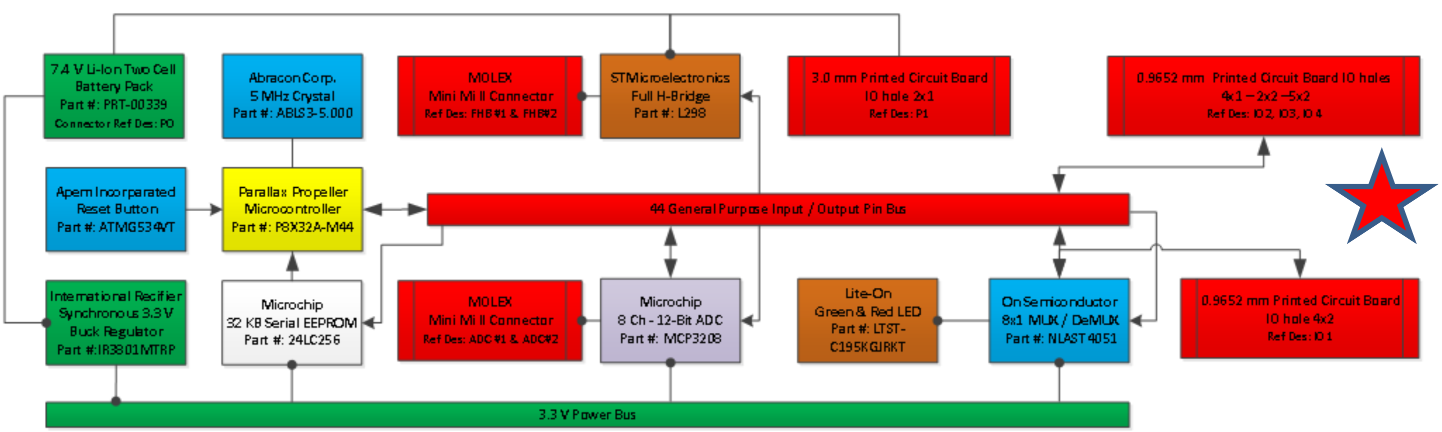
1.0 Product Overview

1.1 Introduction

The GDB E-Series was developed by Solar System Express (Sol-X) to be a *space tolerant* open hardware and software electromechanical prototyping board, enabling any type of person to create extreme environment (desert, radiation spill, ocean floor, burning building…) hardware. Sol-X designed the GDB to be the best prototyping platform on the market and we intend it to replace the Arduino Uno® (and others – See Table 2) as the preferred high-level prototyping environment. Compared to the Arduino Uno® the GDB is up to 85x faster, 74% smaller, has integrated high power drivers (capable of handling 12x the current), and more flexible Input / Output configurations.

The GDB can help create extreme environment products, but it isn't just for that. It's a powerful and versatile programing board that engineers, artists, designers, and students can use in any project they can imagine. This includes prototypes and minimally viable products involving pressure, light, and Inertial Measurement Unit (IMU) sensors, high current motors, servos, LED lighting, and many other human/computer interfaces. Our quick release breakout board (called Ejection Seat™) allows for easy prototyping, yet keeps the GDB form factor small and robust enough to use in company MVP / initial product releases; saving time and lowering the cost to get to market from the prototype stage.

Figure 1- GDB E-Series Block Diagram



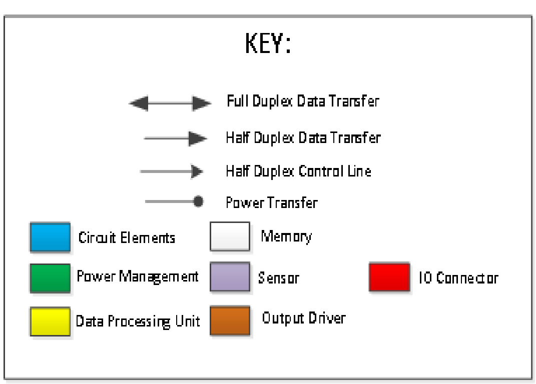


Table 1 – Circuit labels for Figures 2 and Figure 3

0	P8X32A-M44	1	ABLS3-5.000	2	24LC256
3	LTST-C195KGJRKT	4 4C	L298P Connector	5 5C	MCP3208 Connector
6	NLAST4051	7	MJTP1122TR	8	IR3801-3.3
9 9C	PRT-00339 (not shown) Connector	10	3.3V & GND outputs	11	GPIO Pins
12 12C	Prop Plug (not shown) Connector	13	High Current Power Input Connector	14	3 Point Bolt Down Holes

1.2 GDB Series Nomenclature

- E Series - For Earth and Low Earth Orbit based applications where size and ease of programming matter. This GDB E-series is space tolerant through the use of Roger 4003 based PCB's, thermal spreaders, soldermask color, via paste fill, tin-whisker free solder chemistry, and thermally conductive vibration proofing epoxy.
- M Series – For Mars / Planetary based applications where our TDS-1 & Demron® shielding methodology, K-Strap thermal spreaders, and our patent pending DOUBLE triple modular redundancy architecture will protect the electronics.
- S Series - For free space based applications where Intersil RAD hard components are a required. We have not solved all the technical problems for this series yet, but we are working hard to make a GDB based O'Neill space colony possible.

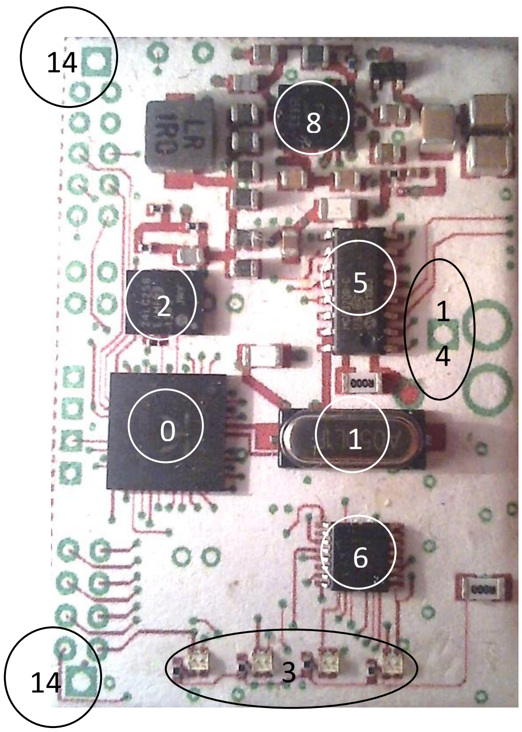


Figure 2 - Bottom view of the GDB E-Series Mark I

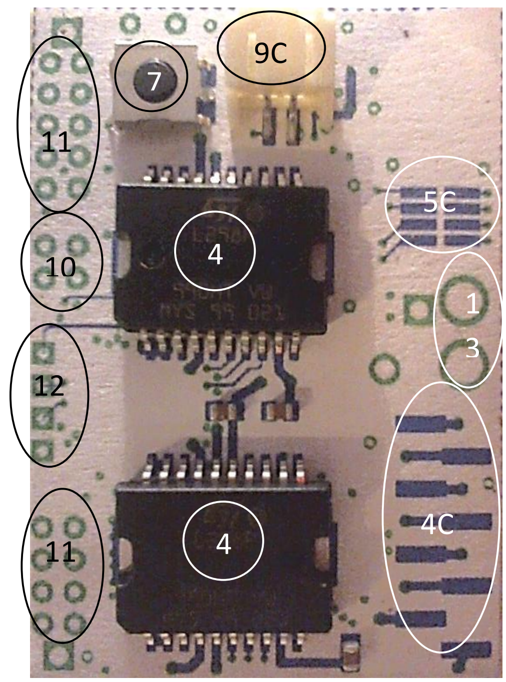


Figure 3 - Top view of the GDB E-Series Mark I

1.3 Stock Codes

Table 1 - GDB Stock Codes					
Product Name	Device Stock Number	General Purpose Input / Output Pins (GPIO)	Input Voltage Range	Minimum and Maximum Current & Power Draw	Physical Dimensions
E-Series Mark I	GDB-EI	20	4.5 to 12 V	10 mA (46 mW) to 6 A (72 W)	55 x 38 x 10 mm
E-Series Mark II	GDB-EII	TBD (Goal: 28)	TBD (1.8 to 16)	TBD (4 mA (23 mW) to 8A (128 W))	TBD (45x45x10 mm)

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revolutionary performance | superior price | unlimited possibilities

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1.3 Key Features and Benefits

The E-Series GDB software controls all the open source hardware functions (LEDS, SPI, PWM, ADC, Full H-Bridges, I/O configuration, chip reset, internal counter timing, sine & log tables, software UART's and memory data logging) creating a high level hardware API for users.

1.3.1 Community Support

- **Propeller Object Exchange** – The place for Propeller community members to share "open source" objects and snippets written for Parallax Semiconductor's Propeller microcontroller.
- **First SPIN YouTube Podcast** - A 30-minute podcast series that assumes you have extremely little to no experience coding, where the three hosts ask and answer questions that experienced programmers may take for granted. – TYMKRS

1.3.2 Ease of Programming and Debugging

- **Sol-X GDB Hardware API** - Proprietary SPIN and computational-efficient Assembly Language software to control all the GDB open source hardware functions.
- **12 Blocks™ / Relativity™ GUI** - An intuitive, powerful environment for programming popular robots on Windows, Mac, or Linux. It is a visual language that makes programming as simple as drag-n-drop.
- **ViewPort™** - The first class debugging environment for the Propeller. The tool combines an integrated debugger with powerful graphics that monitors variables over time with the built in oscilloscope or can change their values while your Propeller is running.

1.3.3 Technical Spec Comparison

See **Table 2 on page 6** for full details:

- **Size:** 74%, 69%, and 67% smaller than the Arduino Uno, Raspberry Pi, and Beagle Bone, respectively.
- **Nominal clock speed:** 80 MHz; however, if you run all eight of the internal processors you can run at 1.024 GHz. The Uno, Raspberry Pi, and Beagle Bone are single processor architectures.
- **RAM:** 32 KB - 16x more than an Arduino Uno.
- **FLASH:** We ship our product with more memory than the Uno, Pi, and Beagle Bone.
- **EEPROM:** 32 KB to save your application code to when power is disconnected.
- **Input Voltage:** 4.5 V to 12 V - Largest range compared to the Uno, Pi, and Bone.
- **Min System Power Draw:** 10.1 mA (45.5 mW), which is 76%, 98.5%, and 94% less current draw than the Arduino Uno, Raspberry Pi, and Beagle Bone respectively.
- **Max Power Output:** 6 Amps (72 Watts) Highest value compared to the Uno, Pi, and Bone. Drive tanks tread right out the box.
- **Digital GPIO:** 20 - Who really needs 66 pins? We trade GDB size and I/O speed for a lower pin count.
- **Analog Input:** Eight 12-bit channels - Highest resolution and number of channels compared to the Uno, Pi, and Bone!
- **Ethernet:** N/A**** - Not really a MVP function since it is not used by beginners normally.
- **USB Master:** N/A - Not used in most DIY projects. Removed to save you money!
- **Video Output:** With a $23 convertor the GDB can do HDMI, but who needs HDMI for embedded projects?
- **Audio Output:** Analog or HDMI

Table 2 – Comparison to competition[1]

