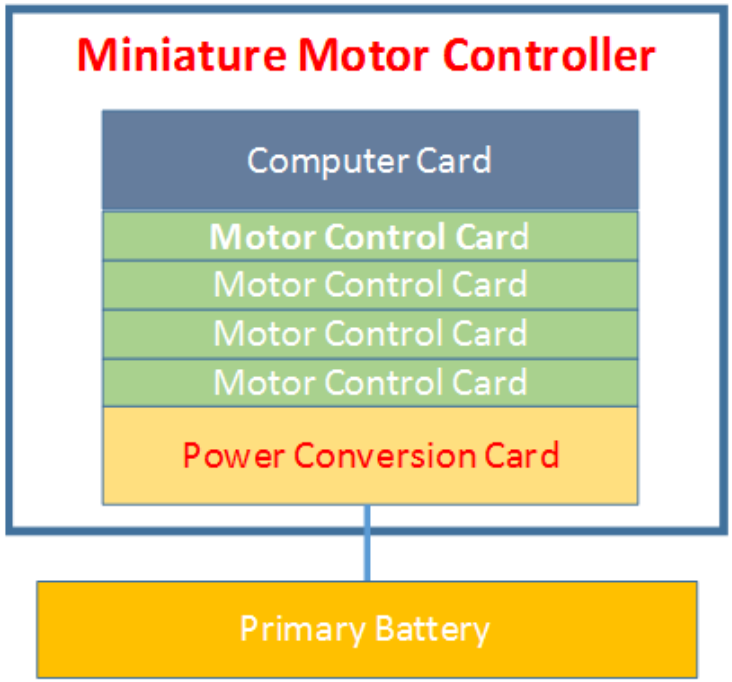
Power (CBE: 18 W, w/Uncertainty: 23.4 W - Worst Case) - Power Numbers are in work

C&DH	**Mode**	**Power**	**Uncertainty, %**	**CBE + Contingency, W**
Computer Card HMC	Worst Case	6.00	30%	7.80
Motor Control Card HMC #1	Worst Case	2.25	30%	2.93
Motor Control Card HMC #2	Worst Case	2.25	30%	2.93
Motor Control Card HMC #3	Worst Case	2.25	30%	2.93
Motor Control Card HMC #4	Worst Case	2.25	30%	2.93
Power Conversion Card HMC	Worst Case	3.00	30%	3.90
End Plate HMC #1	N/A	0.00	30%	0.00
End Plate HMC #2	N/A	0.00	30%	0.00
		18.00		**23.40**



- Each motor card can talk to three motors. Only one motor can run at a time.
- Each resolver module can talk to 3 resolvers.
- Each card has 2 resolver channels per motor.
- One for commutation and one for output position. Six in total. All can be running at any given time.
- There are 4 motor cards in the stack. This gives a total of twelve motors, and 24 resolver channels.

MINIATURIZED MOTOR CONTOL



BASELINE 5.3

10-3-3 Motor Cards

	1	2	3
Driver 1 10A	Excavation Tool	Collection Tool	*spare*
Driver 2 3A	Transfer	Payload Door 3	Wrist Pitch
Driver 3 3A	*spare*	*spare*	HGA El

3-3-3 Motor Cards

	4	5	6	7
Driver 1 3A	Shoulder El	Elbow	Shoulder Az	Wrist Roll
Driver 2 3A	Cap	Payload Door 2	Unload/ Encap.	Payload Door 1
Driver 3 3A	*spare*	*spare*	HGA Az	*spare*

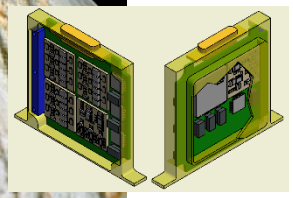
- **Our electronics is now the baselined for the Europa Lander as a standalone motor controller. In this configuration we provide the motor control and motor control computation needs for the Europa Lander. This allowed the Europa Lander to take advantage of our mass and volume savings. The miniaturized motor control assembly is based upon the computer card we developed and motor control modules.**

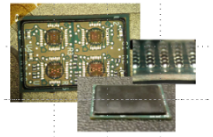
ADVANCED ELECTRONIC PACKAGING

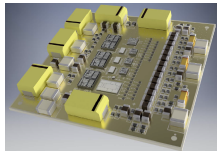
Leverage advanced packaging, cold capable electronics and system on a chip technology to maximize the science return from the baseline Europa Lander.

Advanced Electronic Packaging

Chip On Board Technology

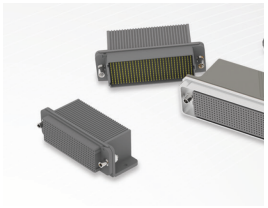






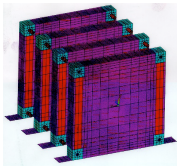
Enables a >10X improvement in board density

