Gibbot v4 PCB

Andrew Griesemer

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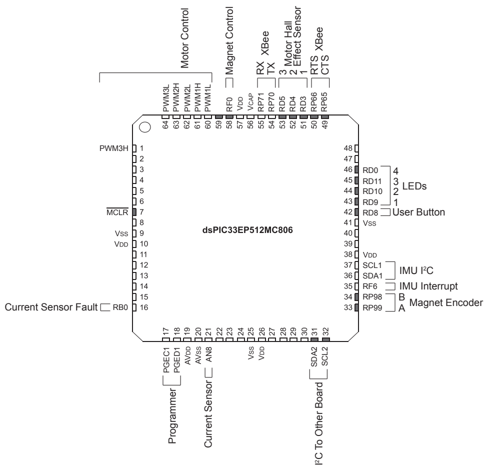
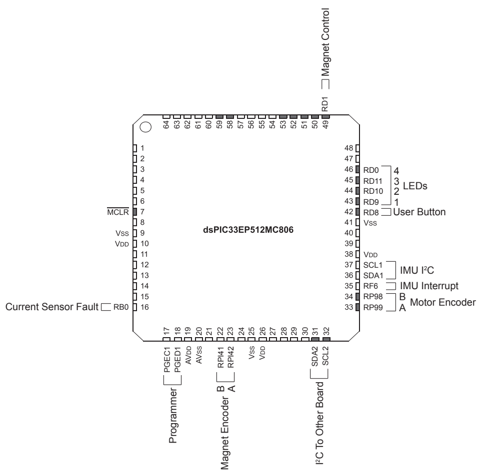
1 dsPIC Pinout



(a) Pin Assignments for Primary board



(b) Pin Assignments for secondary board

2 Power Regulation

The board is powered by a 24V power cable.

2.1 Primary Board

24V

Component	Current per unit	Total Component	Source of Current Value
EM237-24-212 Magnets	230mA x 2	460mA	Current at rated voltage [1]
EC 60 Flat Motor		< 10A	Control specification

15V

Component	Current per unit	Total Component	Source of Current Value
2 Encoders	78mA x 2	156mA	62mA maximum no load current + 8mA x 2 maximum output current[2]

5V

Component	Current per unit	Total Component	Source of Current Value

[1] APW Catalog http://catalog.apwcompany.com/Asset/6489.pdf
[2] E3 1800 CPR product page http://www.usdigital.com/products/e3

E3 Encoders	78mA x 2	156mA	62mA maximum no load current + 8mA x 2 maximum output current[3]

3.3V

dsPIC		320mA	Absolute maximum rating current from VSS[4]
Status LEDs	3.3mA x 6	20mA	Assuming 3.3V and 1k resistor
IMU		10mA	3.9mA gyro + 6mA magnetometer[5]
IR LEDs	10mA x 6	60 mA	3.3V and 330 ohm resistor
Total		**0.410 A**	

2.2 Digital Isolation

3 Inertial Measurement Unit - MPU9150

The MPU9150 is a 9 axis sensor that draws data from a 3-axis gyroscope, a 3-axis accelerometer and a 3-axis magnetometer. One sensor is attached to each board. Neither sensor has been configured. The supporting circuitry follows is shown in Figure 2 below [6].

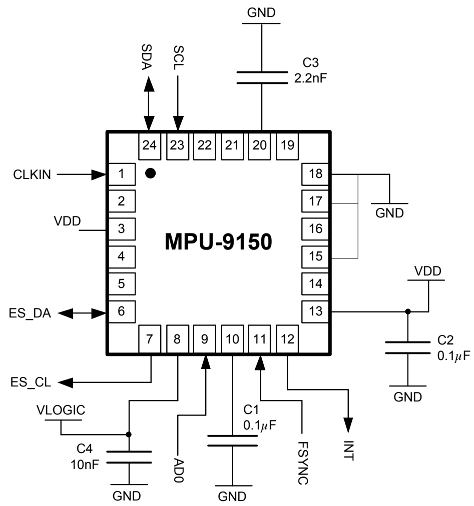


Figure 2: MPU9150 Typical Operating Circuit

This iteration of the board does not have pull-up resistors on the I^{2}C communication lines that would be required for communication between the MPU9150 and the dsPIC.