Category	GDB	Arduino Uno	Raspberry Pi	Beagle Bone
Model Name	E-Series	R3	Model B	Rev A5
Size (millimeters)	54 x 37 x 10	75 x 54 x 19	86 x 54 x 21	86 x 53 x 21
Processor	Parallax Propeller	ATMega 328	ARM11	ARM Cortex-A8
Available Clock Speeds	20 kHz to 128 MHz (1.024 GHz)*	62.5 kHz to 20 MHz	50 MHz to 700 MHz	300 MHz to 1 GHz
Nominal Speed	80 MHz	12 MHz	700 MHz	1 GHz
RAM	32 KB	2 KB	256 MB	512 MB
Flash (ships with)	4 GB (micro SD)	32 KB	(NO SD CARD)	2 GB (micro SD)
EEPROM	32 KB	1 KB	N/A	N/A
Input Voltage	4.5 – 12 V	7 – 12 V	5 V	5 V
Min System Power Draw	10.1 mA (0.0455 W)	42 mA (0.3 W)	700 mA (3.5 W)	170 mA (0.85 W)
Max Actuator Power Output	6 A (72 W)	0.5 A (2.5 W)	0.5 A (2.5 W)	2 A (10 W)
Price (1,000+ units)	$65.00**	$29.96	$35	$45
Digital GPIO pins	20	14	8	66
Analog to Digital Conversion (Input)	Eight 12-Bit	Six 10-Bit	N/A	Seven 12-Bit
Digital to Analog Conversion (Output)	Ten 10-Bit[2] +Two 12-Bit	Six 10-Bit[2]	N/A	Eight 12-Bit[2]
PWM	10	6	N/A	8
TWI/I2C	1	2	1	1
SPI	1	1	1	1
UART	1	1	1	5
Development IDE	Propeller Tools & 12 Blocks™	Arduino Tool	IDLE, Scratch, Squeak™/Linux	Python, Scratch, Squeak™, Linux
Ethernet	N/A****	N/A	10/100	10/100
USB Master	N/A	N/A	2 USB 2.0	1 USB 2.0
USB Slave	1 USB 2.0	1 USB 2.0	2 USB 2.0	1 USB 2.0
Video Output	VGA, HDMI*** or composite video (NTSC or PAL) output	N/A	HDMI or composite	N/A
Audio Output	Analog or HDMI***	N/A	Analog or HDMI	Analog or HDMI

*1.024 GHz if your code can use all EIGHT on the Propellers internal processors.
The Uno, Pi, and Bone are single processor architectures.
**Estimated price at 1,000+ units. The current sale price is $160
*** Possible with a $20 HDMI to VGA/Analog Convertor
**** Will be available via future expansion shields

GO TO THE FOLLOW URL TO GET ACCESS TO THE EMBEDED LINKS http://goo.gl/Z5aE70

1.3.4 Open Source / Free Software Tools

- Eagle™ PCB – provides quality PCB design software with the features that get the job done. This easy to use software utilizes schematic editor, layout editor, and library editor modules with identical user interfaces.
- SchemeIt™ – provides online, in-browser tools for schematic and Bill of Material (BOM) capture. This tools allow students, hobbyists, and professional engineers to design and analyze analog and digital systems before ever building a prototype.
- 123D Design – For people who want to make things themselves, Autodesk 123D is free 3D modeling software integrated with content and fabrication services.
    - Add additional pieces to the GDB using any of these free 3D model websites.
        - CAD Forum
        - Grad CAD
        - 3D Content Center
        - Trimble 3D warehouse
        - Thingiverse
        - Team Platform
        - Sunglass
- **(Future Work)** gEDA Project - Currently, the gEDA project offers a mature suite of free software applications for electronics design, including schematic capture, attribute management, bill of materials (BOM) generation, netlisting into over 20 netlist formats, analog and digital simulation, and printed circuit board (PCB) layout.

1.3.5 Open Source / Free Hardware Tools

- Aligni™ – A cloud-based software for product lifecycle and manufacturing management of BOM's, vendors, and pricing.
- Get free samples to build a GDB :

E-Series: STMicroelectronics
E-Series: Abracon
E-Series: Lumex
E-Series: MicroChip
E-Series: Lite On
E-Series: SAMTEC
E-Series: TDK Corporation
E-Series: Vishay Beyschlag
E-Series: t-Global Tech

E-Series: TE Connectivity
E-Series: IRC Electronics
E-Series: ON Semiconductor
E-Series: APEM
E-Series: JST
E-Series: Panasonic
E-Series: IR
E-Series: Qualitek
E-Series: Bourns

M-Series: Atmel
M-Series: Intersil

More M-Series links coming soon

- Find your local Hacker Space for free tools
    - Map
- ExpressPCB™ - Free PCB software that is a snap to learn and use. For the first time, designing circuit boards is simple for the beginner and efficient for the professional.
- **(Future Work)** Fritizing™ - Fritzing is an open-source hardware initiative to support designers, artists, researchers and hobbyists to work creatively with interactive electronics.

Figure 4 - Do you?

1.4 Applications

What you create is up to you. Here are some of the things the engineers at Solar System Express have thought of http://goo.gl/amoX99 ☺

1.4.1 Possible Applications

- **Students**
  - ✓ Cube Sats
  - ✓ Pocket Cubes Satellites
  - ✓ High altitude balloon flights
  - ✓ Or senior Design Projects
    - Unmanned Aerial Vehicles
    - Medical devices prototypes
- **Hobbyists**
  - ✓ LED walls or clothing
  - ✓ Tracking weather data
  - ✓ Phonebloks
  - ✓ Or small projects around the house
- **Small technology firms**
  - ✓ Open Luna – Suits & Lander
  - ✓ LiftPort Group - Lunar Elevator
  - ✓ Vulcan Aerospace - Rebreather unit
  - ✓ Google Lunar X PRIZE teams
  - ✓ Space Energetics - Nuclear power rocket engines
  - ✓ Or proof of concepts for investors
- **Government**
  - ✓ AWESOM - Small cheap robots for humans to Mars missions

1.4.2 Past Applications

- **Students**
  - ✓ Scanning Electron Microscope Sample Introduction Device
  - ✓ Plasma Speakers
- **Hobbyists**
  - ✓ Laser Projection
  - ✓ J-Nav - GPS for large campuses
- **Small technology firms**
  - ✓ JURBAN Google Lunar X PRIZE Team
    - Name in Space program
    - Regolith sampler collector
  - ✓ Solar System Express
    - RL Mark VI - Space Diving Suit
    - SolSpike – Hybrid aerospike
- **Government**
  - ✓ UAH & NASA Lunar Wormbot
  - ✓ LA Tech & NASA Lunar Wormbot

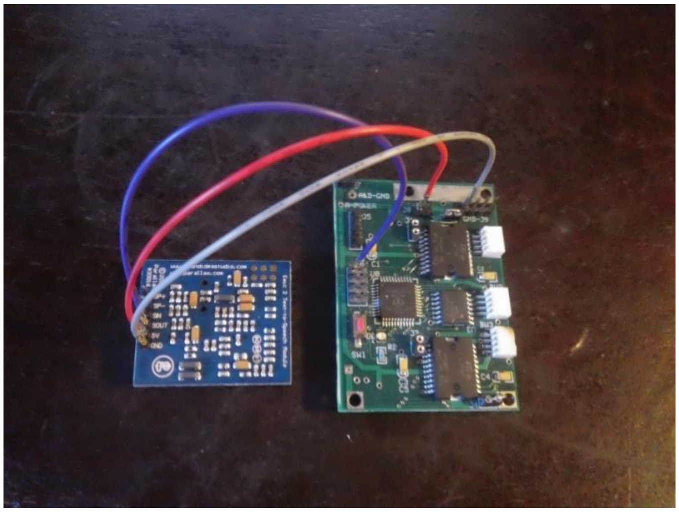


Figure 5 - A GDB connected to the EMIC2 for JURBAN's Name in Space program.

2.0 Connection Diagram

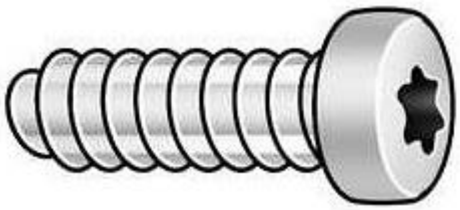
Time to learn how to wire up the GDB to the outside world! Additional details can also be found in the GDB ***Getting Started*** document at http://www.solarsystemexpress.com/software.html

With the Sol-X Ejection Seat™

http://youtu.be/wj6BZqVBVww

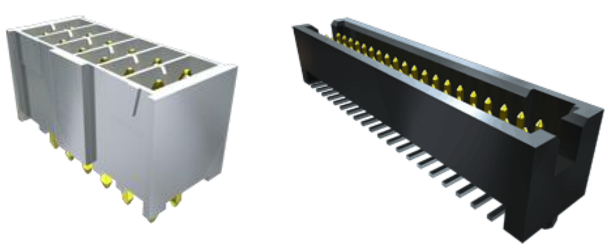
Step 1: Place the GDB onto the Ejection Seat™

Step 2: Screw down M2x0.25 bolt #1, #2, and #3



Step 3: Insert normal wires (like these Pololu Jumpers) into the Ejection Seat™ headers (H1, H2, H3, H4 and H5)

Step 4: Connect motors (or other devices) to the full H-Bridges using headers (FHB0) or analog signals to Analog to Digital Convertors using headers (ADC0) with the include SAMTEC IPL1-108-02-L-S-K & TFM-104-01-L-D-A-K connectors.



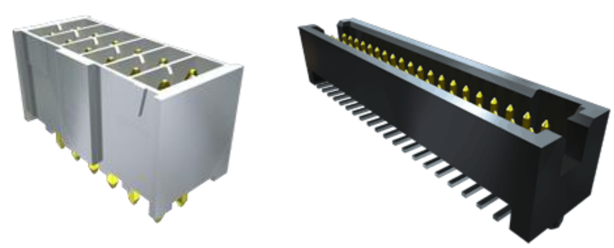
Step 5: Connect a battery (like this SparkFun Li-Ion) to the GDB using JST-PH Battery Connector P0 (Included in the Cordelia Bonus Kit)

Step 6: Turn on your computer and start the Parallax Propeller Tool V1.3 and Parallax Serial Terminal programs.

Without the Sol-X Ejection Seat™

Step 1: Insert and solder project wires into GDB holes (IO0, IO1, IO2, and UT0)

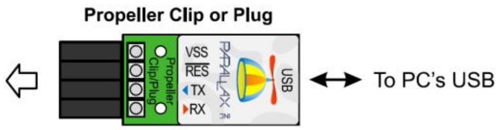
Step 2: Connect motors (or other devices) to the full H-Bridges using headers (FHB0) or analog signals to Analog to Digital Convertors using headers (ADC0) with the include SAMTEC IPL1-108-02-L-S-K & TFM-104-01-L-D-A-K connectors.



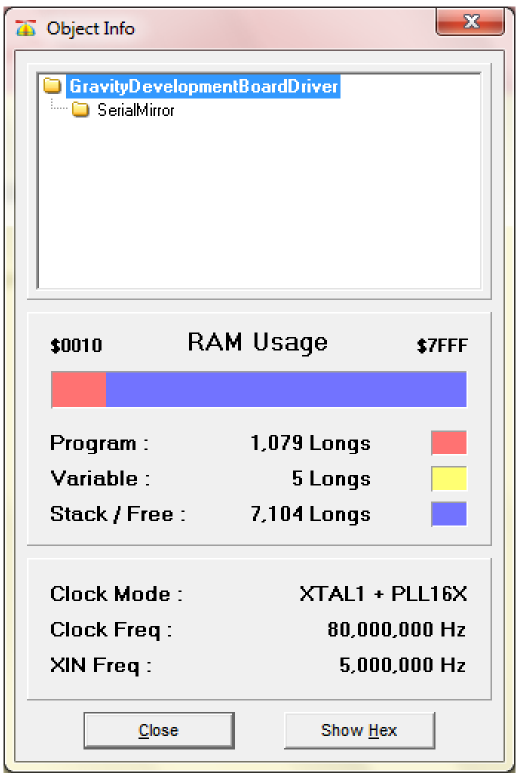
Step 3: Connect a battery (like this SparkFun Li-Ion) to the GDB using JST-PH Battery Connector P0 (Included in the Cordelia Bonus Kit)

Step 4: Turn on your computer and start the Parallax Propeller Tool V1.3 and Parallax Serial Terminal programs.

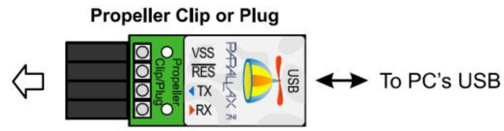
Step 7: Plug Prop Clip or Plug into Ejection Seat™ header H0.