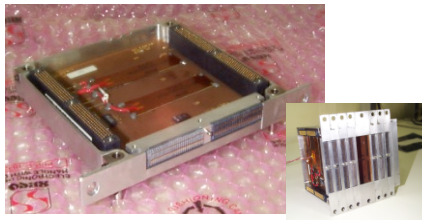
High Density Connectors



Up to 500 pins per connector
3x density of standard micro-D

Slice Based Design

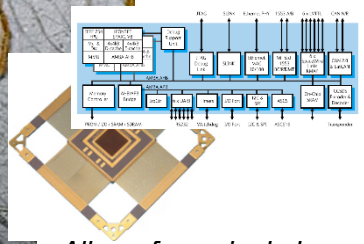




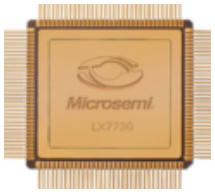
Eliminates backplane and chassis mass

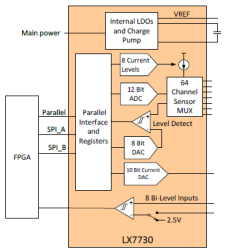
System On A Chip

Single Chip Computer



Single Chip Telemetry Collection

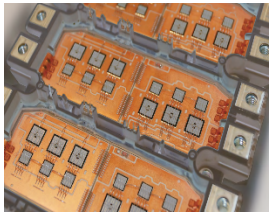




Allows for a single board command and data handling system

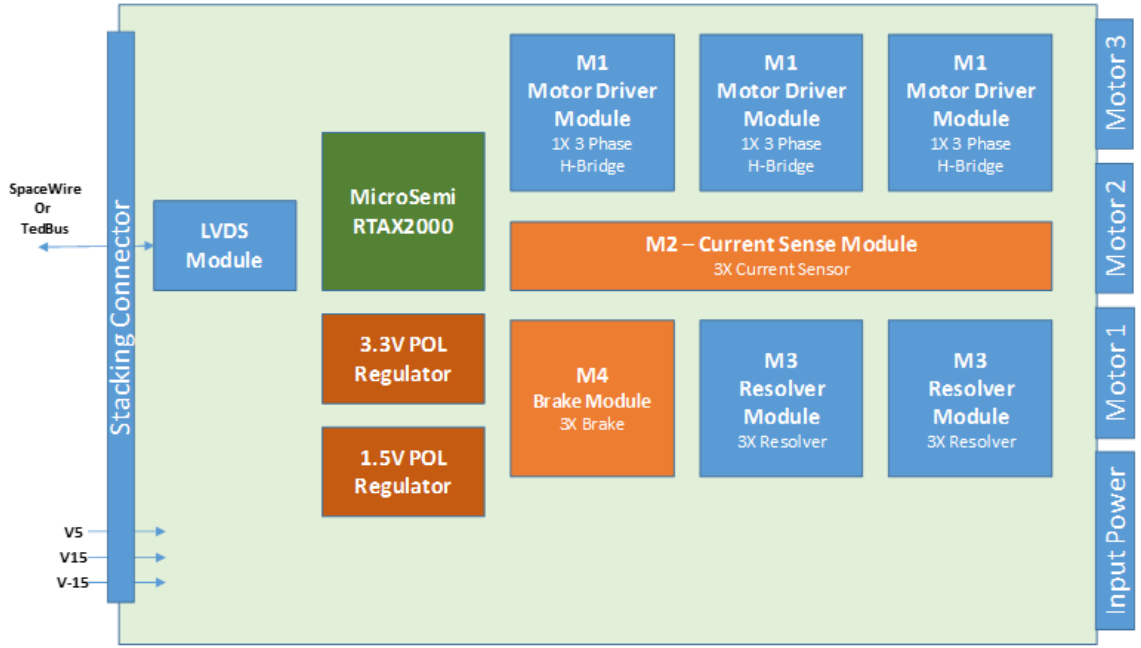
Cold Capable Electronics

Conductive Epoxy



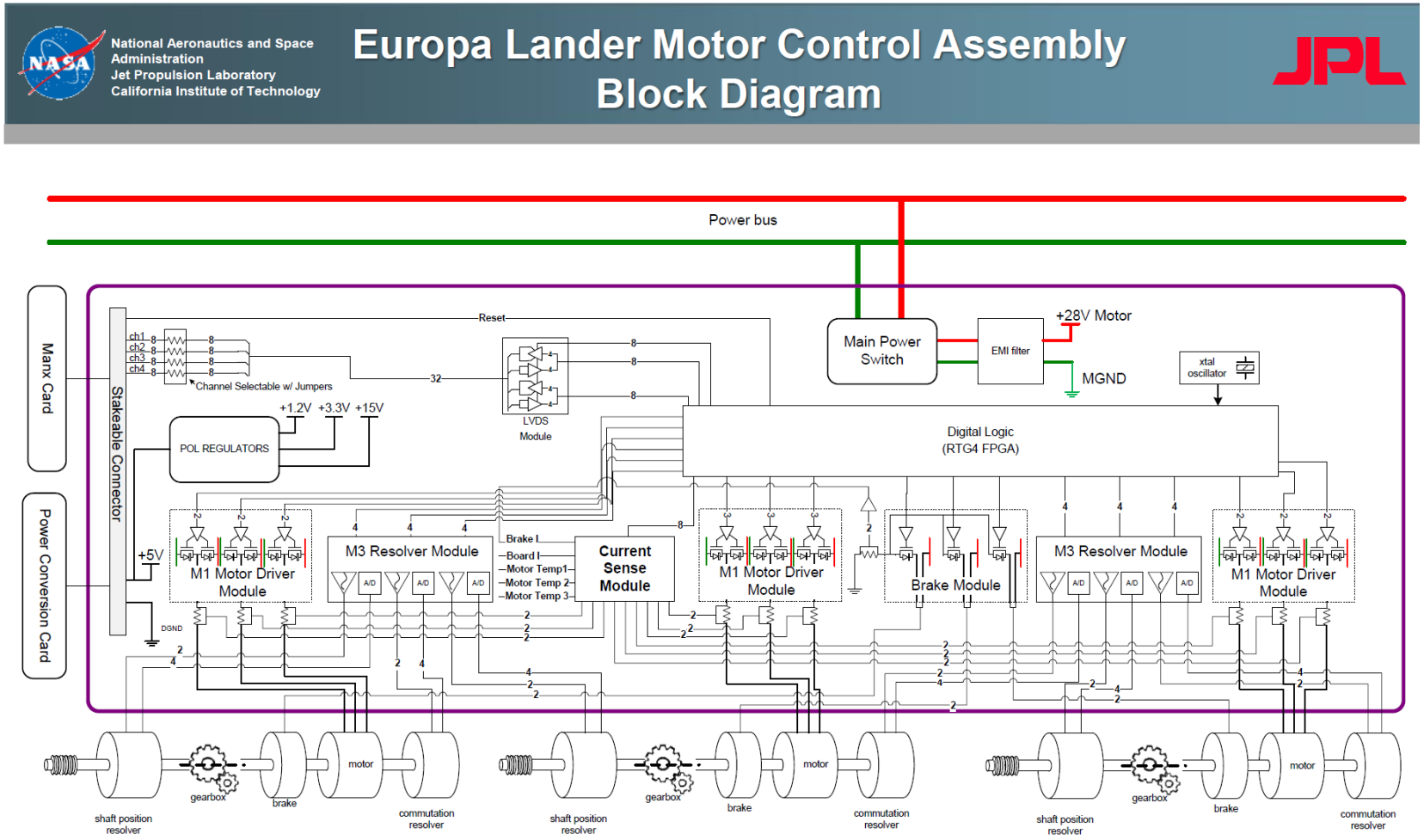
Allows for -200C survival temperatures

Motor Control Card

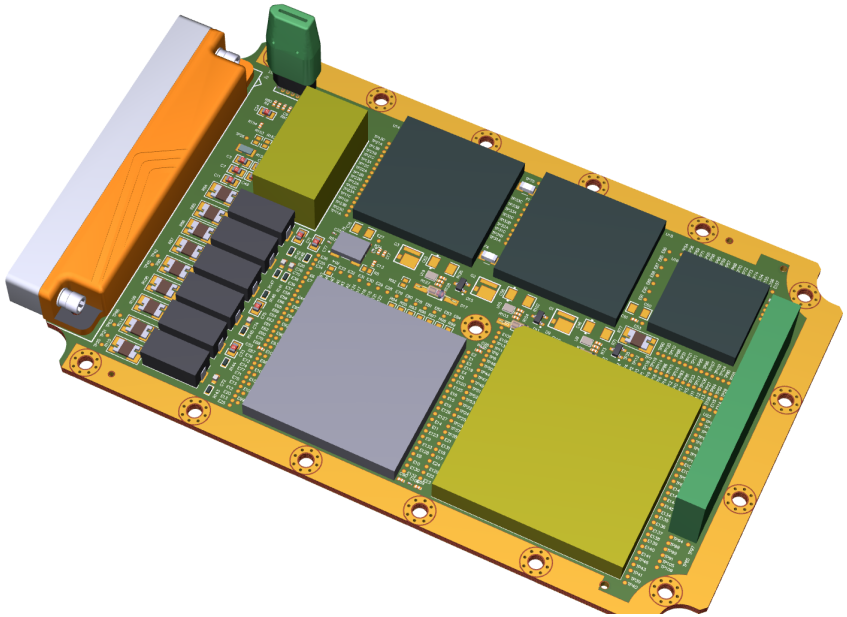


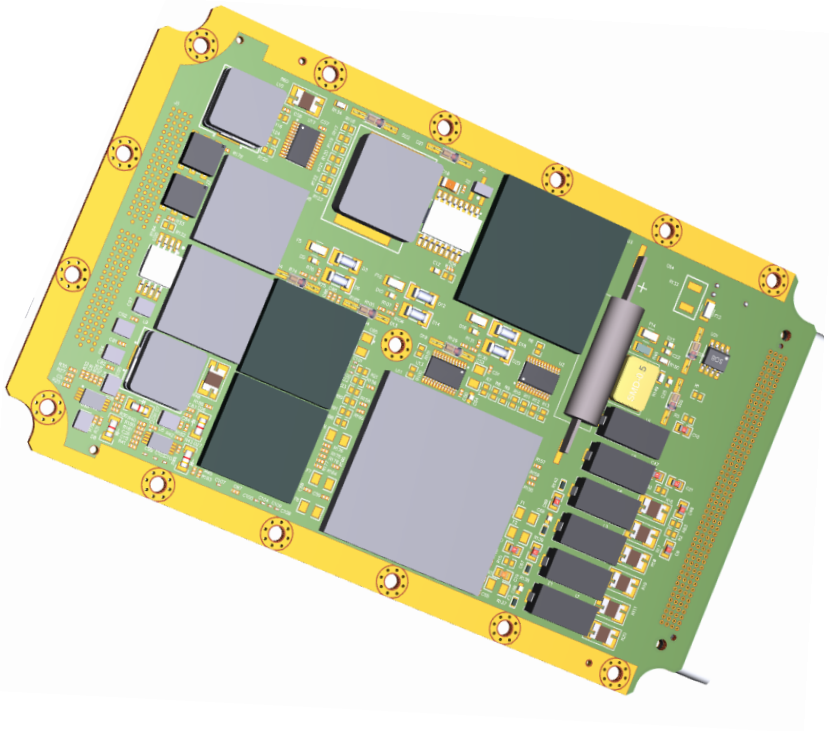
- The design consists of our computer card along with enough Motor Control Cards necessary to control 12 motors.
- Each motor card can control up to three motors.
- Only one motor can run at a time per card.
- Our design allows for the position of each motor to monitored by two resolvers, one motor shaft and one on the output of the gear box. Each resolver module can talk to 3 resolvers. Each card has two resolver modules. Each card has 2 resolver channels per motor. One for commutation and one for output position. Six in total.