4 BLDC Motor Driver

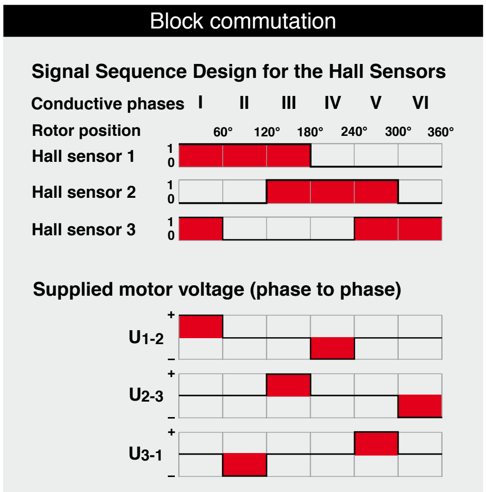
4.1 BLDC Motor Background

A Brushless DC Motor is different from a brushed DC motor because it lacks the internal brushes that allow a typical DC motor to reverse the direction of current flow as the rotor coil rotates within the magnetic stator. In order to drive a BLDC motor the direction of current flow must be actuated by external control circuitry. The benefits of BLDC motors over brushed motors is lighter weight for the same amount of torque and increased longevity.

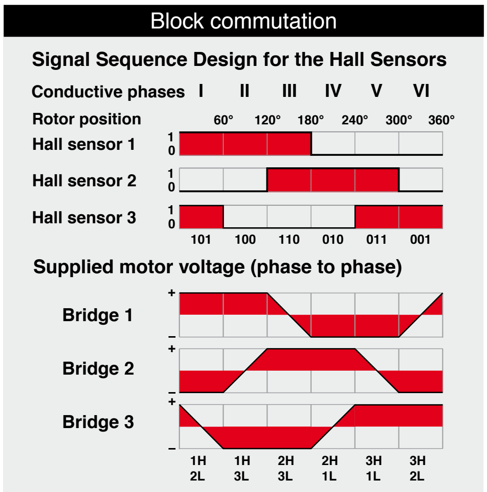
A typical BLDC motor has two or more coils and a sensor that can determine the angular position of the rotor. A microcontroller reads the state of the sensor and changes the direction of current across the

[3] E3 1800 CPR product page http://www.usdigital.com/products/e3
[4] dsPIC33EP512MC806 datasheet http://ww1.microchip.com/downloads/en/DeviceDoc/70616g.pdf
[5] MPU-9150 datasheet http://dlnmh9ip6v2uc.cloudfront.net/datasheets/Sensors/IMU/PS-MPU-9150A.pdf
[6] MPU9150 Product Specification p21 http://www.invensense.com/mems/gyro/documents/PS-MPU-9150A-00v4_3.pdf

coils in order to maximize torque. The BLDC motor on the Gibbot is the Maxon EC 60 Flat which has 3 coils and 3 Hall Effect sensors that detect the angular position of the rotor. The commutation pattern from the Maxon E-Paper Catalog is shown in Figure 3a and modified for clarity in Figure 3b.



(a)



(b)

Figure 3: The commutation pattern for the Maxon EC 60 Flat Motor.[7]

The pin connections for the Maxon EC 60 Flat motor hall effect sensor ribbon cable are given in Table ??a. Note: The pin numbering from the EC 60 Flat catalog page is for a connector that has been removed and replaced. The motor pole connections are given in Table ??b.

Table 5: Motor Connections

(a) Hall Effect Cable Pin Connections

Color	Pin Number	Connection
Blue	1	5V
Gray	2	GND
Gray	3	1
Gray	4	2
Gray	5	3

(b) Motor Pin Connections

Color	Pin Connection
Red	1
Black	2
White	3

For a lower power application the control of each coil of the motor could be accomplished by a typical H-bridge. Because the Gibbot requires up to 10A at 24V the commutation circuitry requires higher power H-bridges using MOSFETs. Figure 4 shows the schematic of an H-bridge connection for a single coil.