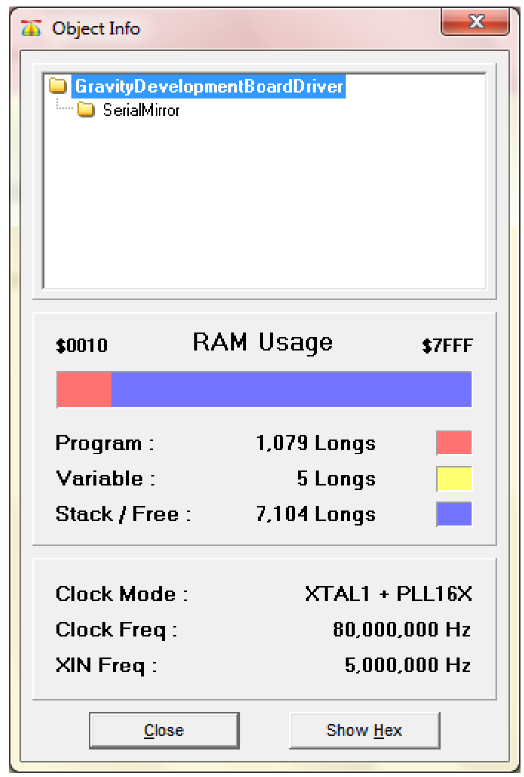
Step 8: Compile code using Crtl+F11 inside Parallax Propeller Tool V1.3 program and watch it run on the GDB.



Step 5: Insert Prop Clip or Plug with male header pins into hole IO1.



Step 6: Compile code using Crtl+F11 inside Parallax Propeller Tool V1.3 program and watch it run on the GDB.



2.0.1 Open Source Licensing

To encourage the reuse of our designs, especially in open-source hardware projects, Sol-X releases design files for selected products under the Creative Commons Attribution 3.0 license.

We release code for the GDB on the Propeller Object Exchange and GDB API GitHub account under the MIT license. All code posted there, whether originating from us or a third party, and is required to be released under the MIT license.

2.1 Pin Assignments

"{"– Denotes pin Reference Designators internal to the Parallax Propeller microcontroller.
"~" – Denotes a printed circuit board silkscreen Reference Designator label.

~IO2

{P1	{P3	{P5	{P7	{P9
{P0	{P2	{P4	{P6	{P8

High speed (Up to 128MHz) pins, capable of the following communication methods: PWM, SPI, and I2C. Along with Digital & Analog functions.

~UT0

3.3 V	GND
3.3 V	GND

Project utility pins. Current draw limit on pins is up to 0.616 Amps

~IO1

RX {P30	TX {P31	/RES {RESN	GND

Prop Clip or Plug pins for GDB programming, USB Slave communication, and Parallax Serial Terminal connection.

~IO0

MUX1 {P10	MUX3 {P10	MUX5 {P10	MUX7 {P10
MUX0 {P10	MUX2 {P10	MUX4 {P10	MUX6 {P10

Low speed (Up to 10 MHz) pins, capable of Digital and Analog functions. They also drive the four bi-color LED'S.

JST-PH Battery Connector

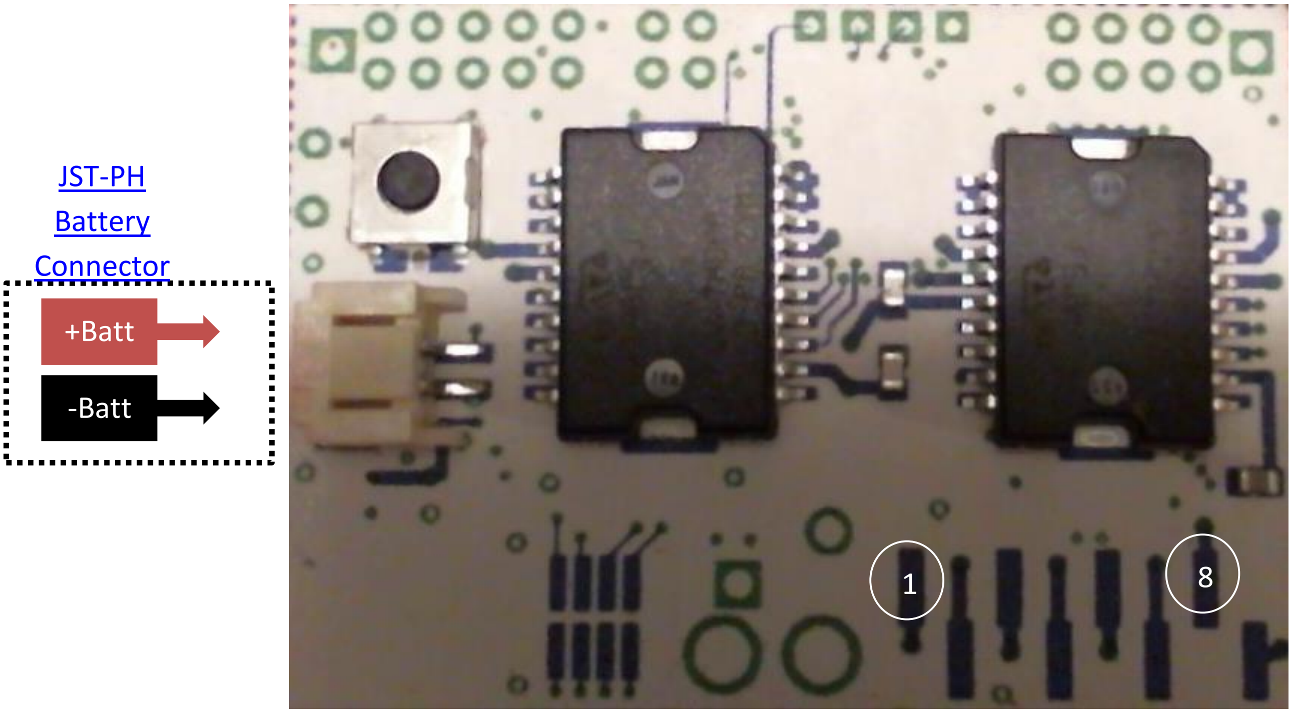


Figure 6 – GDB top view

~ADC0

ADC CH 7	ADC CH 6	ADC CH 5	ADC CH 4
ADC CH 0	ADC CH 1	ADC CH 2	ADC CH 3

A-to-D: (Into GDB) High speed, up to 100,000 samples per second (100 ksps) of eight 12-bit analog input.

D-to-A: (Out of GDB) High speed, up to 100,000 samples per second (100 ksps) of two 12-bit digital outputs on P31 and P30 **(~IO.1 & ~IO.0)**

~FHB0

1) L298 #1 Channel A+	5) L298 #2 Channel A+
2) L298 #1 Channel A-	6) L298 #2 Channel A-
3) L298 #1 Channel B+	7) L298 #2 Channel B+
4) L298 #1 Channel B-	8) L298 #2 Channel B-

High power pins (Up to 3 Amps), capable of driving large motors with a one line of code. Protected with 4 Amp self-resetting thermal fuses.

2.2 Pin Description

RELEASE

PENDING

REVIEW

2.3 Internal Connection Diagrams

2.3.1 32 KB EEPROM / Reset Circuit

The 32 KB EEPROM (Part # 24LC256-E/MF) stores GDB application code when power is not connected (This is known as non-volatile memory). It's loaded with code using the Parallax Prop Clip or Plug and the Parallax Propeller Tool V 1.3.2 Integrated Development Environment (IDE). The GDB can be reset within 50 ms via; internal software, an onboard push button (Part# MJTP1122TR), or an easy to wire in reset button on your own project enclosure via the SW0 solder holes.

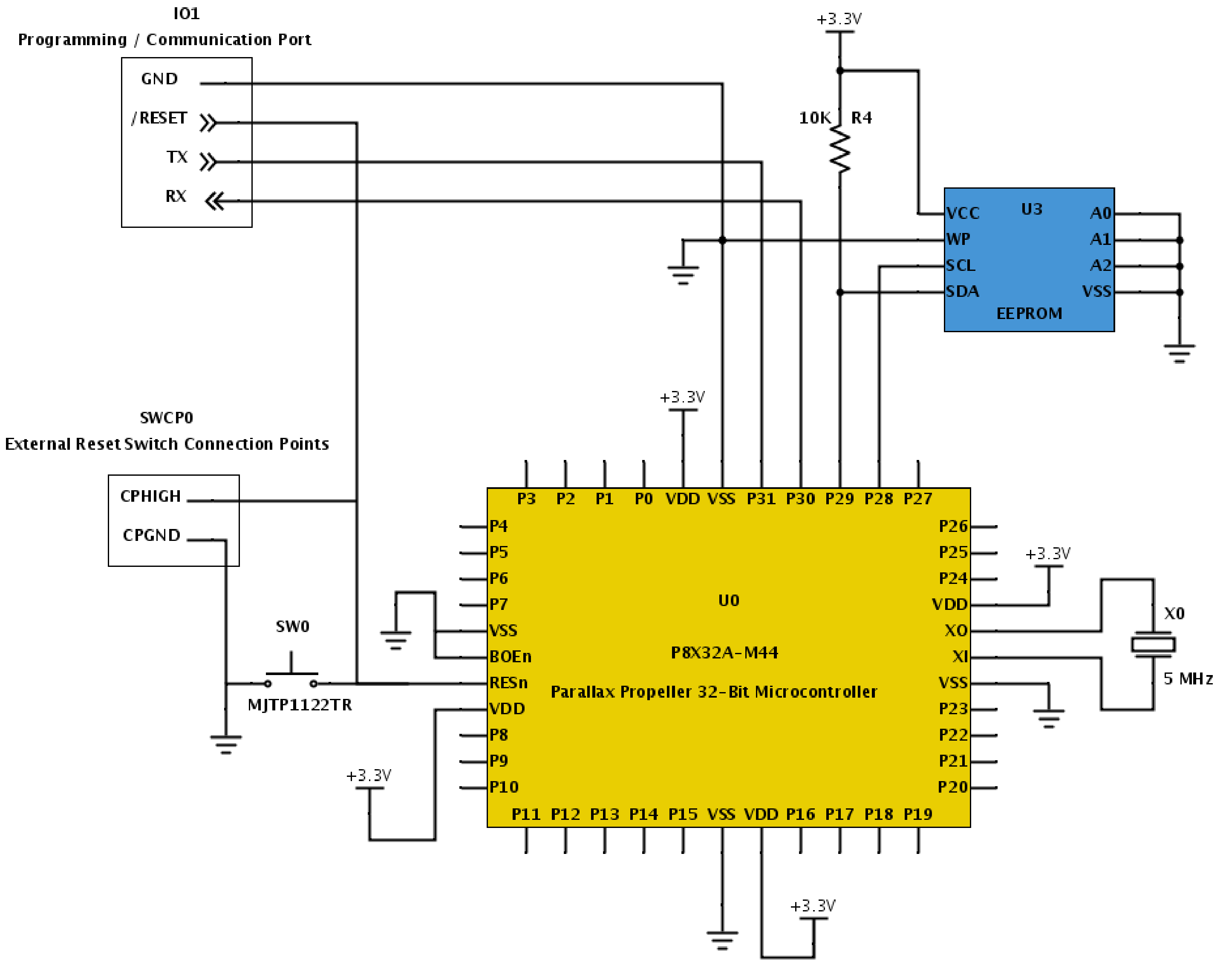


Figure 7 - EEPROM, crystal, input / output port #1, power, and reset switch connection diagram. Click on figure 7 above to enlarge and open an interactive online circuit & Bill of Material (BOM).