- There are four motor cards in the stack.
- This gives a total of 12 motors, and 24 resolver channels.

Motor Control Card Block Diagram

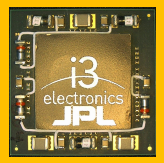
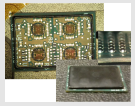
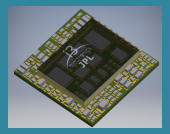
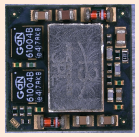
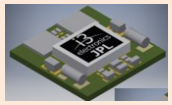


Motor Control Card Board Layout





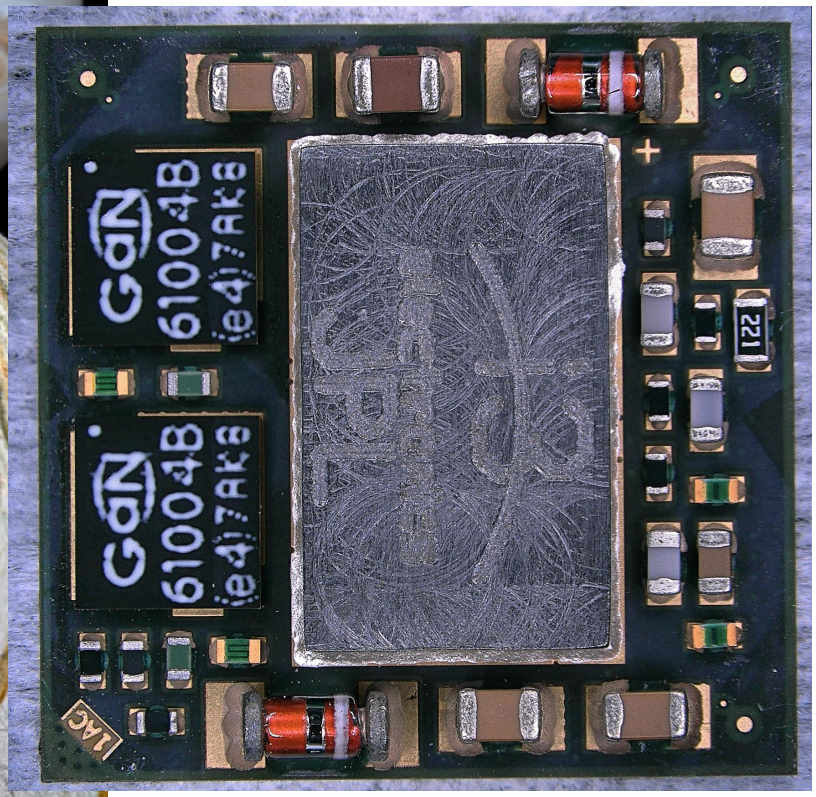
Module Development Heritage

Funding Source	Technology	Picture	Heritage	Status	Current TRL	Ending TRL
GCD	Motor Driver Module		GCD – Ultra Low Temperature Electronics	Prototype module testing complete	5	5
	Resolver Module		GCD – Ultra Low Temperature Electronics	Prototype module testing complete	5	5
RTD	Low Voltage Differential Switching (LVDS) Module		JPL Internal R&TD funding	Prototype module testing complete	5	5
EL	Current Sense Module		Europa Lander	Circuit prototype	2	5
CSDMC	Point of Load Regulator Module		NASA Coldtech	Circuit prototype complete Module design complete	4	5
	Isolated Converter Module		NASA Coldtech	Circuit design in progress	2	5

All of the needed motor control modules will be ready for infusion into the Europa Lander Motor Control Card by March 2019.