4.2 HIP4086 Driver

The driver circuit uses Intersil's HIP4086 3-Phase MOSFET driver[8]. This chip solves two issues with driving the MOSFETs from a dsPIC, (1) stepping up the control voltage for the low side MOSFET from the microcontroller's logic level 3.3V to the 15V required to fully turn on the MOSFET. (2) stepping up the gate voltage for the high side MOSFET to 15V plus the motor drive voltage. This voltage level is required because the high side MOSFET's source is connected to the motor coil so the gate-to-source voltage on the high side MOSFET is referenced to the motor voltage. The HIP4086 accomplishes this with Bootstrap capacitors (more info in Section 4.5). The chip also has added functionality such as programmable deadtime and a bootstrap capacitor refresh pulse.

4.3 MOSFET Selection

The bridge MOSFETs are the most critical components in the BLDC driver.

[7]Figure 3 is taken from pg 32 of the Maxon E-Paper Catalog http://epaper.maxonmotor.ch/en/
[8]Datasheet http://www.intersil.com/content/dam/Intersil/documents/hip4/hip4086-a.pdf

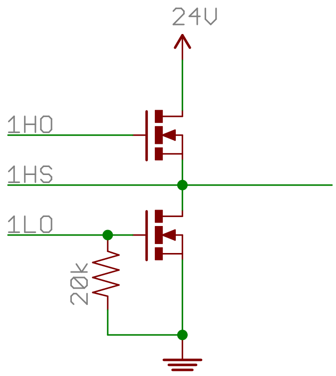


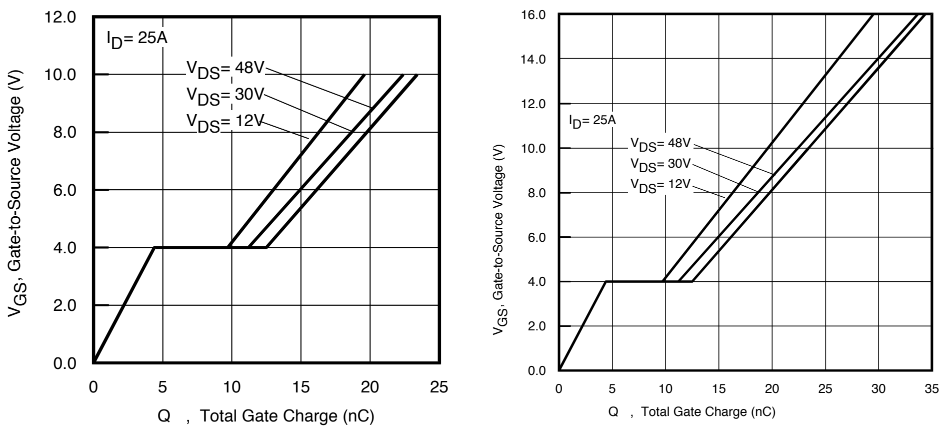
Figure 4: A single H-bridge for the BLDC motor

Max Continuous Current The required continuous current for the motor to achieve the desired torque is 10A.

Max Drain to Source Voltage (V_{DS}) The required drain-to-source voltage is the same as the Motor Supply Voltage, which was 48V, but is now 24V. To keep the design flexible to the higher voltage range V_{DS} is set a value above 48V.

Max Gate-to-Source Voltage (V_{GS}) The required gate-to-source voltage is determined by the gate drive voltage of the HIP4086 driver. This gate drive voltage is the same as the supply voltage for the HIP4086. The recommended maximum operating supply voltage on the HIP4086 datasheet[9] is 15V. To keep the design flexible to supply voltages for the HIP4086 the max gate-to-source voltage should be at least $\pm 15V$.