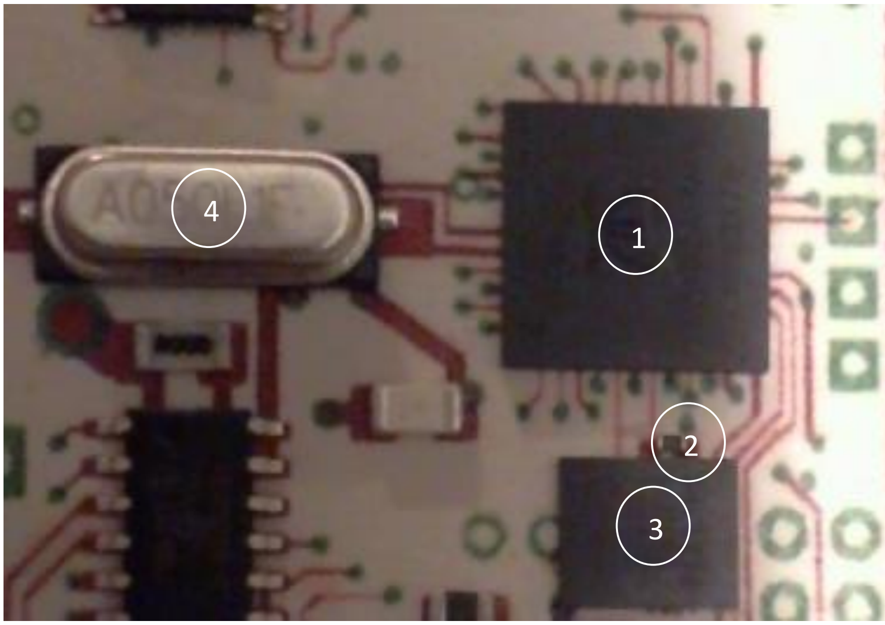


Figure 8 – Photo of the Parallax Propeller chip (1), 10 kΩ pull up resistor (2), 5 MHz Crystal (3) and 32KB EEPROM (4).

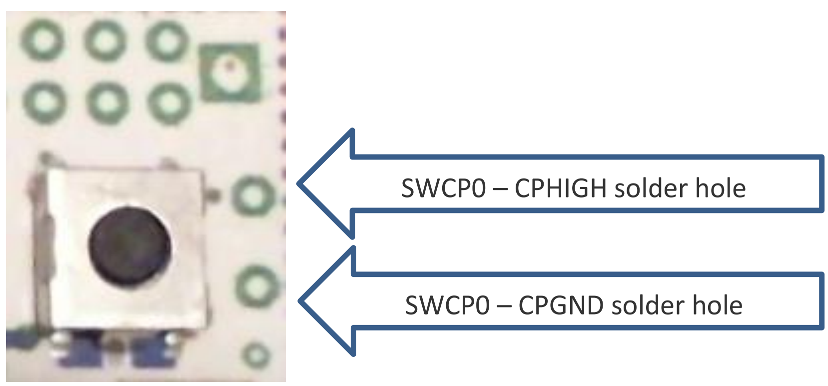


Figure 9 – Photo of on-board reset button SW0 solder holes to wire a reset button on your enclosure into the GDB.

2.3.2 LED Display Circuit

The eight LED’s on the GDB are comprised of four bi-color LED’s (Red & Green - Part # LTST-C195KGJRKT). The GDB LED’s can be focused with the included light pipes (Part # LPA-C041301S-10) to create professional LED status panels. How would you use this 12-bit data output? Leave your ideas here.

ADD MORE

Figure 10 – Lumex light pipes included with the GDB

Photo rights: Hello Pro UK™

Figure 11 – Example usage of light pipes

Video 1 – GDB LED multimeter test of the four bi-color (Red and Green) LED's at 25% brightness.

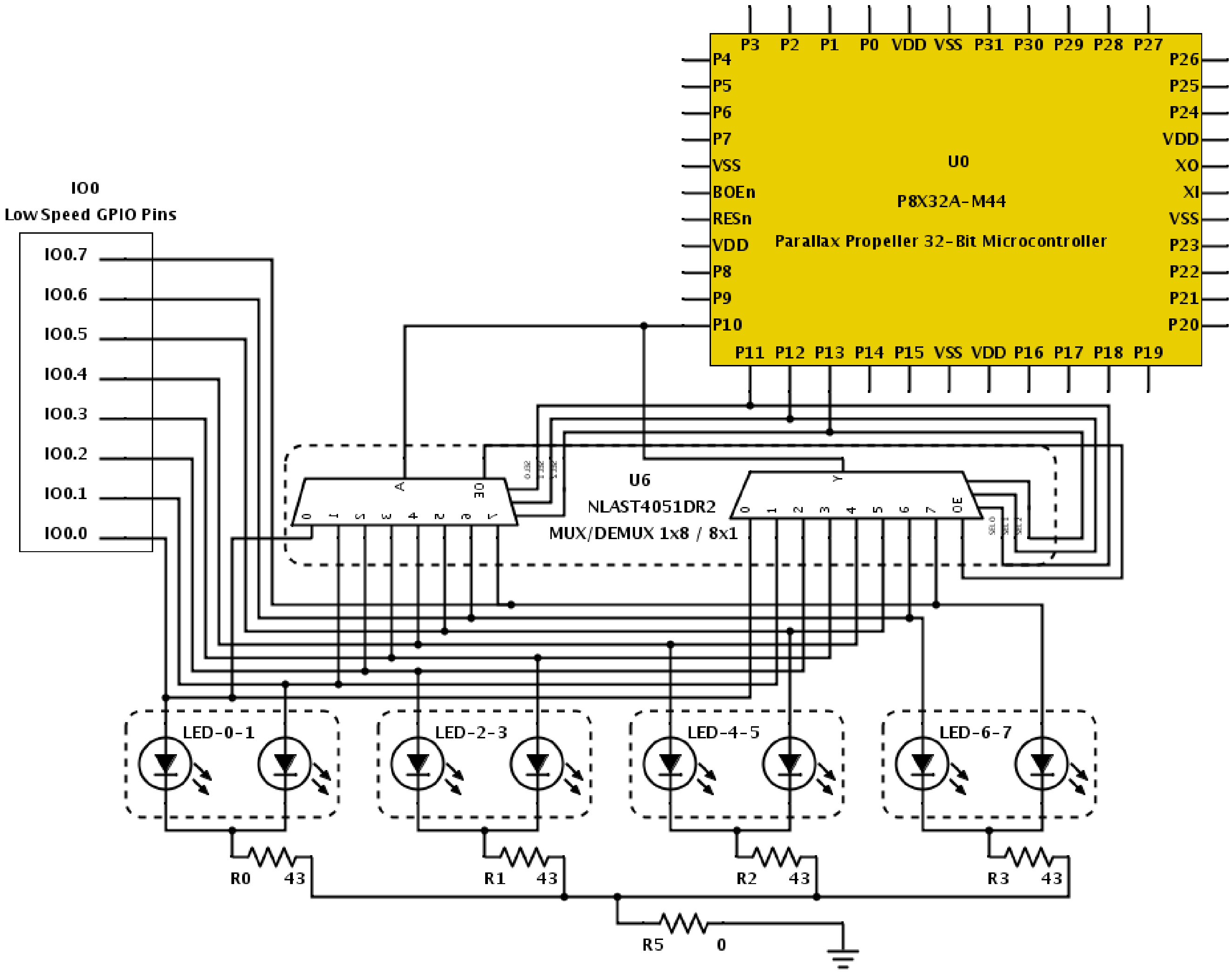


Figure 12 – LED, multiplexer / de multiplexer, and input / output port #0 connection diagram. Click on figure 12 above to enlarge and open an interactive online circuit & Bill of Material (BOM).

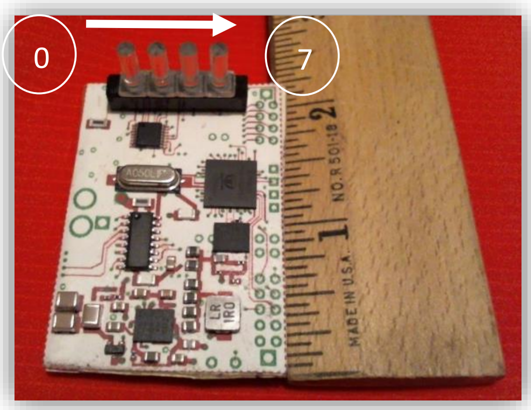


Figure 13 – GDB with light pipes & LED's off.

Figure 14– GDB inside enclosure with LED's on.

2.3.3 Power Management / Voltage Regulation

The GDB's input voltage regulator (Part# IR3801MTRPBF) enables the GDB to be powered by a larger input voltage ranges (4.5 to 12 V) and/or less stable input voltage source (like TASC solar cells) than the Arduino and Raspberry Pi. The IR3801MTRPBF is an easy-to-use, fully integrated and highly efficient Synchronous Buck DC/DC regulator.

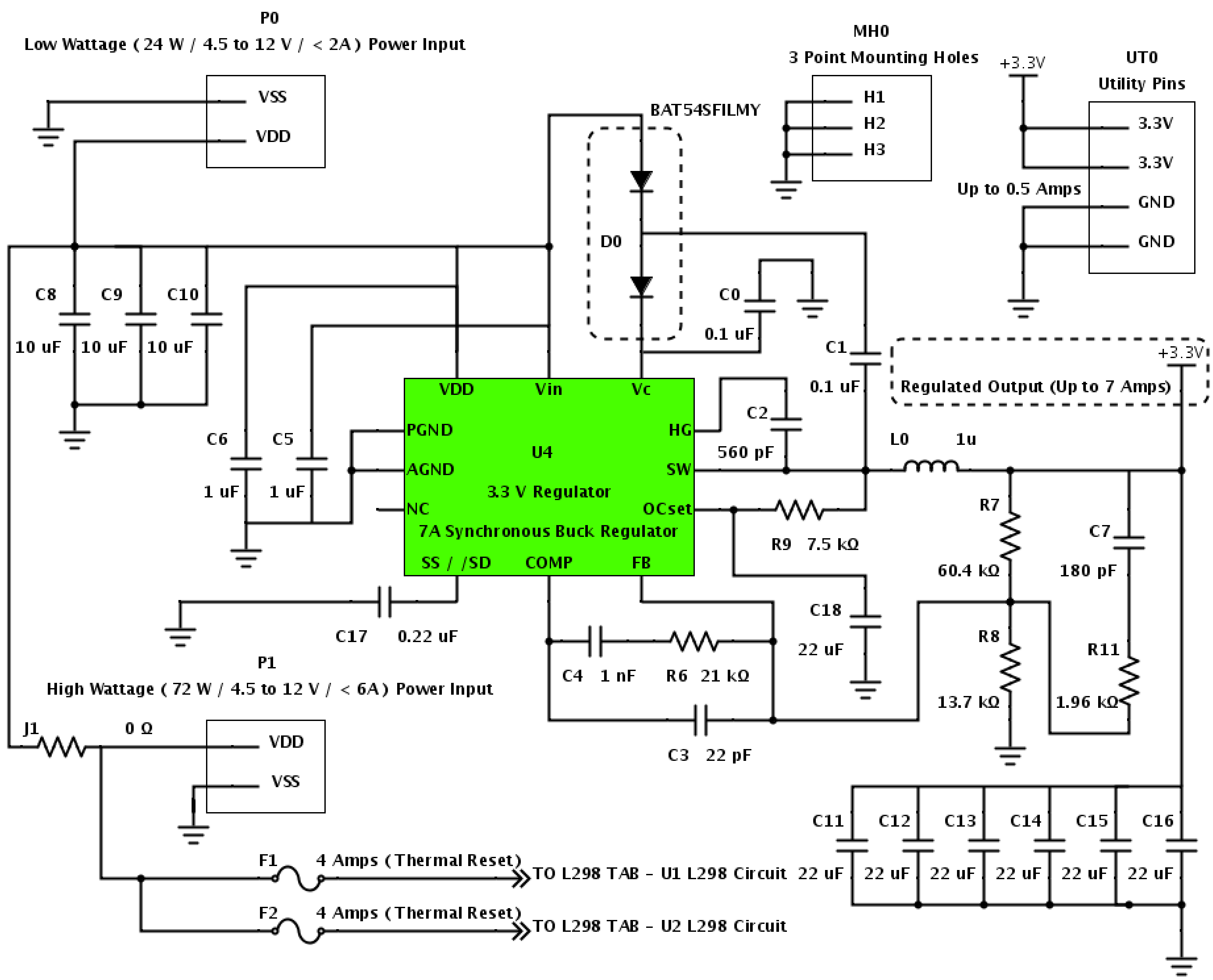


Figure 15 – Voltage Regulator, Power Input / Output connectors, Thermal Fuses, and Grounded Mounting Holes connection diagram. Click on figure 15 above to enlarge and open an interactive online circuit & Bill of Material (BOM).