Technical Progress

Point Of Load Module



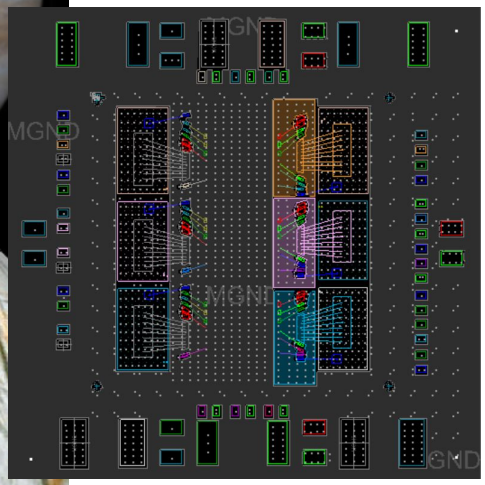
- Input Voltage: 3.3V to 36.0V
- Output Voltage[1,3]: 1.225V – 15.0v
- Output Current[2] up to 5A
- Efficiency > 90% (5V input, 3.3V 3.0A)
- Buck Converter Topology
- Adjustable switching frequency
- Input voltage under voltage protection
- 300KRAD Tolerant
- 1.7cm x 1.7cm compact size
- Storage temperature as low as -180C
- Over current protection
- Under voltage lockout

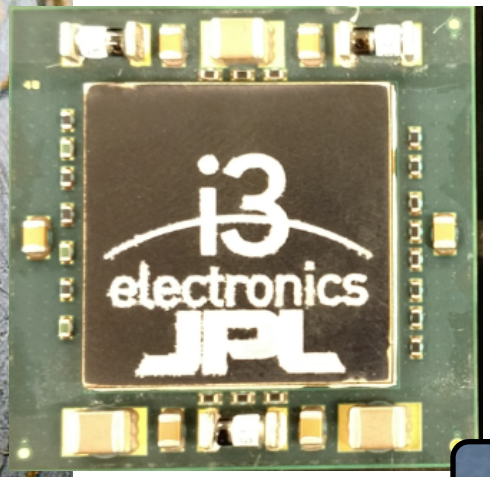
[1]Output voltage is user selectable.
[2]Output current is determined by external inductor and capacitor selection.
[3]Output voltages below 1.225V are possible with application of an external reference.

Our POL module represents the only integrated point of load regulation solution for Europa missions that require 300Krad radiation tolerance.
Applying this module to the industry standard RAD750 would cut its power consumption by 25%.