Gate Charge (Q_G) Because the turn on speed of the MOSFET is partially determined by the gate charge, gate charge should be minimized. The gate charge listed on a datasheet is typically the gate charge at a $V_{GS} = 5V$. If the HIP4086 has a supply voltage of 15V then V_{GS} will be 15V . Figure 5 shows a plot of Q_G vs V_{GS} for the MOSFET on the V4 board. From the plot Q_G = 33nC at V_{GS}=15V



(a) (b)

Figure 5: Typical Gate Charge vs. Gate-to-Source Voltage (a) from the IRFR3806 datasheet [10] (b) linearly extrapolated to $V_{GS} = 15V$.

On State Drain-to-Source Resistance ($R_{DS(ON)}$) The on state resistance effects the efficiency of the drive circuitry and partially determines the temperature rise during operation. $R_{DS(ON)}$ should also be minimized.

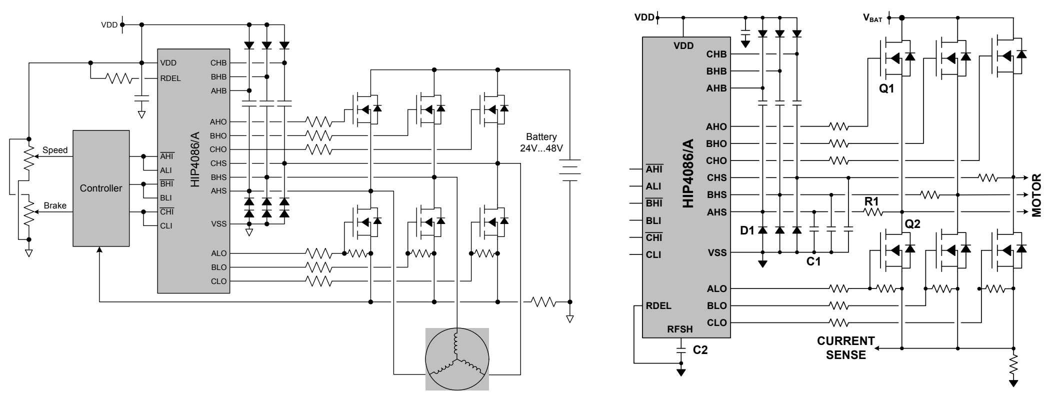
[9] HIP4086 Datasheet pg 5 http://www.intersil.com/content/dam/Intersil/documents/hip4/hip4086-a.pdf
[10] IRFR3806PbF datasheet pg 3 http://www.irf.com/product-info/datasheets/data/irfr3806pbf.pdf

Maximum Power Dissipation (P_D) This value is not considered in MOSFET selection. While the ability of the MOSFET to dissipate heat from conducting is important, the way in which $P_{D,MAX}$ is defined varies widely between manufacturers. Moreover, the ability of a MOSFET to dissipate heat should not vary significantly between different devices in the same physical package. Determining a specification for power dissipation would also be difficult because it involves a combination of the power dissipated during turn-on and turn-off periods when R_{DS} is high and the power dissipated during the fully on state at the much lower $R_{DS(ON)}$.

4.4 Clamping Circuit

The HIP4086 Datasheet and the HIP4086 Demo Board User Guide provide two different methods of clamping the HS pin to prevent negative transients. The two methods are shown in Figure 6. The purpose of the clamping circuit is to limit the negative transient voltage that is induced when the high side MOSFET is turned off to the -6V voltage limit specified for the HIP4086. The two methods accomplish this while limiting the current that is able to flow through the path during the deadtime when both MOSFETs are off. The method used in the HIP4086 Datasheet (Figure 6a) uses two diodes in series. The method used in the HIP4086 Demo Board User Guide (Figure 6b) uses a single diode with a resistor in series. Because values are not established for the resistor in the Demo Board User Guide method we used the simpler method from the Datasheet (Figure 6a).

Figure 6: Alternate clamping circuitry from the HIP4086 documentation[11].



(a) HIP4086 Datasheet

(b) HIP4086 Demo Board User guide

4.5 Bootstrap Capacitor, Diode and Resistor Selection

The boot capacitor value is chosen so that the capacitor can provide the gate charge of the driven FET without causing the capacitor voltage to sag excessively.