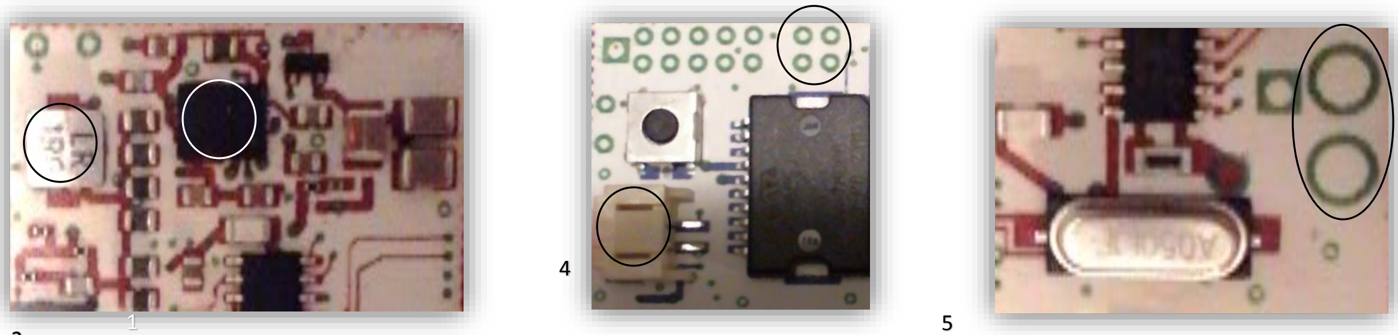


Figure 16 - Photo of the GDB voltage regulator U4 (1) and its passive components resistors, capacitors, and inductor L0 (2), the input power connectors P0 (3) & P1 (5), and Utility Pins UT0 (4) for 3.3V & GND access. See section 9.2 for grounded mounting.

2.3.4 Crystal Circuit

The E-Series GDB's 5 MHz crystal (Part# ABLS3-5.000MHZ-D4Y-T) hardware circuit has been designed to be stable at **industrial** temperature ranges, 6 Gee acceleration, and Space-X Falcon 9 vibration profiles. This is achieved by mounting the crystal to the PCB with EP42HT-2AO-1BLACK, a thermally conductive epoxy. All PCB footprints for Abracon 3-Series crystals (from 3.579 MHz to 30 MHz) are the same, enabling GDB overclocking. As of the writing of this document the fastest stable clock speed for ONE CPU inside the eight CPU Parallax Propeller microcontroller architecture is 128 MHz (See uOLED-96-PROP for more details).

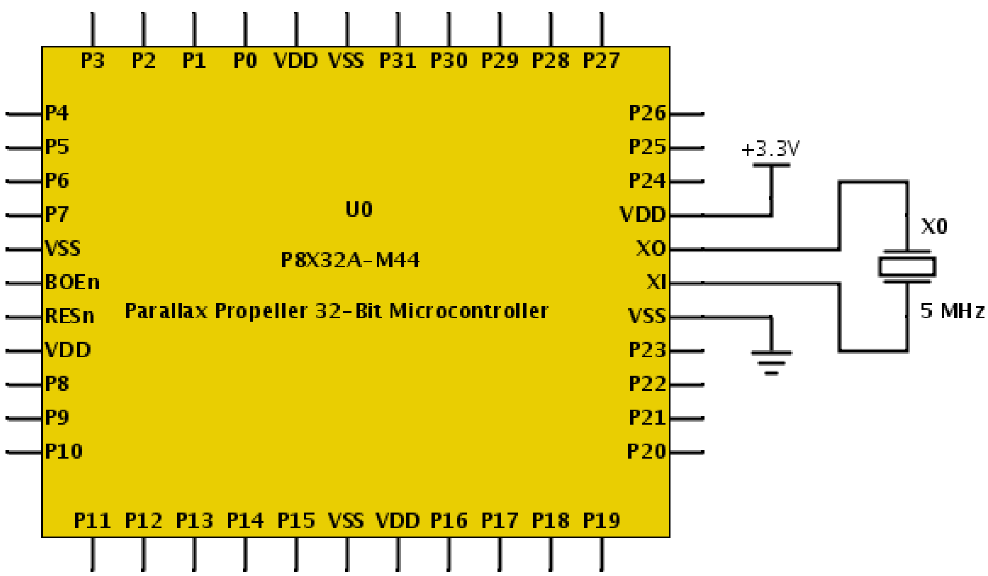


Figure 17 – Surface Mount Technology (SMT) crystal X0 and Parallax Propeller U0 connection diagram. Click on figure 17 above to enlarge and open an interactive online circuit & Bill of Material (BOM).

1

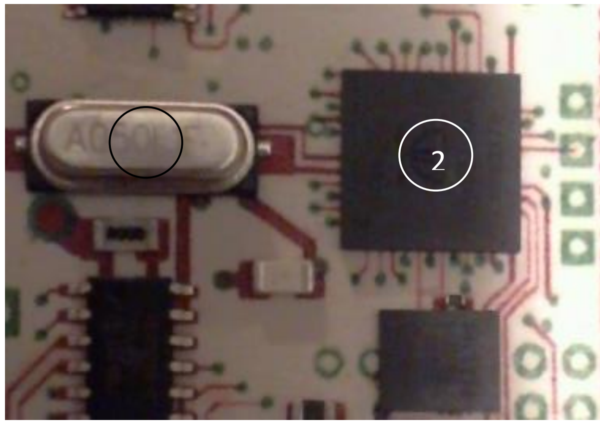


Figure 18 - Photo of the GDB crystal (1) and Parallax Propeller Microcontroller (2).

The M-Series GDB 10 MHz crystal (Part# XR-P (SM1)) hardware circuit has been designed to be stable at **military** temperature ranges, 3000 Gee acceleration, and Space-X Falcon 9 vibration profiles. The XR-P trades small footprint size for increased stability over the E-Series. Final testing for this circuit has not been completed at the time of the writing of this document.

NOT COMPLETE YET

2.3.5 High Power Driver/Output Circuit

The GDB's two Full H-Bridges (Part# L298P) enable you to power four full size motors without the need to design your own large, slow, and power inefficient driver circuit :) With the GDB you can power things four Firgelli L-16 linear actuators, plasma speakers, and Dynamixel high power servos used in Japanese fighting robots. Check out current GDB applications on the Sol-X Blog here, and post your GDB project on Twitter using the hash tag #Sol-XGDB

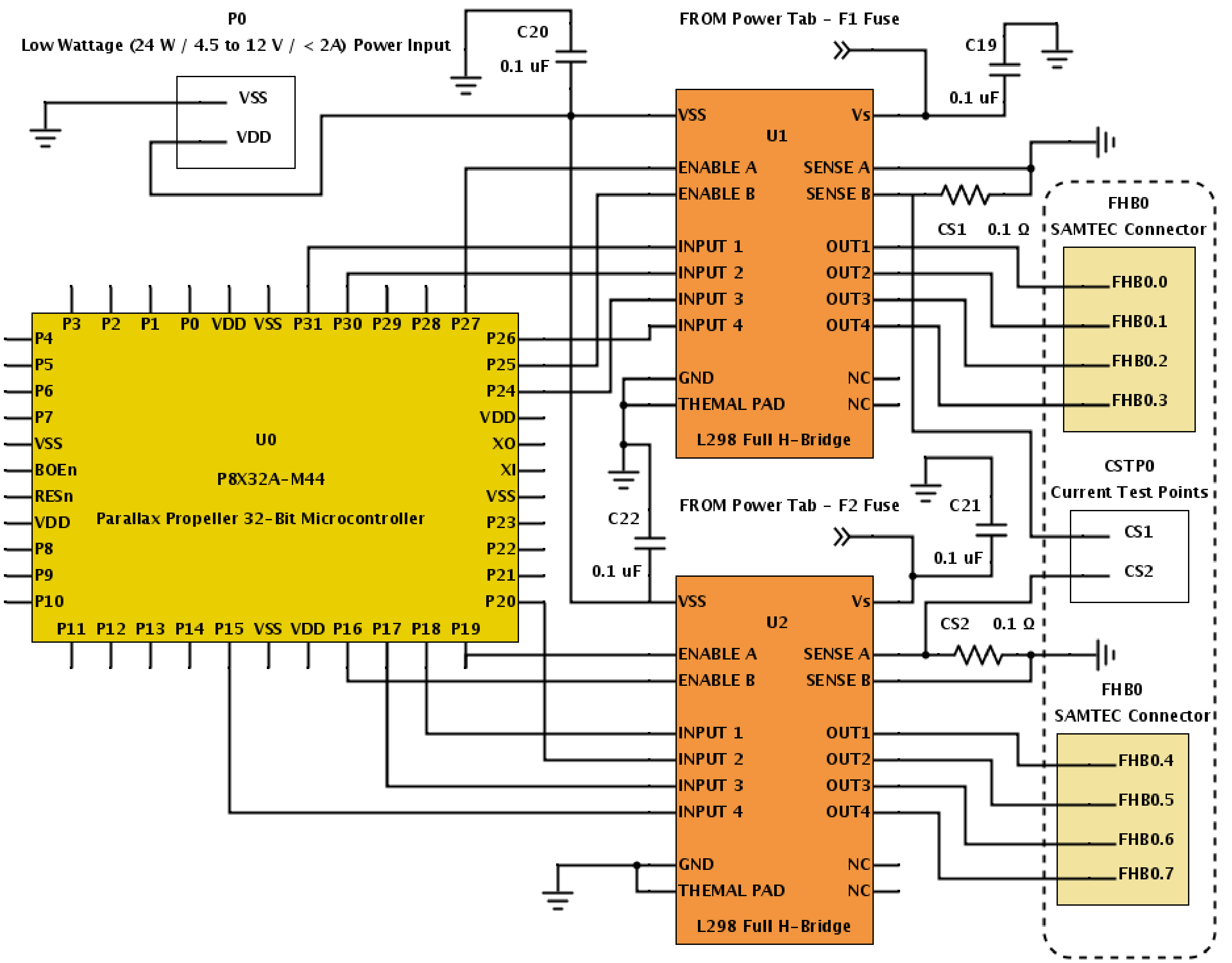


Figure 19 – Full H-Bridge UI & U2, L298 Current Test Point CSTP0, L298 connector FHB0, and Propeller U0 connection diagram. Click on figure 19 above to enlarge and open an interactive online circuit & Bill of Material (BOM).

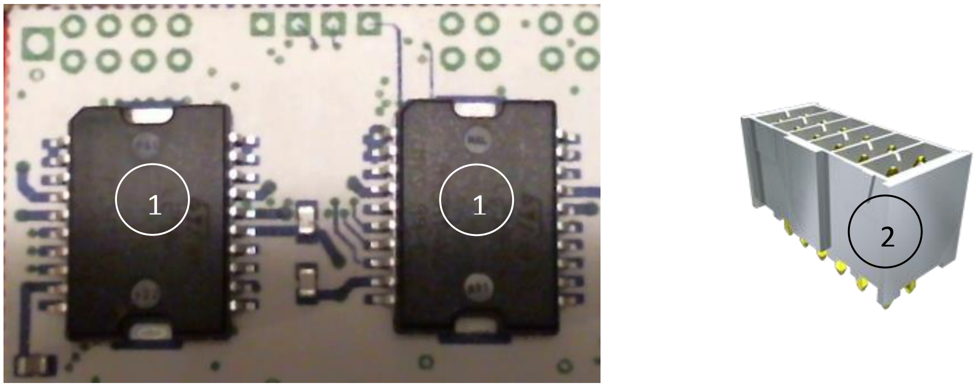


Figure 20 - Photo of the GDB Full H-Bridges (1) and high quality SAMTEC output connector (2).