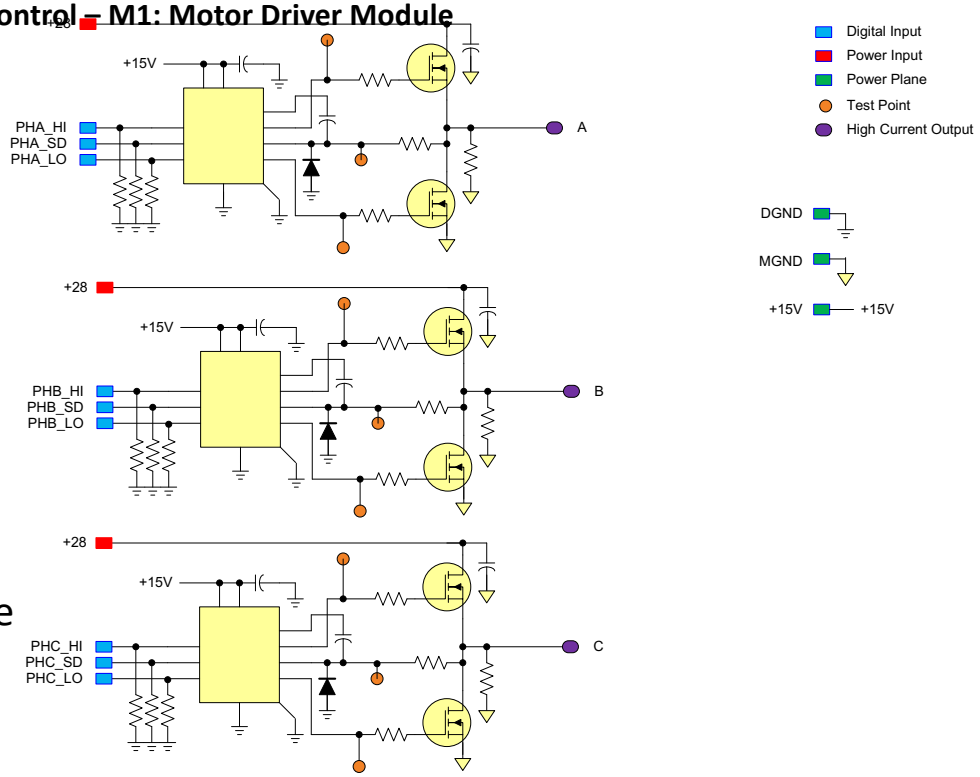
Motor Driver Module

I3 M1: Motor Driver Module - Status





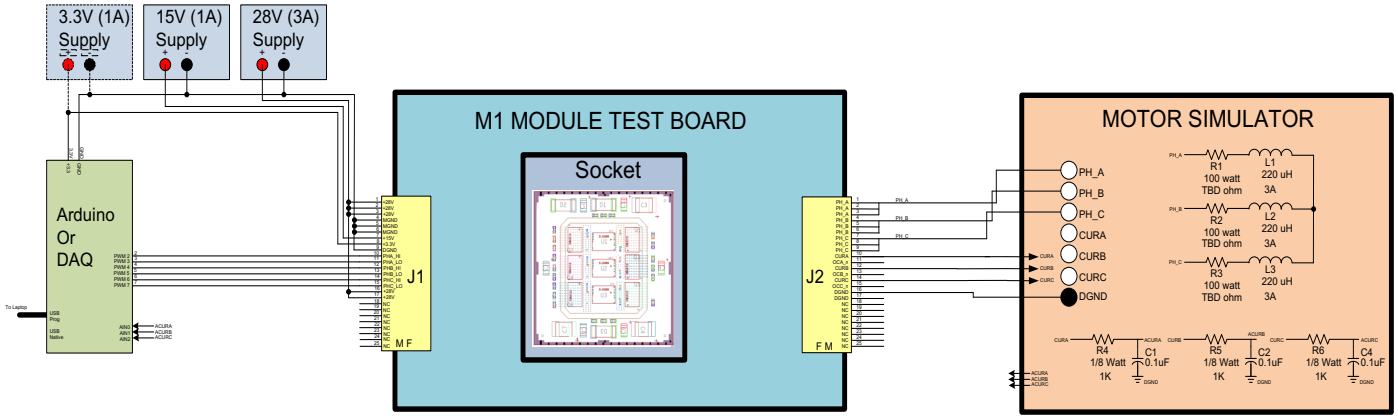
- S# - 001
- M1 Module

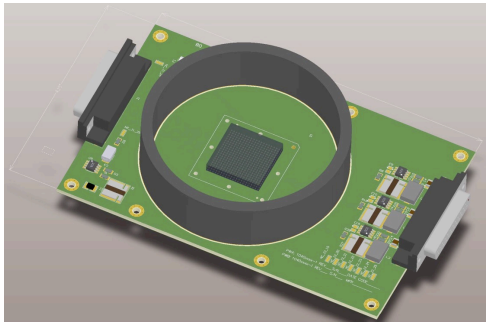


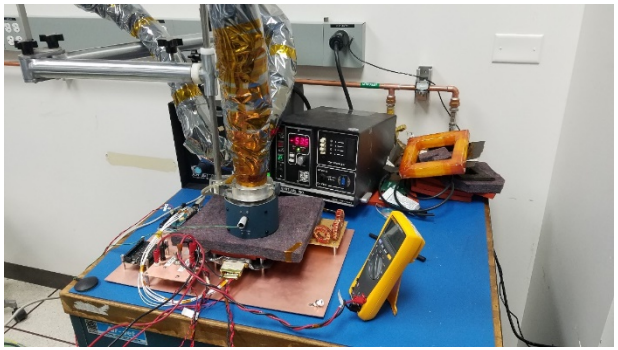
EUROPA LANDER
MOTOR CONTROL M1 MODULE
J. WATERS – Edited by Gary Bolotin
12 FEBRUARY 2016

7cm x 7cm worth of circuitry reduced to 2.5cm x 2.5cm

Motor Driver Module Testing



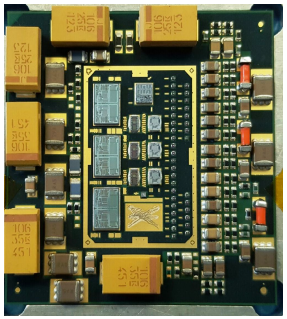


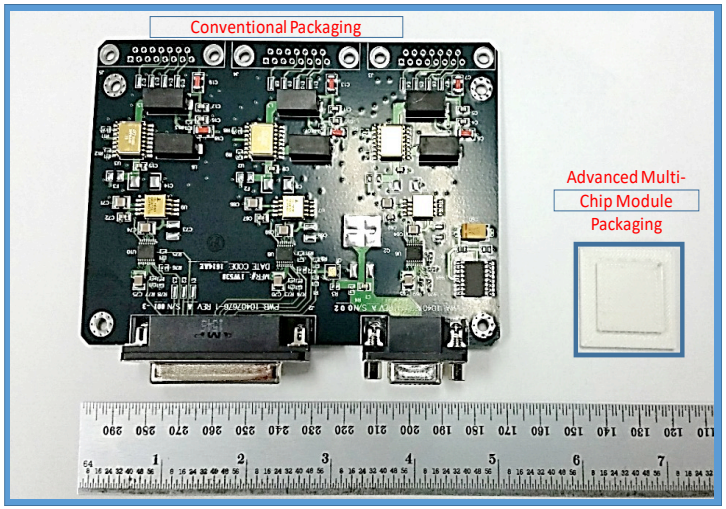


Module testing is complete

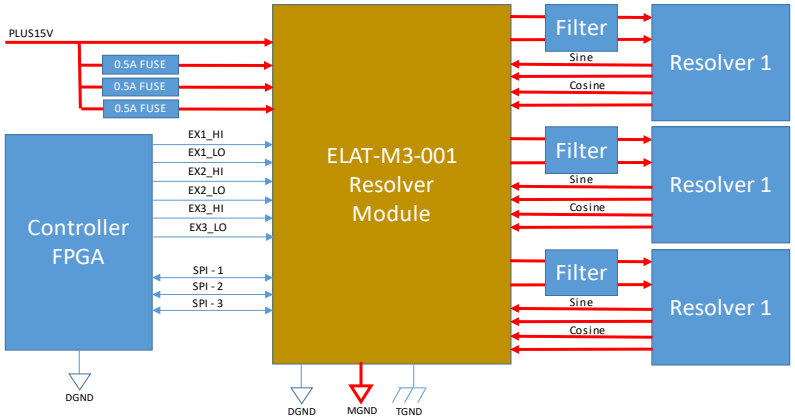
Resolver Module

- Advanced Packaging – M3 – Resolver Module
  - Production of first module is complete. First part received at JPL 12/21/16.