The formula for calculating bootstrap capacitance from the HIP4086 datasheet is:

$$Q_C = Q_{GATE} + Period \cdot \left(I_{HB} + \frac{V_{HO}}{R_{GS}} + I_{GATELEAK} \right)$$

Because there is no gate-to-source resistor for the high side MOSFETs, the $\frac{V_{HO}}{R_{GS}}$ term can be eliminated. The other values are calculated as follows:

Q_{GATE} = 32nC, gate Charge of the MOSFET at $V_{GS} = 15V$ and $V_{DS} \approx 30V$ from Figure 5.
$Period$ = 50μs, maximum on time of the high side MOSFET at 100% Duty Cycle.
I_{HB} = 100μA, worst case high side current through the xHB pin of the HIP4086.
$I_{GateLeak}$ = 100nA, leakage current of the MOSFET gate.

$$Q_C = 32nC + \frac{1}{20,000Hz} * (100uA + 100nA) = 37nC$$

[11]HIP4086 datasheet pg 12 http://www.intersil.com/content/dam/Intersil/documents/hip4/hip4086-a.pdf and HIP4086 Demo Board User Guide, Application Note 1829 pg 7 http://www.intersil.com/content/dam/Intersil/documents/an18/an1829.pdf

$$C_{BOOT} = \frac{Q_C}{Ripple \cdot V_{DD}}$$

$$C_{BOOT} = \frac{37nC}{5\% \cdot 15V} = 49nF \approx 0.047uF$$

4.6 Set Dead Time on the HIP4086

Because the gate capacitance of the MOSFET keeps the MOSFET on for a period of time after the control signal has gone low, there must be a delay between the turn-off event of one PWM output in a complementary pair and the turn-on event of the other. Otherwise shoot through might occur when both MOSFETs are conducting causing the power to short to ground. The time between transitions of the control PWM signal is called dead time. In the current configurations of the Gibbot dead time is redudantly programmed into both the dsPIC PWM control as well as the HIP4086.

Dead time on the HIP4086 is set using a resistor between ground and the pin R_{DEL} on the HIP4086. Figure 7 from the HIP4086 datasheet can be used to set R_{DEL} approximately.

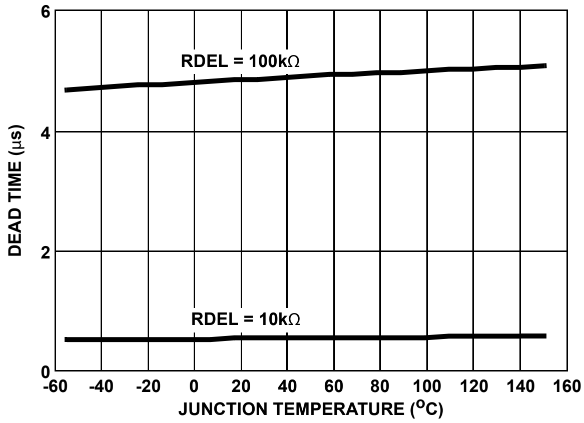


Figure 7: R_{DEL} vs. Dead Time[12]

5 XBee

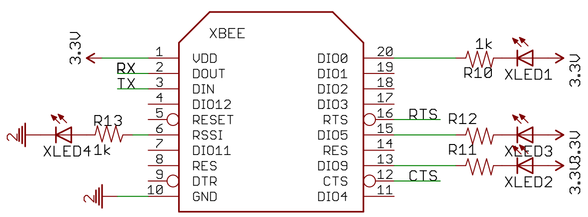
Besides connections to the dsPIC for RX, TX, CTS and RTS, multiple LEDs are connected to outputs from the XBee to provide a visual indicator of its status. The schematic for these connections are shown in Figure 8.

RSSI Recieved Signal Strength Indicator - A high speed PWM output ranging from 24% to 100% duty cycle depending on the strength in decibels above the sensitivity threshold of the last recieved RF packet.