2.3.6 Analog-to-Digital & Digital-to- Analog Conversion Circuit

The GDB's Analog-to-Digital (ADC) and Digital-to- Analog Convertor (DAC) (Part# MCP3208) enables the GDB to interact with the analog world that surrounds us, with 12-bit resolution. All at a sampling rate of up to 100 kpbs. The ADC/DAC is easily swappable since it's external to the GDB microcontroller; enabling the GDB to be easily upgraded using Sol-X open source documentation, as advances in Integrate Circuits (IC) continue.

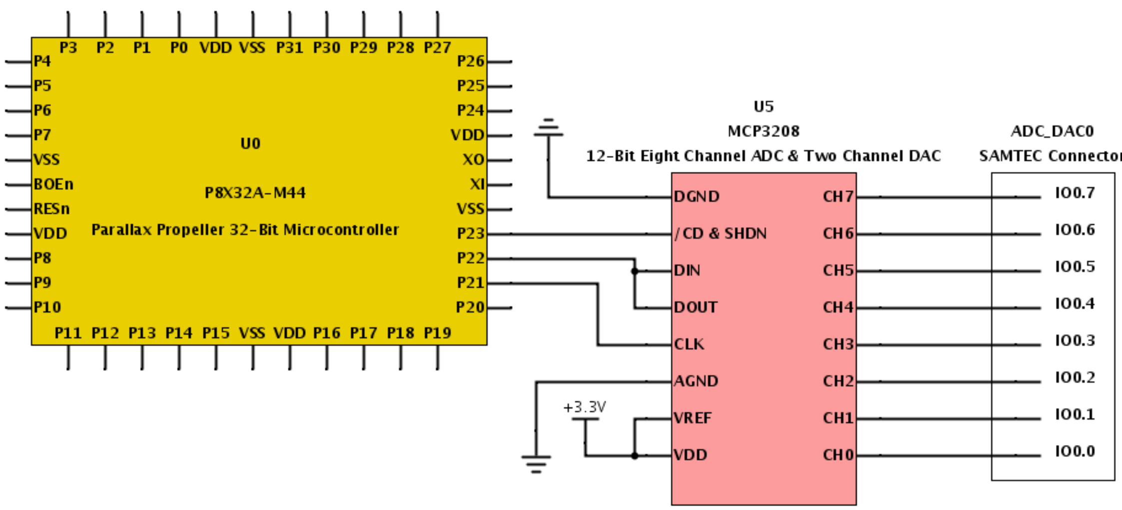
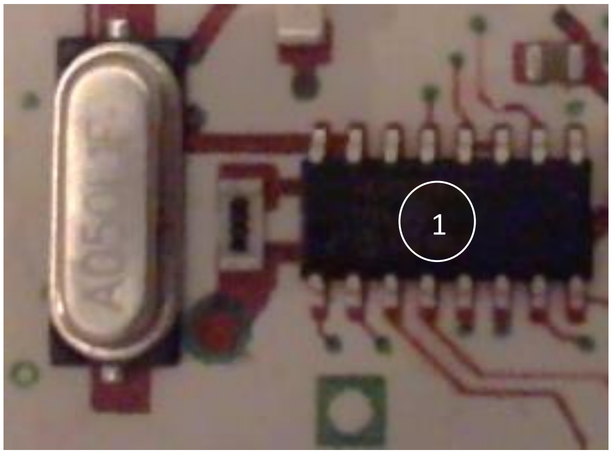


Figure 21 – Full H-Bridge UI & U2, L298 Current Test Point CSTP0, L298 connector FHB0, and Propeller U0 connection diagram. Click on figure 21 above to enlarge and open an interactive online circuit & Bill of Material (BOM).



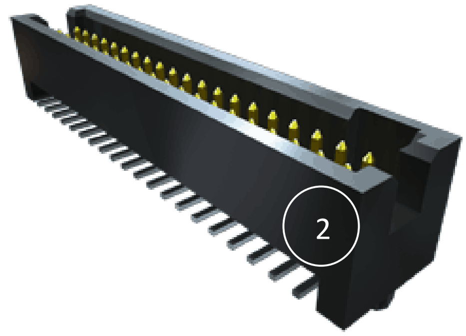


Figure 22 - Photo of the GDB ADC / DAC Integrate Circuit (1) and high quality SAMTEC input/output connector (2).

2.3.7 Input / Output (I/O) Connection Circuit

The GDB uses the simplest and most space & cost efficient method for connecting to the outside world. Holes (aka vias) in the PCB itself. Just solder up to a 20 AWG wire (0.812 mm diameter)into the via, or insert a 0.1 in (2.54 mm) pitch solderless header (Part# 1025 into GDB IO0, Part# 1014 into GDB IO1, Part# 1024 into GDB IO2, , and Part# 1022 into GDB UT0 – THESE PARTS ARE NOT INCLUDED WITH YOUR GDB) in the PCB.

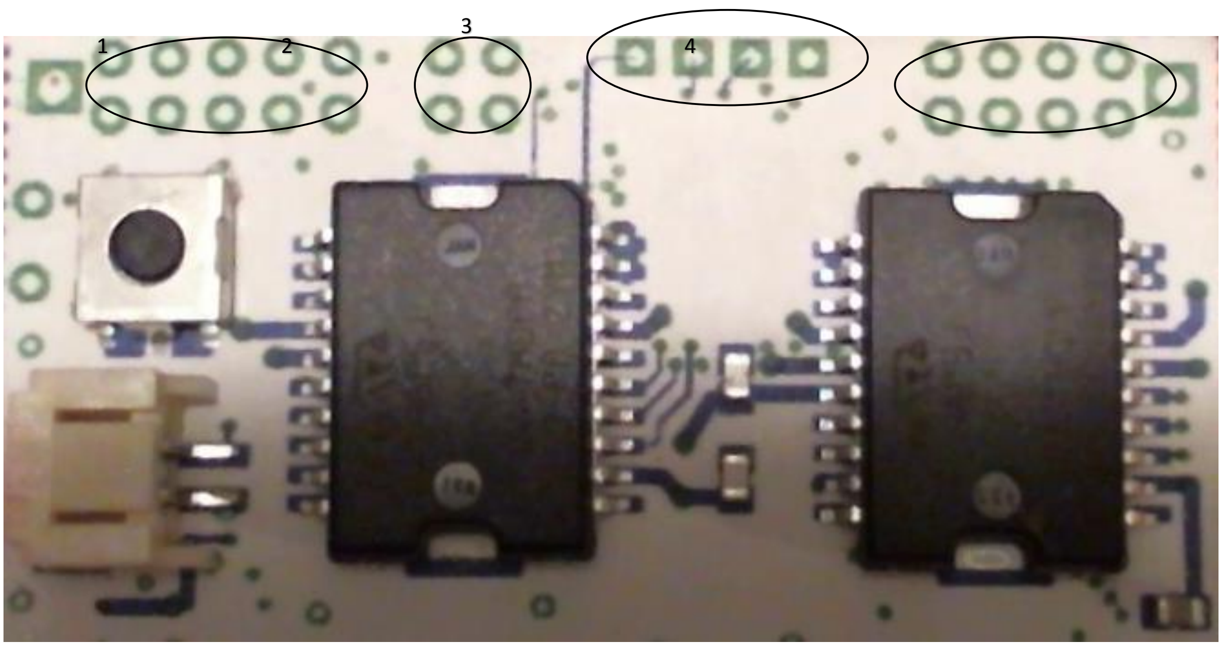


Figure 23 - Photo of the GDB 0.1 in (2.54 mm) pitch Input / Output IO0 (1), IO1 (2), UT0(3), and IO2(4) solder holes.

3.0 Operating Procedures

Download the ***Getting Started*** document at http://www.solarsystemexpress.com/software.html for a quick guide to get you started with the GDB in less than 15 minutes.

3.1 Boot-Up Procedure

The Boot Loader performs one or more of the following tasks, in order:

1. Detects communication from a host, such as a PC, on pins P30 and P31. If communication from a host is detected, the Boot Loader converses with the host to identify the Propeller chip and possibly download a program into global RAM and optionally into an external 32 KB EEPROM.
2. If no host communication was detected, the Boot Loader looks for an external 32 KB EEPROM on pins P28 and P29. If an EEPROM is detected, the entire 32 KB data image is loaded into the Propeller chip's global RAM.
3. If no EEPROM was detected, the boot loader stops, Cog 0 is terminated, the Propeller chip goes into shutdown mode, and all I/O pins are set to inputs.

3.2 Run Time Procedure

A GDB Application is a user program compiled into its binary form and downloaded to the Propeller RAM or external 32K EEPROM. An application consists of code written in the Propeller chip's SPIN language, C++, 12 Blocks™ / Relativity™ GUI, JAVA, or Pellerduino™ (high-level code) with optional Propeller Assembly language components (low-level code). High level code is interpreted during run time by a cog running the SPIN Interpreter while code written in Propeller Assembly is run in its pure form directly by a cog. Every GDB application consists of at least a little high level code and may actually be written entirely in high level code or with various amounts of high level code and Propeller assembly. The SPIN Interpreter is started in Step 3 of the Boot Up Procedure, above, and is what gets your Solar System changing GDB application running.

3.2.1 Your first program (Hello World)

Your GDB can be programmed with up to six different programming languages. Visit us at www.solarsystemexpress.com/software.html for other programming languages and for more programming instructions. The following steps will walk you through the process of creating your first GDB application using the SPIN language. **You should have already completed all the step in the easy to read and follow *Getting Started* document at www.solarsystemexpress.com/software before completing the following steps.**

1. To start the Propeller Tool IDE, click the Propeller Tool shortcut or:
   a. Click **Start** icon on your PC
   b. Click on **All Programs**
   c. Click on **Parallax Inc.** folder
   d. Click on **Propeller Tool v1.3.2** folder
   e. Click on **Propeller Tool v1.3.2** shortcut
2. Download the GDB API from GitHub at https://github.com/solx/GDB
3. Save this code in the standard Parallax Folder **C:\Program Files (x86)\Parallax Inc\Propeller Tool v1.3.2** or wherever you want, if you are that Boss :)
4. Click **File** / Click **Open…** / Click **GDB Hello World /** Click Open

5. Verify that **GDB Hello World** is the **Top Object File.** If it's NOT, right click on the **GDB Hello World** tab, and click on **Top Object File.**
6. Click on **Run /** Click on **Compile Top** / Click on **Load EEPROM**
7. Verify the following GDB outputs occur:
    a. The four bi-color LED'S flash in a drag race style countdown.
    b. The following text should display in the **Parallax Series Terminal window,** "HAL 9000 TEST: Hello World… Daisy, Daisy, give me your answer, do, I'm half-crazy all for the love of you. It won't be a stylish marriage, I can't afford a carriage, but you'd look sweet upon the seat Of a bicycle built for two."
8. If all outputs fail, verify your USB and power supply cables are connected properly (See section #3 of the Getting Started Guide) and that your COM port settings are correct (See section #5 & section #6 of the Getting Started Guide).

3.3 Shutdown Procedure

When the Propeller goes into shutdown mode, the internal clock is stopped causing all cogs to halt and all I/O pins are set to input direction (high impedance). Shutdown mode is triggered by one of the three following events:

1. VDD falling below the brown-out threshold (~2.7 VDC), when the brown out circuit is enabled
2. The RESn pin going low.
3. The application requests a reboot (see REBOOT command in the Propeller Manual v1.2).

Shutdown mode is discontinued when the voltage level rises above the brown-out threshold and the RESn pin is high.