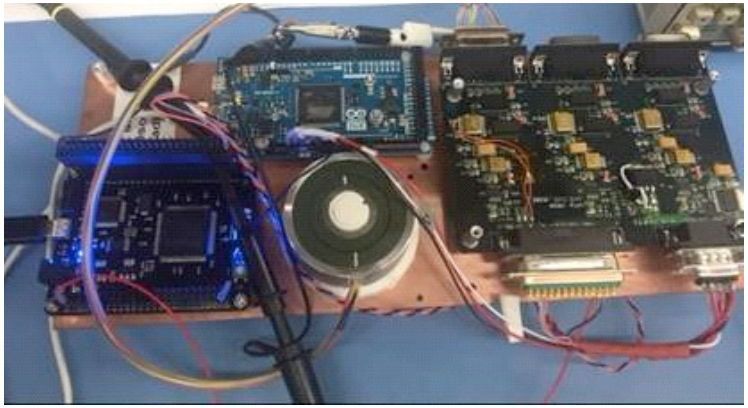


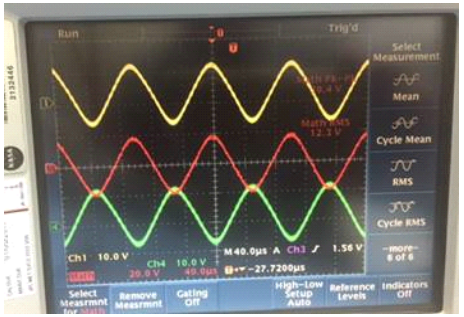


  - Single provides interface to 3 resolvers

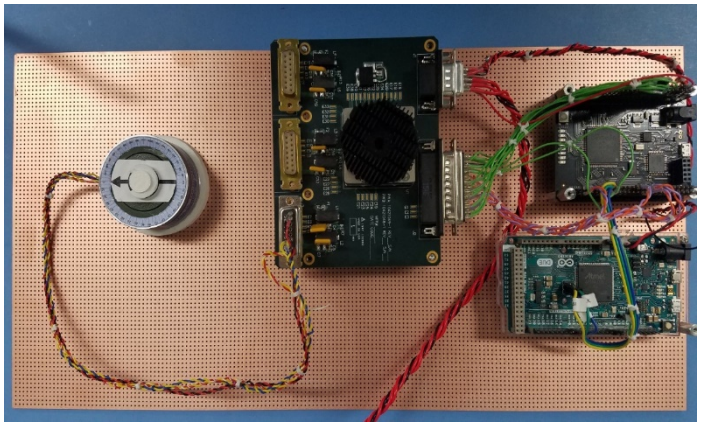


Resolver Module Testing





Resolver Module Breadboard

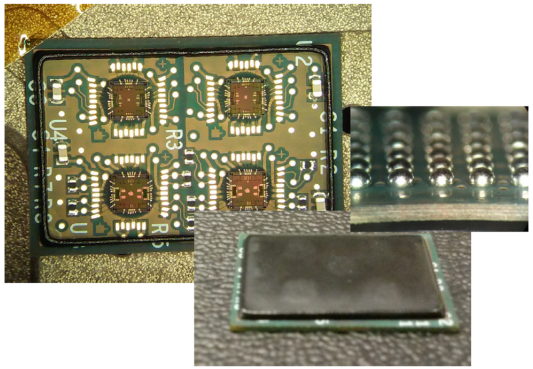


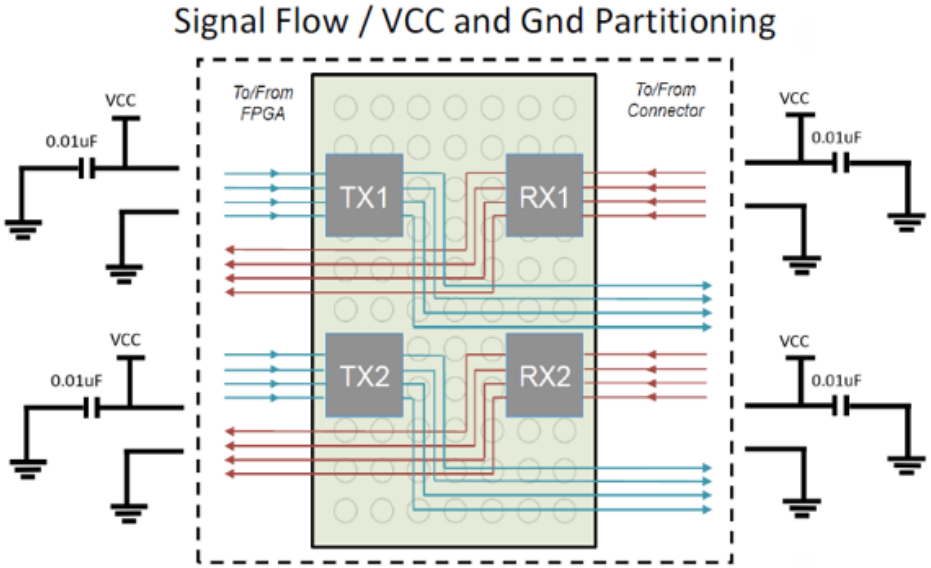
Resolver Module Test board

Module testing is complete

LVDS Module

- Developed under JPL's IRAD: 5x UNIBUS R&TD
- 2 Aeroflex LVDS receiver die
- 2 Aeroflex LVDS transmitter die
- On module bypass and termination
- 5x reduction in board area compared to conventional packaging
- 1.7 x 1.1 cm

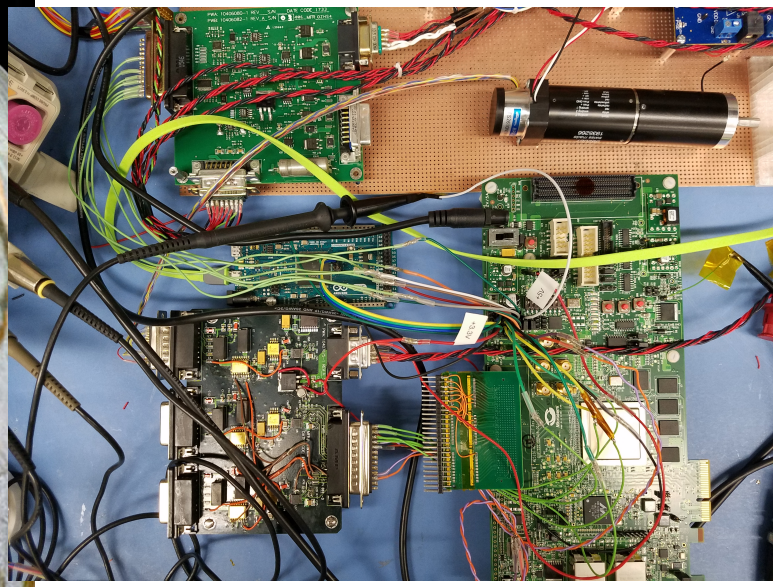




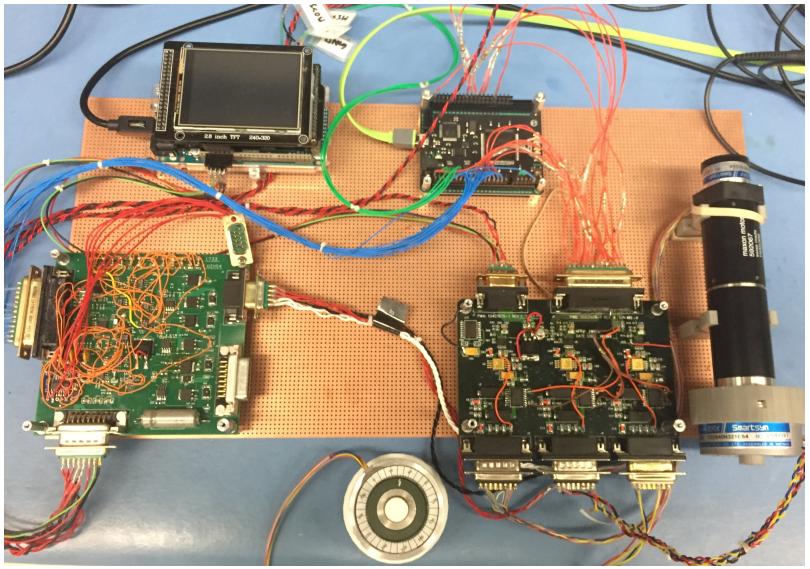
1.2 Motor Control Demonstration

- Two testbeds were constructed to show that our designs are able to play together and to allow for firmware and software development.