Associated Blinks when the XBee is associated with a coordinator.

[12]From HIP4086 3-Phase Bridge Driver Configurations and Applications pg 4
http://www.intersil.com/content/dam/Intersil/documents/an96/an9642.pdf

Figure 8: XBee Connections



6 Magnet Control

Logic level MOSFETs control the electromagnets. To maintain isolation between the noisy 24V line and the 5V digital line the magnet MOSFET control signal is transmitted through a digital isolator.

7 IR LEDs

The Gibbot is mounted with six Optitrack IR LEDs. The LEDs are mounted on the face plate in three clusters (2 above the top magnet, 1 above the motor, 3 above the bottom magnet) so that the Optitrack cameras can detect the position of each magnet and the motor joint.

7.1 IR LED Resistor Values

In this iteration all of the LEDs are powered on 5V lines. The minimum resistor values were calculated as follows:

1 LED

$$\frac{5V - (1 * V_{F,MAX})}{I_{F,MAX}} = \frac{5V - 1.6V}{100mA} = 34\Omega$$

2 LED

$$\frac{5V - (2 * V_{F,MAX})}{I_{F,MAX}} = \frac{5V - 3.2V}{100mA} = 18\Omega$$

3 LED

$$\frac{5V - (3 * V_{F,MAX})}{I_{F,MAX}} = \frac{5V - 4.8V}{100mA} = 2\Omega$$

Where:
$V_{F,MAX} = 1.6V$
$I_{F,MAX} = 100mA$
To avoid the risk of running maximum current through the resistors these value should be increased by about 50%.

8 Current Sensor

The current sensor used on the board is the ACS716KLATR-12CB-T which has an optimized accuracy range of +/- 12.5A and a linear sensing range of +/- 37.5A. The sensor outputs an analog voltage proportional to the current through its sensing path, centered at 1.65V for zero current with a slope of 37mV/A.

8.1 dsPIC ADC Inductor

The dsPIC33EP512MC806 datasheet[13] recommends an inductor between the V_{DD} and A_{VDD} to improve ADC noise rejection. The inductance of this inductor is calculated as follows:

$$L = \left(\frac{1}{2 \cdot \pi \cdot \frac{F_{CNV}}{2} \cdot \sqrt{C}} \right)^2$$

Where:
F_{CNV} = ADC Conversion Rate

When the ADC is configured to read a single input using manual read triggering and automatic sampling triggering with $T_{AD} = 250ns$ the maximum F_{CONV} = 115kHz.

$$L = \left(\frac{1}{2 \cdot \pi \cdot \frac{115kHz}{2} \cdot \sqrt{.1uF}} \right)^2 = 76\mu H$$

[13]dsPIC33EPXXX(GP/MC/MU)806/810/814 datasheet pg 32
http://ww1.microchip.com/downloads/en/DeviceDoc/70616g.pdf

The datasheet also specifies that the inductor should have a maximum impedance of 1Ω and a current rating of at least 10mA. The largest inductance value available on Digikey that was still in a relatively small package was 47μH. From this value, the maximum F_{CNV} should be:

$$F_{CNV,MAX} = \frac{1}{\pi \cdot \sqrt{L \cdot C}} = \frac{1}{\pi * \sqrt{47\mu H \cdot 0.1\mu F}} = 147kHz$$

8.2 ACS716 Filter Capacitor

The ACS716 allows for a filter capacitor to limit noise in the sensor. The capacitance is determined from the plot below. Since the motor is driven with a PWM frequency at 20kHz an appropriate bandwidth is between 10 and 20kHz. The corresponding capacitance from Figure 9 is between 5 and 9nF.