4.0 System Organization

4.1 Look Up Tables

4.1.1 Sine Table

The GDB provides 2,049 unsigned 16-bit sine samples spanning from 0° to 90°, inclusively (0.0439° resolution). A small amount of assembly code can mirror and flip the sine table samples to create a full-cycle sine/cosine lookup routine that has 13-bit angle resolution and 17-bit sample resolution. (See page 385 of Propeller Manual v1.2 for more details)

4.1.2 Log & Anti-Log Table

The log table contains data used to convert unsigned numbers into base-2 exponents. The log table is comprised of 2,048 unsigned words which make up the base-2 fractional exponents of numbers. (See page 382 of Propeller Manual v1.2 for more details)

The anti-log table contains data used to convert base-2 exponents into unsigned numbers. The anti-log table is comprised of 2,048 unsigned words which are each the lower 16-bits of a 17-bit mantissa (the 17th bit is implied and must be set separately). (See page 384 of Propeller Manual v1.2 for more details)

4.2 Communication Buses

4.2.1 USB

Any computer with a USB 2.0 port can communicate with the GDB using interface software written in C/C++/C#, Delphi, Real BASIC and Visual BASIC to name a few. A Visual BASIC demo can be found at www.parallaxsemiconductor.com/sites/default/files/appnotes/AN018-CommPC-v1.0_0.pdf

Basic debugging communication between the GDB and a Personal Computer (PC) occur on the same USB Serial Port as advanced PC and GBD interfacing

Table 3 – GDB USB pin layout

Standard SPI Signals	GDB Ref Des Label . Pin #
V_{CC} (+3.3V)	~IO1.0
Data-	~IO1.1
Data+	~IO1.2
Ground	~IO1.3

4.2.2 SPI Bus

The GDB SPI bus can run at up to 20 MB/s and has increased clock frequency reliability via; short impedance controlled traces, decoupling capacitors, and ground plane cooper pour shielding. Suggestions on how to match SPI devices with the GDB via an in series resistor can be found in section 4.2.2.1 below.

Table 4 – GDB SPI pin layout

Standard SPI Signals	GDB Ref Des Label . Pin #
SCLK	~IO0.?
MOSI	~IO0.?
MISO	~IO0.?
SS	~IO0.?

4.2.2.1 SPI Device Impedance Matching

TESTING REQUIRED

4.2.3 I_2C

The GDB I_2C bus can run at up to 1 MHz (Fast-mode plus Fm^+) and has increased signal integrity via; short impedance controlled traces and ground plane cooper pour shielding.

Table 5 – GDB I2C pin layout

Standard I_2C Signals	GDB Ref Des Label . Pin #
SDA	~IO1.?
SCL	~IO1.?

4.2.4 VGA

With the GDB VGA impedance adapter (basically just adds resistors to the high speed I/O pins) you can drive up to eight (8) VGA or composite video (NTSC or PAL) displays. One (1) HDMI output is also possible with this $20 VGA to HDMI adapter. We suggest building a spacecraft cockpit display system, but we welcome your ideas here.

Video 2 – Example of VGA text & graphic outputs (Video here)

Want to learn more?

- Color PAL and VGA SPIN Demo
- ???

4.2.5 ModBus (Future Work)

A serial communication protocol for use with PLC's. Simple and robust, it has since become a *de facto* standard communication protocol, and it is now a commonly available means of connecting industrial electronic devices. The main reasons for the use of Modbus in the industrial environment are:

- Developed with industrial applications in mind
- Openly published and royalty-free
- Easy to deploy and maintain
- Moves raw bits or words without placing many restrictions on vendors

4.3 Internal Counters

There are 16 differential internal counters (2 per CPU) available in the GDB for timing real world events at a resolution as low as 7.81 nS. (See page 8 of Propeller P8X32A Datasheet 1.4.0 for more details)

4.4 Generic Software UART (Future Work)

5.0 Memory Organization

5.1 Main Memory

The Main Memory is a block of 64 K bytes (16 K longs) that is accessible by all cogs as a mutually-exclusive resource through the Hub. It consists of 32 KB of RAM and 32 KB of ROM. Main memory is byte, word and long addressable. Words and longs are stored in little endian format; least-significant byte first.

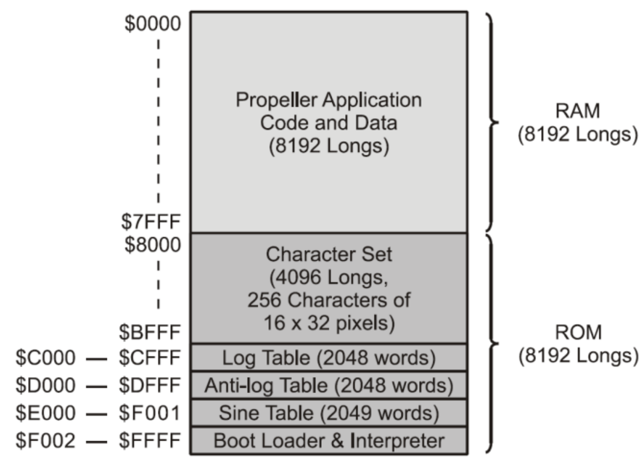


Figure 24 – GDB Parallax Memory Map

5.1.1 Main RAM

The 32 KB of Main RAM is general purpose and is the destination of a Propeller Application either downloaded from a host or from the external 32 KB EEPROM (I2C Code Demo to read and write to EEPROM memory).

5.1.2 Main ROM

The 32 KB of Main ROM contains all the code and data resources vital to the Propeller chip's function: character definitions, log, anti-log and sine tables, and the Boot Loader and Spin Interpreter.

5.2 Interfacing with SRAM via SPI Bus

If you need extra memory access speed (greater than 1 MHz), use the SPI bus; if you need a lot of memory devices, physical separated to increase redundancy against radiation or physical damage use the I_2C bus (Section 4.2.3). (AN012 Code Demo to read and write to SRAM memory).

6.0 Programming Languages

With limited funds and expertise, prototyping a new technology can be a cumbersome and unnecessarily expensive process, especially for undergrad students, hobbyists, and small technology firms. You can program the GDB seven different ways depending on your coding skill level and need for efficiency (The 12 Blocks™ GUI, C , JAVA, Parallax SPIN IDE, Pascal P4, Pellerdunio (an Arduino IDE) or Assembly Language). You should not have to decide between ease of coding and efficiency. You can have both! For more information visit solarsystemexpress.com/software

6.0.1 12 Block™

- Graphical Interface
- Simple Drag and Drop Coding
- Graphical Debugging Tools
- Source Code can be viewed and edited

6.0.2 SPIN – Propeller Tool / BST

- Designed specifically for the GDB's CPU
- Mac, Windows and Linux capable IDE
- Go to language for Parallax users

6.0.3 SimpleIDE

- Robust and efficient code inherent to C
- Mac, Windows and Linux capable IDE
- Uses the Propeller-GCC™ compile

6.0.4 Assembly Language

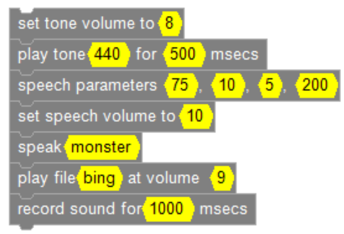
- Fast execution inherent to machine language
- Mac, Windows and Linux capable IDE
- Great if porting code from an old project

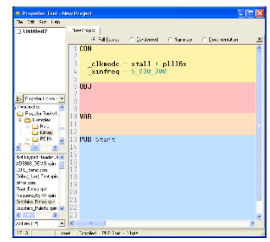
6.0.5 JAVA

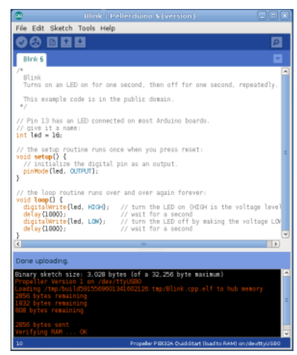
- Simple grammar inherent to JAVA
- Easy to use Javelin Stamp IDE
- The Java Virtual Machine runs on the GDB

6.0.6 Arduino IDE – Pellerdunio

- Continue to use the Arduino IDE and API's
- DEVELOPMENT ON SOFTWARE HAS STOPPED
- HELP COMPLETE THIS SOFTWARE







```
' Compute square-root of y[31..0] into x[15..0]
'
root            mov     a, #0           'reset accumulator
                mov     x, #0           'reset root
                mov     t, #16          'ready for 16 root bits

:loop           shl     y, #1   wc      'rotate top two bits of y …
                rcl     a, #1           ' … into accumulator
                shl     y, #1   wc
                rcl     a, #1
                shl     x, #2           'determine next bit of root
                or      x, #1
                cmpsub  a, x    wc
                shr     x, #2
                rcl     x, #1
                djnz    t, #:loop       'loop until done

root_ret        ret                     'square root in x[15..0]
```

```
// Example Program - Hello World!

public class HelloWorld{
  public static void main(){
    System.out.println("Hello World!");
  }
}
```

7.0 Electrical Characteristics

7.1 Absolute Maximum and Minimum Ratings

Stresses in excess of the absolute maximum ratings can cause permanent damage to the device. Exposure to absolute maximum ratings for extended periods can adversely affect device reliability.

Table 6 – Absolute Maximum and Minimum Ratings

Symbol	Parameter	Value
T_O	Operating Temperature	-25 °C to 85 °C
T_S	Storage Temperature	-35 °C to 110 °C
P_{Total}	Total Power Dissipation	0.045 Watts to 72 Watts
I_{P0}	Current through P_0	0.010 A to 2 A
I_{P1}	Current through P_1	0.010 A to 6 A
I_{IO}	Current through I/O pins	0.0038 mA to 40 mA
V_{DD}	Voltage across P_0 or P_1 with respect to V_{SS}	4.5 V to 12 V
V_{IO}	Voltage per I/O pin with respect to V_{SS}	0 V to 4 V
ESD_{SSP}	ESD (Human Body Model) Supply Pins	3 kV
ESD_{NSSP}	ESD (Human Body Model) All Non-Supply Pins	8 kV

7.2 DC Characteristics

(Operating temperature range: -25 °C < T_a < 85 °C unless otherwise noted)

Table 7 – DC Characteristics

Symbol	Parameter	Condition	Min	Typ*	Max	Units
V_{DD}	Supply Voltage		4.5	6	12	V
V_{LH}	Logic High		$0.6xV_{DD}$	-	V_{DD}	V
V_{LL}	Logic Low		V_{SS}	-	$0.3xV_{DD}$	V
I_{II}	Input Leakage Current			TBD		µA
I_{SO}	Brownout Detector Current			0.0038		mA
I_{Qu}	Quiescent Current	RESn = 0V, BOEn = V_{dd}, P_0-P_{31}=0V		TBD		µA

* Note: Data in the Typical ("Typ") column is T = 25 °C unless otherwise stated.

7.3 AC Characteristics

(Operating temperature range: -25 °C < T_a < 85 °C unless otherwise noted)

Table 8 – AC Characteristics

Symbol	Parameter	Condition	Min	Typ*	Max	Units
F_{EX}	External XI Frequency		DC	-	80	MHz
F_{OSC}	Oscillator Frequency	Direct drive (no PLL) RCSLOW RCFAST Crystal using PLL	DC 13 8 4	- 20 12 -	80 33 20 8	MHz kHz MHz MHz
C_{IN}	Input Capacitance		-	6	-	pF

* Note: Data in the Typical (“Typ”) column is T = 25 °C unless otherwise stated.

7.4 Current Consumption Characteristics

The main drivers for GDB current/power consumption are CPU clock frequency**, memory write duty cycle, H-Bridge output, LED duty cycle, voltage regulator switching speed, Analog-to-Digital convertor duty cycle, and MUX & DeMUX operating temperature.