Testbed incudes FPGA, Resolver, Motor Driver and Current sense module breadboards or modules



Testbed #1



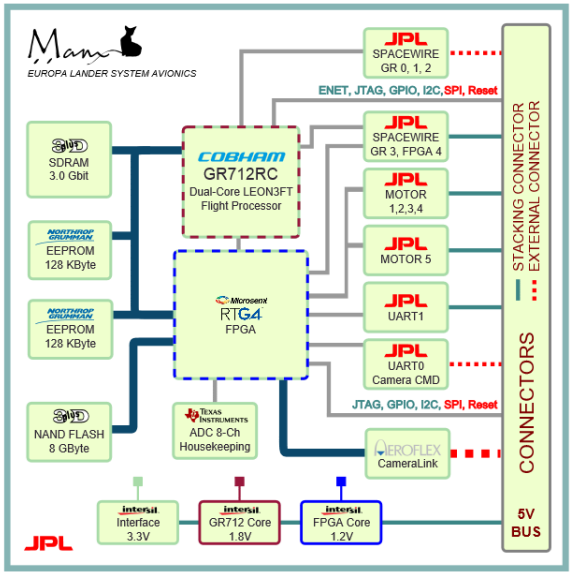
Testbed #2

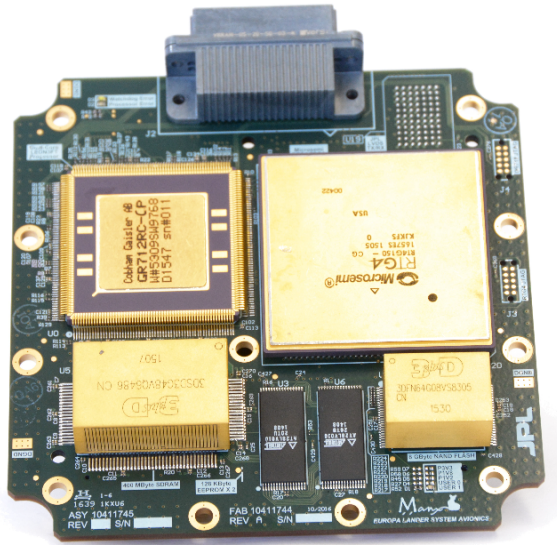
We have completed a demonstration that shows all major pieces are working together.

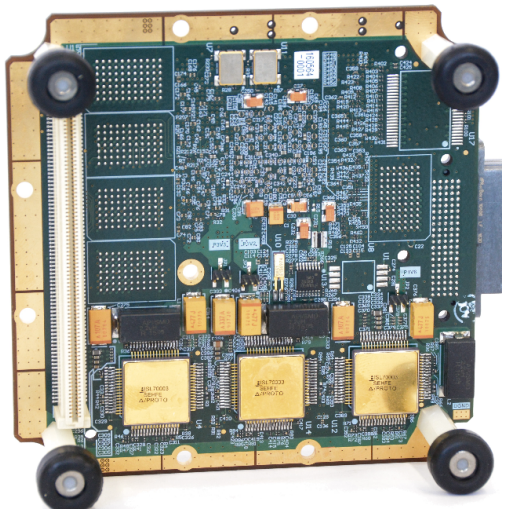
Manx: Low Power Computer

link to agenda

Processor	Gaisler Cobham GR712, Sparc, Dual-Core
FPGA	Microsemi RTG4
Radiation Environment Target	300 kRad TID
Operating Voltage	5V
Input Voltage (recommended)	5V
Input Voltage (limits)	5-TBD V
Spacewire Links	10 (5 scoped for Motor Control)
UARTS	2 (FPGA)
Peripherals	ENET, I2C, SPI, GPIO, CameraLink
Housekeeping	8ch ADC (Voltage, Temp, Curre
Non-Volatile Memory	8GBytes NAND, 128KBytes X 2 bootloader
Processor Memory	400MBytes SDRAM
Processor Clock Speed	100 MHz (configurable)
Connectors	100 Pin VerSI, 160 Pin Mezzanine







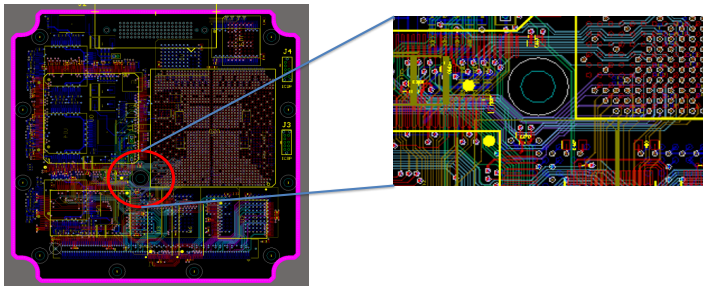


Illustration of Computer Card Wiring Density

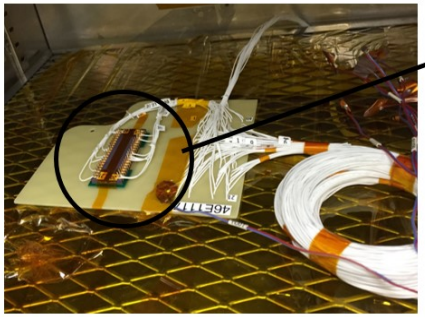
Cold Capable Electronics

- Work in the area of cold cable electronics consisted of three major thrust areas.
  - The first was cryogenic testing of key components.
  - The second area was thermal cycle testing of packages representative of the type of packages we envision using on the Europa Lander.
  - The third area was recommendation of design rules for cryogenic temperature cycles.

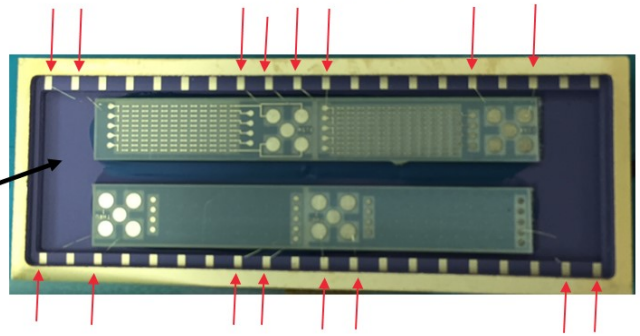
CRYOGENIC DAISY CHAIN SOLDER TESTING WITH COTS COMPONENTS

Tests were conducted to test the effectiveness of the i3 CoreEZ substrate / ENEPIG finish / Gold and Aluminum wire bonds