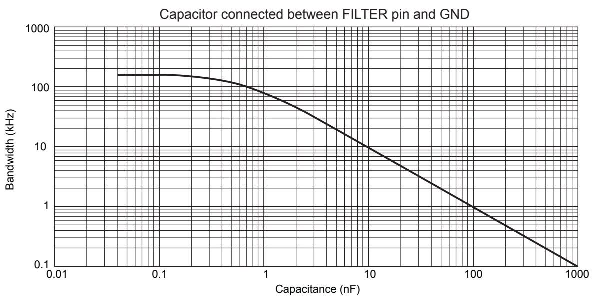


Figure 9: ACS716 Bandwidth versus External Capacitor Value, C_F[14]

8.3 Overcurrent Threshold

The overcurrent threshold voltage allows us to detect if the current level is above a user-set limit, likely because of a short. The overcurrent limit is set using a voltage divider composed of R_H and R_L to set a reference voltage on pin V_{OC}. When the current through the current path is detected to be higher than

$$C_{OC} = I_{OC} * 37mV/A$$

the ACS716 drives the output of the FAULT pin high. We chose to set the current threshold at 30A.

$$C_{OC} = 30A * 37mV/A = 1.1V$$

Resistors values of $R_H = 2k$ and $R_L = 1k$ set V_{OC} at

$$V_{OC} = 3.3V * \frac{1k}{1k + 2k} = 1.1V$$

To prevent the fault detection from triggering because of noise a capacitor is connected between fault and ground. The maximum recomended value of 22nF is used. In previous iterations this features was configured, but the FAULT pin was not connected to the PIC. The pin is now connected to pin B0 on the PIC.

9 Wire Gages

9.1 Wire Sources

The standard wire gages on purchased connectors are:

Orbex Slip Ring 2A: AWG26 or AWG28

Sparkfun JST PH Jumper Wire: 24 AWG

Sparkfun JST SH Jumper Wire: 28 AWG

[14] From ACS716 Datasheet pg 10 http://www.allegromicro.com/~/media/Files/Datasheets/ACS716-Datasheet.ashx

Mechatronics Lab Red & Black 22 AWG

Nick's stores Red, Blue & Green 30 AWG

NxR 30 AWG Black
22 AWG Green
16-19 AWG Lime Green
22 AWG Black, Blue, Red White, Green, Orange in Grey case
16 AWG Blue, Brown Green
Unknown AWG Red, Black, White shielded clear
22 AWG Striped

9.2 Wire Requirements

24V Power
Current Sensor
Main Board 5V Power 22 AWG Red & Black
Secondary Board 5V Power 22 AWG Red & Black
1 LED Power 30 AWG Red & Black
2 LED Power 30 AWG Red & Black
3 LED Power 30 AWG Red & Black
Top Magnet Control 30 AWG Red, Green, Blue & Red
Bottom Magnet Power 22 AWG Red & Black
Top Magnet (Slip Ring) 28 AWG Red, Yellow & Black
Bottom Magnet (Slip Ring) 28 AWG Red, Yellow & Black
Top Magnet Encoder 30 AWG Black, Red, Green & Blue
Bottom Magnet Encoder 30 AWG Black, Red, Green & Blue
Motor Encoder 30 AWG Black, Red, Green & Blue
I2C 30 AWG Green & Blue

10 PCB Bill of Materials

Part Number	Quantity	Description
Microcontrollers & Sensors		
PIC1, PIC2	2	DSPIC33EP512MC806
X1	1	XBee Series 1 Wired Antenna
CS1	1	ACS716KLATR-**6BB**-T Current Sensor
IMU1, IMU2	2	MPU-9150 (Out of Stock)
	2	MPU-6000 (Replacement)
MD1	1	HIP4086 BLDC Motor Driver
Resistors		
R40, R41, R43	3	0 ohm
R70	1	3.3 Ω
R34, R35, R36, R37, R38, R39	6	10 Ω
R25	1	22 Ω
R24	1	47 Ω
R2, R7, R8, R9, R10, R11, R12, R13, R17, R18, R19, R31, R66, R67, R68, R69, R77, R78	18	1k Ω
R1	1	2k Ω
R14, R42, R61, R73	4	2.2k Ω
R16	1	10kΩ
R4, R5, R6	3	20k Ω
R3	1	330k Ω
Capacitors		
C34, C35, C36, C37, C50, C51, C52, C53, C61	9	.01uF 0603
C1, C11, C12, C13, C21, C22, C25, C26, C28, C29, C31, C32, C33, C38, C40, C41, C42, C43, C54, C55, C56, C57, C59, C60, C62	25	.1uF 0603
C7, C8	2	.1uF 0603 25V Rated
C39	1	.1uF 0603 50V Rated
C6, C46, C47	3	.1uF 1206
C17, C18, C19	3	.03uF 0603 16V Rated
C2	1	1nF 0603
C64	1	1uF 1206
C23, C27	2	2.2nF 0603
C20, C24	2	10nF 0603
C15, C48, C49, C63	4	10uF 0603 Polarized
C5, C30	2	10uF 0603
C14, C44, C45, C58, C65	5	10uF 1206
C66, C67	2	10uF 1206
C4	1	22nF 0603
C9, C10	1	22uF 0603 15V Rated
C3	1	7nF 0603
Diodes		
D1, D2, D3, D4, D5, D7, D8, D9, D10, D11, D12	11	ES1B 100V, 1A
Power Converters		
P2	1	24V to 5V DC-DC Converter
P3	1	24V to 15V & 5V Linear Regulator
P1, P4	2	5V to 3.3V LDO Regulator
P5	1	15V to 5V Linear Regulator
Digital Isolators		
DI2, DI3	2	1 Channel

Part Number	Quantity	Description
DI1	1	6 Channel
MOSFETs		
1H, 1L, 2H, 2L, 3H, 3L	6	IRFR3806
M1, M2	2	SSM3K329RLFCT-ND, 30V, Logic Level
LEDs		
	12	0603 LED
Switches & Buttons		
SW1	1	SPDT Slide Switch
RESET1, USER1, RESET2, USER2	4	Momentary, Normally Off, Tactile Switch
Connectors		
J1, J6, J7, J8, J9, J14, J15, J20, J21	9	JST PH 2pos Right Angle Header
	9+	JST PH 2pos Housing
	5+	JST KR 2pos IDC
J4, J13	2	JST PH 3pos Right Angle Header
	2+	JST PH 3pos Housing
	5+	JST KR 3pos IDC
J2, J17, J18	3	JST PH 4pos Right Angle Header
	2	JST PH 4pos Housing
	5+	JST KR 4pos IDC
J3, J12	2	JST PH 8pos Right Angle Header
	2	JST PH 8pos Housing
	2	JST PH 8pos IDC
	40+	JST PH Contact 22-26AWG
	40+	JST PH Contact 24-30AWG
	40+	JST PH Contact 28-32AWG
J10, J11, J16, J19	4	JST SH/SR 2pos Right Angle Header
	4+	JST SR 2pos IDC
J5	1	JST SH/SR 5pos Right Angle Header
	1	JST SR 5pos IDC
	20+	JST SH Contacts 28-32AWG
JP1, JP2, JP3, JP4, JP5	5	Molex Mini Fit Jr. 2pos Right Angle Header
	5	Molex Mini Fit Jr. 2pos Vertical Header
	5	Molex Mini Fit Jr. 2pos Housing
JP6	1	Molex Mini Fit Jr. 3pos Right Angle Header
	1	Molex Mini Fit Jr. 3pos Housing
	15	Molex Mini Fit Jr. Contacts 16AWG
	15	Molex Mini Fit Jr. Contacts 18-24AWG
	15	Molex Mini Fit Jr. Contacts 22-28AWG
Miscellaneous		
	10	18650 Battery Holder

11 Board Issues

Triangles on programming pins DC-DC Converter RC Pin shorted to 24V, should be shorted to GND. Pads for standoffs misaligned. Motor Board Current Sense and Input Voltage mislabeled On 8 pin connector between PIC board and motor board 3.3V and GND are reversed in order Motor hall effect sensors connection pins are labeled in reverse order RDEL is not connected to 15V. Encoder inputs are in different order on different boards Magnet MOSFET - "SOT23F" label is the footprint, part number is actually SSM3K329R SCL and SDA on secondary board labeled incorrectly