Table 9 – Power / Current consumption per component, with correct significant figures :)

Component Name (Part Number)	**Minimum Power Draw**	**MODE 1 Power Draw**	**MODE 2 Power Draw**	**Maximum Power Draw**
Parallax Propeller Microcontroller* (P8X32A-M44)	0.0231 mW 0.00700 mA @ 3.30 V ~20 kHz **RCslow**	2.64 mW 0.800 mA @ 3.30 V ~12 MHz **RCfast**	9.57 mW 2.90 mA @ 3.30 V 40 MHz clock	15.8 mW 4.80 mA @ 3.30 V 80 MHz clock
32 KB EEPROM (24LC256)	0.00550 mW 0.00122 mA @ 4.50 V StandBy @ 85 °C	0.0275 mW 0.00611 mA @ 4.50 V StandBy @ 125 °C	2.20 mW 0.489 mA @ 4.50 V EEPROM Read	16.5 mW 3.67 mA @ 4.50 V EEPROM Write
Dual Full H-Bridge (L298P)	45.4 mW 10.1 mA @ 4.50 V Quiescent V_{en} = LOW	166 mW 37.0 mA @ 4.50 V V_{en} = HIGH & V_i = LOW	256 mW 57.0 mA @ 4.50 V V_{en} = HIGH & V_i = HIGH	72.0 W 6.00 A @ 12.0 V Both Channels ON
Bi-Color LED (LTST-C195KGJRKT)	0.00 mW 0.00 mA @ 3.30 V All eight LED's OFF	75 mW 30 mA @ 2.50 V One Red LED ON	75 mW 30 mA @ 2.50 V One Green LED ON	600 mW 75 mA @ 3.30 V All eight LED's ON
Voltage Regulator (IR3801MPbF)	0.09 mW 0.0200 mA @ 4.50 V Soft Start Current	90 mW 20.0 mA @ 4.50 V No Switching	225 mW 50.0 mA @ 4.0 V Dynamic Switching	84.0 W 7.00 A @ 12.0 V ***Max Sourcing Current***
ADC (MCP3208)	0.0000033 mW 0.000001 mA @ 3.30 V Chip Select = HIGH	0.00165 mW 0.0005 mA @ 3.30 V StandBy	0.495 mW 0.150 mA @ 3.30 V Chip Select = LOW	825 mW 250 mA @ 3.30 V Operating
8x1 MUX / DeMUX (NLAST4051DR2)	0.0135 mW 0.0041 mA @ 3.30 V StandBy @ 25 °C	0.135 mW 0.041 mA @ 3.30 V StandBy @ 85 °C	0.267 mW 0.081 mA @ 3.30 V StandBy @ 125 °C	165 mW 50.0 mA @ 3.30 V Max Sourcing Current
SUBTOTALS	**10.1 mA / 45.5 mW**	**87.8 mA / ???**	**141 mA / ???**	**6383 mA / ???**

*More clock speed and current consumption configurations available at
www.solarsystemexpress.com/hardware.html
**www.forums.parallax.com/showthread.php/143703-Propeller-clock-speed
**http://forums.parallax.com/showthread.php?84907-Propeller-Current-Draw
**http://forums.parallax.com/showthread.php/132961-Propeller-Power-Consumed-Based-on-Code/page3?p=1019874&viewfull=1#post1019874

Table 10 – Power / Current consumption of GDB CPU during other operation modes

Component Name (Part Number)	MODE 3 Power Draw	MODE 4 Power Draw	MODE 5 Power Draw	MODE 6 Power Draw
Parallax Propeller Microcontroller* (P8X32A-M44)	0.0429 mW 1.30 mA @ 3.30 V 5 MHz: XTAL1 + PLL1x	2.64 mW 0.800 mA @ 3.30 V Reset Button Pushes	12.87 mW 3.90 mA @ 3.30 V GDB being programmed	0.5 mW 0.198 mW 0.2 mA @ 2.5 V 0.09 mA @ 2.2 V Brownout at low voltage level on the CPU

7.4.1 Why?

The reason that the running power is so low is because the Propeller has extensive clock-gating. This is a BIG TABOO in the usual standard-cell-based design flow that perhaps every modern processor is built in. Standard cell flows let you make high-level changes very quickly, but then you must spend very considerable time insuring that the computer-generated layout will meet your timing requirements. This basically comes down to managing chaos and is often punctuated by sporadic needle-in-haystack searches for problems (except the haystack looks more like a city-wide rat's nest). Not to worry, there are million-dollar software tools that can be used to help you here. The tools we used cost only $20k (used to be $5k) from Tanner EDA. They were completely adequate for our job, perhaps much more apt, since they are simple and unburdened.

The Propeller was built from the inside-out, so that every functional block was actually SPICE-verified before being assembled into the chip. This took a lot more time, but made things small, fast, and lower power. It's kind of the assembly-language approach to chip design vs. the high-level compiler approach. Big companies have got ZERO patience for this kind of development. Unless it's a matter of some finite, but mission-critical block that needs this kind of attention, nothing else will get it. They'll settle for parts and pieces and whatever's available and lump the bugs. We learned from programming Windows that not much beyond a ScrollBar was trustworthy, and silicon is not that different. For the Propeller, we even made our own I/O pads. In fact, the entire chip is full-custom. Every single polygon on every layer was designed at Parallax. I don't think it's a stretch to say that this is unheard-of today.

The way silicon technology advances, the standard cell approach just keeps getting thrown at newer technologies, so performance gains come from the newer process, not the newer (or I should say "older") design methodology. Who knows what's possible at the 45nm node via the raw approach?

SOURCE: http://forums.parallax.com/archive/index.php/t-84907.html

7.5 Electronics Reliability

An examination done by Dr. Monas in the *Small Satellite Reliability Modeling: A Statistical Analysis* paper concluded that the Telemetry, Tracking and Command (TT&C) system, Electrical Power System (EPS), and Mechanisms & Structures (M&S) and Thermal Control System (TCS) contribute most to fatal failures of small satellites. TT&C, M&S and TCS system failures occur mostly in the first few days in orbit and are often related to malfunctioning responders and deployment failures, respectively. To combat this, Sol-X focused its engineering design work in those areas.

The radiation environment may seem like a big challenge; however, its well characterized and all Sol-X hardware will be able to handle the 100 rad(Si)/ year levels with basic plastic shielding and Sol-X's basic PMBus reset schemes.

The current failure rate (λ) of the GDB E-Series Mark I is ?? failures/day, we are still in the burn in period and expect the Mark II to have a 60% lower failure rate.

Sections 9.3 to 9.6 highlight the "Accelerated Life Testing" Sol-X performed to calculate the MTBF and MTTF.

Additional Information:

1. www.xppower.com/pdfs/Reliability.pdf
2. www.vicr.com/documents/quality/Rel_MTBF.pdf

7.5.1 Mean Time Between Failures (MTBF)

GDB leasing units have a calculated MTBF of ?? as determined by ?? on ?? ??, 2014 NOT COMPLETED YET

7.5.2 Mean Time to Failure (MTTF)

Purchased GDB units have a calculated MTTF of ?? as determined by ?? on ?? ??, 2014 NOT COMPLETED YET

8.0 Physical Characteristics

8.1 Mass and Material Characteristics

- Mass: 12 grams
- GDB low thermal coefficient PCB options:
  - Roger 4003: 40 ppm/°C
  - Thermoset: For GDB E-Series Mark II
- LF4300: Lead free reduced Tin whisker solder paste to stop Zero-G short circuits.
- PHP-900 Series IR-10FE: NASA outgas compliant *Via Fill Paste*

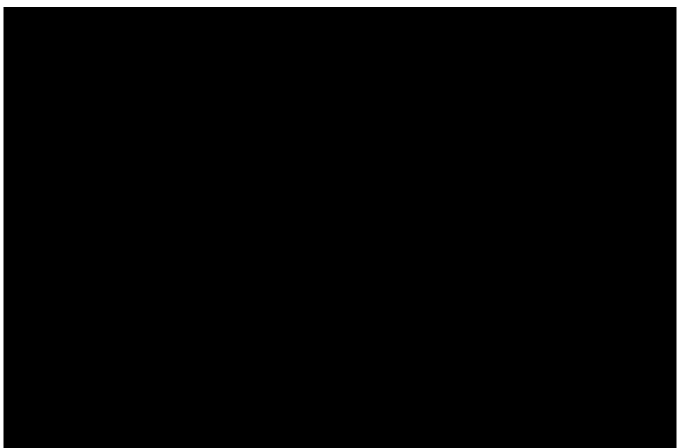
8.2 Package Dimensions

- 3-point mounting hole centers - The following offsets are from the lower left corner of LED side of PCB. Each holes has a 1.67 mm diameter. (Suggested hardware: 90116A027 a Pan M2 x 0.4 x 20 bolts and 1074N1 an extreme environment light duty vibration damping mount)
  - Hole #1 – (2.2, 35.21) mm
  - Hole #2 – (52.8, 35.21) mm
  - Hole #3 – (29.14, 6.35) mm

Figure 25 – Mounting hole pattern (grid in mm)

- Surface Area: 1,998 mm^2 (55 x 38 mm)
- Volume: 19,980 mm^3 (55 x 38 x 10 mm)

Video 3 – GDB CAD model (Click here for YouTube Video)



Interactive 1 – Click here for interactive Sunglass CAD model

8.3 Temperature and Pressure Characteristics

The GDB passed (NOT COMPLETED YET) thermal-vacuum testing in the lab of a large UK aerospace firm, the ISP Lab at Michigan Tech, MicroSpace, and the V-6 Thermal-Vacuum chamber at MSFC. (Cost $26,000). The GDB was rated at the following specs:

- Pressure 1x10-5 ATM
- Temperature -40 to 60 °Celsius

8.4 Radiation Characteristics

The GDB was designed to operate in extreme Earth environments like nuclear power plants after accidents and space environments like low inclination (less than 28° latitude) Low Earth Orbit (less than 500 km). This is achieved via the Sol - Invictus™ Radiation Shield. Our patent pending Sol-Invictus™ Radiation Shield is a modified whipple shield that stops lower-energy cosmic rays, X-Rays, low energy Gamma emissions, high and low energy Beta and Alpha particles, as well as ultraviolet electromagnetic (EM) radiation.

The GDB was rated at the following specs:

- A radiation simulation was perform in the lab of a large UK aerospace firm to confirm the GDB can withstand dose rates of 100-1,000 rad (Si)/ year.
- An Autodesk CAD model can be found here.

8.4.1Total Ionizing Dose (TID) Testing

GDB units have a max measured TID of ?? rads as determined by ?? on ?? ??, 2014 NOT COMPLETED YET

8.4.2 Single Event Testing

When a high-energy particle travels through a semiconductor, it leaves an ionized track behind. This ionization may cause a highly localized effect similar to the transient dose one - a benign glitch in output, a less benign bit flip in memory or aregister or, especially in high-power transistors, a destructive latchup and burnout.

Source: en.wikipedia.org/wiki/Radiation_hardening

8.4.2.1 Single Event Latchup (SEL)

GDB units were tested in a ?? rad environment and ?? SEL's occured as determined by ?? on ?? ??, 2014 NOT COMPLETED YET

8.4.2.2 Single Event Upsets (SEU)

GDB units were tested in a ?? rad environment and ?? SEL's occured as determined by ?? on ?? ??, 2014 NOT COMPLETED YET

8.5 Vibration Characteristics

The GDB was designed and tested to operate within the vibration profile of the Falcon 9, Ariane V, & Orbital Sciences Taurus rockets. The GDB shall be able to withstand G loads up to 6 Gees at 3 kHz

NOT COMPLETED YET

8.6 Radio Frequency (RF) & Electromagnetic Interference (EMI) Characteristics

NOT COMPLETED YET

8.7 Operation and Design Life Characteristics

The GDB has an estimated operation and design life of 2.1 years. NOT COMPLETED YET

9.0 Manufacturing Info

9.1 Reflow Peak Temperature

Mark Number	Reflow Peak Temperature
Mark I	255+5/-0 °C
Mark II	275+5/-0 °C

NOT COMPLETED YET

9.2 Green/RoHS Compliance

All GDB E-Series Mark I units are certified Green/RoHS Compliant. RoHS, Green, and ISO certificates are available online at NOT COMPLETED YET

10.0 Revision History

10.1 Changes for Rev 1.0

This is the first public release of the GDB datasheet. Beta datasheets were released to select users to create the best user documentation in the solar system.