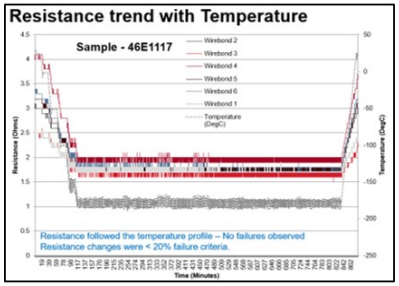
Test Vehicle

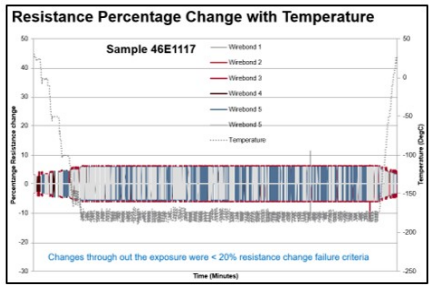


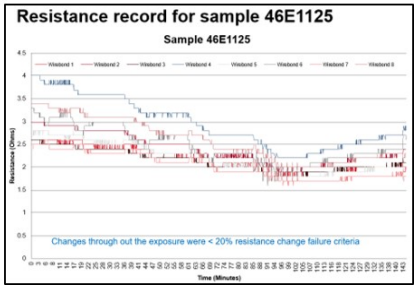
Wirebonds



- Ceramic Test Package
- Epoxy attach
- CoreEZ Substrate
- Au Wirebonds





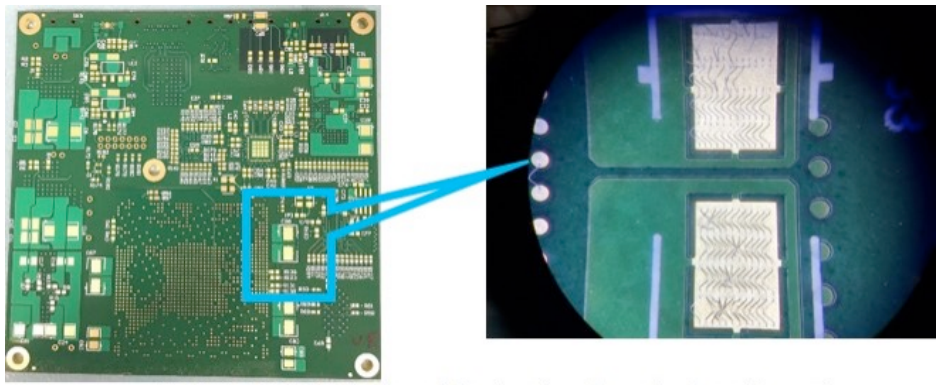


No anomalies found over the temperature ranges 25C to 0C to -50C to -100C to -150C to -180C with (20 hr soak) back to 25C (15 dwell @ each temperature).

- pass criteria was no more than a 20% increase in resistance at a specific temperature

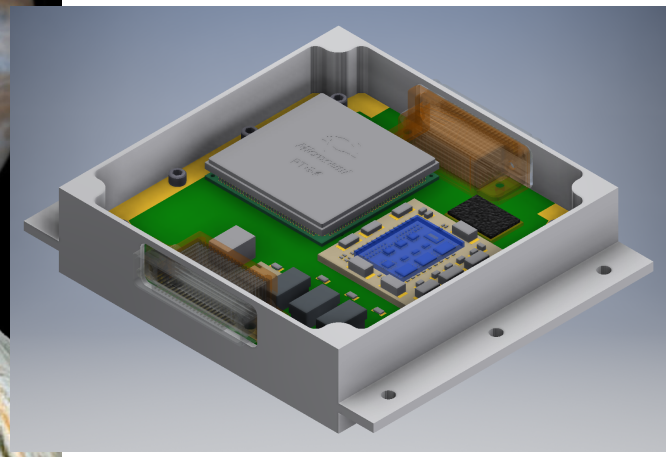
Cryogenic testing of standard Polyimide Substrates with ENEPIG finish and Au and Aluminum 1mil wire bonds

- Efforts at JPL have qualified Electrolytic Au with gold and aluminum wire bonding to survive Martian environments using conventional polyimide substrate.
- A new SOA commercially available finish is required to achieve fabrication of fine features need for MCM solutions. ENEPIG was selected.
- After 500 thermal cycle (–55°C to 125°C) and 250 thermal cycles (–130°C to 85°C), no destructive wire bond pull test per MIL-STD-883 for 1 mil wire was observed to have values below the average pull strength minus three times the standard deviation or less than 3.0 grams.

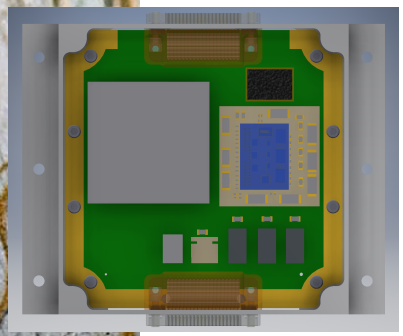


ENIPIG Wirebond Evaluation Sample Bond Locations

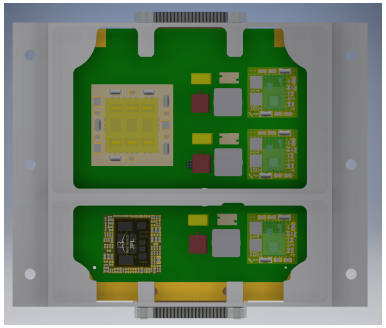
Cold Survivable Distributed Motor Controller



Proposed CSDMC Configuration



CSDMC Front



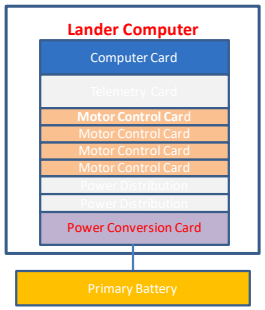
CSDMC Rear

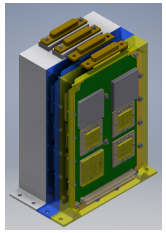
- Controls 1X - 3A Brushless DC Motor
- Constructed out of already developed modules
- Features
  - 2 Resolver channels
  - 1 Brake Driver per motor channel
  - 1 Motor Driver
  - Point of Load Regulation
  - Supports resolver, hall sensor or encoder for commutation
  - 28 Volt power bus
  - On board commutation and control logic
- **Compact 10cm x 10cm x 3cm design**
- CMC Mass CBE = 0.3Kg; Vol CBE = 300cm^3
- Survival temperature: -180C to +125C
- Operation temperature: -55C to +85C

Our CSDMC is small enough to be distrusted at the actuators and to fit within the hollows of the robotic arms. No energy is required for survival heating.

Path Forward

- Europa Lander Project Baseline
  - A standalone centralized motor controller based upon our technology is incorporated into the 4.0 baseline that will carry them through the MCR
  - Project is taking advantage of our mass and volume savings
  - Computer handles motor control functions.





100mm x 160mm x 74mm

- The SMD COLDTECH proposal "Cold Survivable Distributed Motor Controller (CSDMC)" 2-year, $1.2M, PI: Gary Bolotin, was selected.
  - This proposal is aimed at developing a distributed motor controller
  - Proposal is based upon modules developed during this effort
  - Funding is now at JPL. Work started March 1, 2017

Summary

- Our LDVS, Motor Driver and Resolver Modules have all been design, built and tested over the Mil-Spec. temperature ranges.
- These modules are ready to be incorporated into future designs for the potential Europa Lander and other missions.
- Our computer card has been built and tested in an ambient temperature.
- There are two main areas of infusion for our technology.
  - Our avionics package is the baseline for motor control for the Europa Lander concept.
  - Another venue for infusion is through the selected COLDTECH proposal “Cold Survivable Distributed Motor Controller”.
- The potential Europa Lander delivery would include our motor control modules packaged into a motor control card along with our computer card.
- A NASA funded COLDTECH task called COLD SURVIVABLE DISTRIBUTED MOTOR CONTROLLER (CSDMC) will use our motor control modules as the basis for developing a motor control package capable of controlling one motor and packaged small enough to be distributed at the motors.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov