Motor Controller

Shell ECO Marathon Team AU 2014

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Contents

1 Introduction

This project's focus is to design and implement a high efficient DC-motor controller, aimed at Aarhus University's participating car "Zenith 33" in the annual European Shell Eco Marathon. The concept of the design has to be rigid and simple to ensure durability during the race. Furthermore it has to be highly adjustable to make useful in every challenge along the way from design to finished product. Certain physical demands has to be taken into account, the motor controller has to be as physically small as possible and its weight has to be kept down as well.

In terms of functionality the motor controller has to be able to handle the motor output, a speed input, a motor feedback, CAN-bus communication and collection of internal data. The motor output must be regulated so that at any given time the DC-motor operates as efficient as possible. The driving algorithm has to be controlled in the manner of an already described "Burn and Coast" principle. The driving algorithm and regulation functionality is preferred to be as automatically controlled as possible to ensure he highest possible efficiency.

Preliminary work 2

This chapter describes the work performed to get to grips with the functionality of the complete system. The chapter will cover system diagrams, requirements specifications and use case models.

2.1 Requirements

2.1.1 Description

The motor drive system has to fulfill the requirements to qualify for participation in Shell Eco-marathon. Functional requirements are derived from SEM[1], OOD[2] and the BMS[3]. The internal structure of the motor drive system is depicted in Figure 2.1.

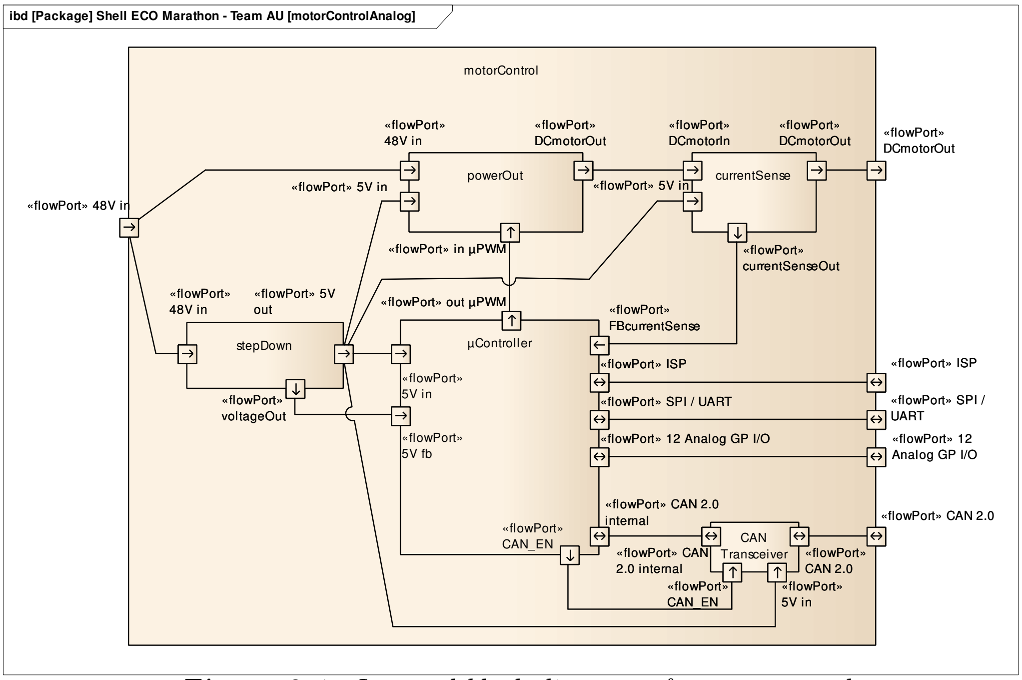

Figure 2.1: *Internal block diagram of motor control*

To ease the use of the individual requirements, each requirement is given a specific number in the form of mC.x-x.

[1]SEM global official rules 2014.
[2]Reports and conclusions on optimization of the drivetrain.
[3]Documentation of the battery management system.

2.1.2 Functional requirements

Motor control Functional requirements

Interfacing		
Req.#	***Requirement description***	***Reference***
mC.1-1	Accessing and setting of internal functions and parameters in the system while driving is done via the analog GP I/O interface. Listed beneath is all the functions and parameters controlled and accessed via the analog interface. • A drivetrain speed feedback is available in the form of pulses from a sensor mounted in the drivetrain. • Lower and upper speed limits for the burn and coast, see Figure 2.3, can be adjusted from zero to max speed in steps of 1 km/h. Upper limit will always be at least 1 km/h higher than the lower limit. • Go function can be called from an external interrupt. When Go is called and the speed is equal to zero, the launch procedure will be performed. If Go is called and speed is different from zero, the cruise procedure will be performed.(See transactions in Figure 2.4) • Stop function can be called from an external interrupt. When Stop is called the motor controller output will be disabled, regardless of the state. (See transactions in Figure 2.4)	Internal Requirements and OOD-Section 23.5(Montering af hastighedssensor)
mC.1-2	The communication with other components of the complete system is either done via SPI, UART or CAN. Each of these three interfaces are available as connectors on the PCB.	BMS Section 1.5.3.1.(CAN communication protocol)
mC.1-3	A six pin ISP (In-System Programming) interface is available for programming the MCU.	Internal Requirements
mC.1-4	Additional analog GP I/O ports are available as connectors on the PCB.	Internal Requirements
mC.1-5	The power input is rated to 15 A@12 V - 75 V	Internal Requirements

Internal Boundaries		
Req.#	***Requirement description***	***Reference***
mC.1-6	To supply the control circuit an internal supply of 100 mA@5 V is needed. *Tolerance:* V_{CC}: 4,8 V - 5,2 V	Internal Requirements
mC.1-7	A step down converter with a voltage input range of 12 V-75 V, and an output of max. 380 mA@5 V is implemented in the system.	Internal Requirements
mC.1-8	The internal current sense has a resolution of approximately 330 mV/A through a buffered low pass filter.	Internal Requirements
mC.1-9	The output is controlled by adjusting the duty cycle of the internal PWM signal. • Voltage: 0 V-5 V *Tolerance:* Low_{max}: 0,7 V $High_{min}$: 4,2 V • Current: Max. 40 mA • Frequency: Adjustable from 15 kHz - 100 kHz	ATmega64M1 datasheet section 28.2(DC characteristics)
Power output		
Req.#	***Requirement description***	***Reference***
mC.1-10	The components of the power output has to be able to handle a continuous max current of 15 A@75 V	OOD-section 14.3(Delkonklusion) (200 W DC motor)
mC.1-11	The motor drive is only able to operate DC motor in 1^{st} quadrant of the I_A-N_{rpm} plane, Figure 2.2	Internal Requirements
mC.1-12	The output control is based on the burn and coast principle, Figure 2.3	OOD-section 16.2(Simuleringscyklus)
mC.1-13	Launch procedure is implemented as a ramp acceleration derived from a torque curve available from the test bench group. An array of ten integers is made in the software to define the current output according to rpm in the acceleration ramp.	OOD-section 16(Accelerations Principper)
mC.1-14	The output control is maintained via feedback from both output current and drivetrain speed.	Internal Requirements

Table 2.1: Functional requirements table

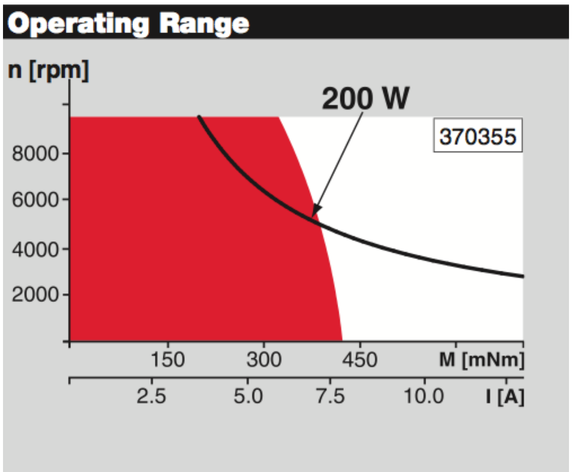

Figure 2.2: *DC motor operating area graph from motor datasheet, available area in this system is* 1^{st} *quadrant.*

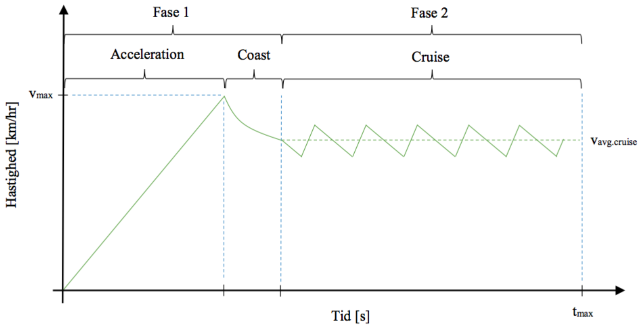

Figure 2.3: *Graph on burn and coast principle from OOD-section 16.2(Simuleringscyklus). Higher and lower speed limits are at to top and the bottom of the sawtooth respectively*

2.1.3 Non-functional requirements

Motor control Non-functional requirements

Rules and Regulations		
Req.#	***Requirement description***	***Reference***
mC.2-1	Sufficient overload protection has to be incorporated in the electrical cucuits. Fuses are incorporated to accommodate various current ratings in the system. Output current is furthermore limited by the control system.	SEM-Article 57:e
mC.2-2	The system is incorporated in a transparent enclosure/ the enclosure has to have a transparent lid.	SEM-Article 57:l
mC.2-3	Text "SEM" has to be incorporated in the mask of all PCB's.	SEM-Article 67:a

Table 2.2: Non-functional requirements table

2.1.4 Functionality

The use of the system is simplified to the use om two buttons "Go" and "Stop". The functionality is described in the state machine in Figure 2.4.

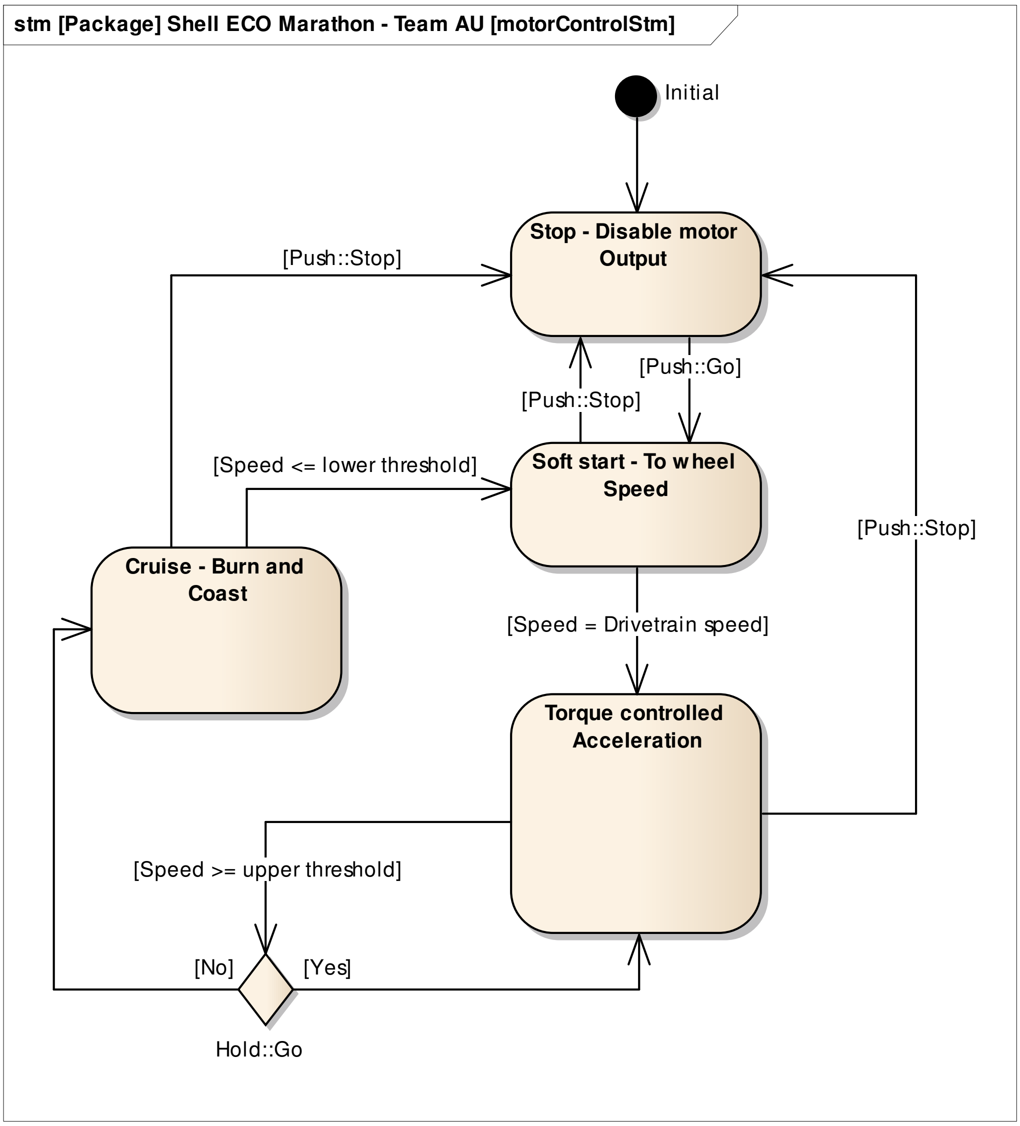

Figure 2.4: *System functionality state machine*

Design and Implementation 3

The purpose of this chapter is to describe the design of the motor controller in details, both for the hardware and the software. For the hardware a graphical schematic will be given and the purpose of each element will be described with its considerations and equations. The software will be described by graphical UML diagrams and element functionality for each section.

3.1 System Description

The system description summarizes the considerations and design choices of the system.

3.1.1 Hardware

The complete Hardware circuit is designed as shown in the schematic in Figure 3.1, and implemented on a printed circuit board. Considerations about spacing, EMC and high frequency noise has been made prior to the physical implementation. In this section the functionality of each subcircuit of the hardware is described in details.

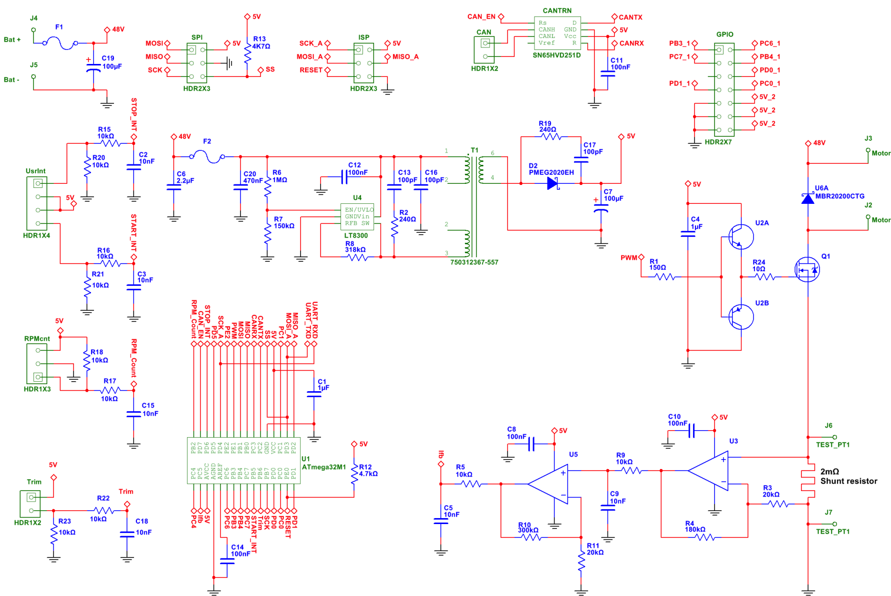

Figure 3.1: Complete motor controller circuit

3.1.1.1 Input and Main Protection

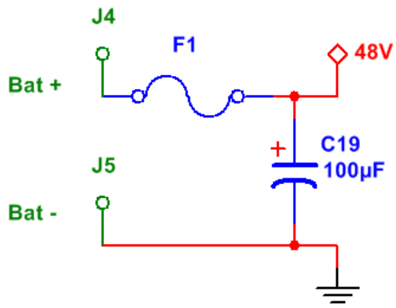

Figure 3.2: Input circuit including protection an voltage stabilization

The main protection of the motor controller is dona via a sand filled fuse rated 250 V@16 A. The fuse acts as both overcurrent and short circuit protection. Cables protected by this fuse is sized to 2,5 mm^2, cable size is chosen according to the table in Appendix B, Section 5.2. Furthermore the input voltage is stabilized by a 100 µF electrolytic capacitor.

3.1.1.2 Micro Controller Circuitry

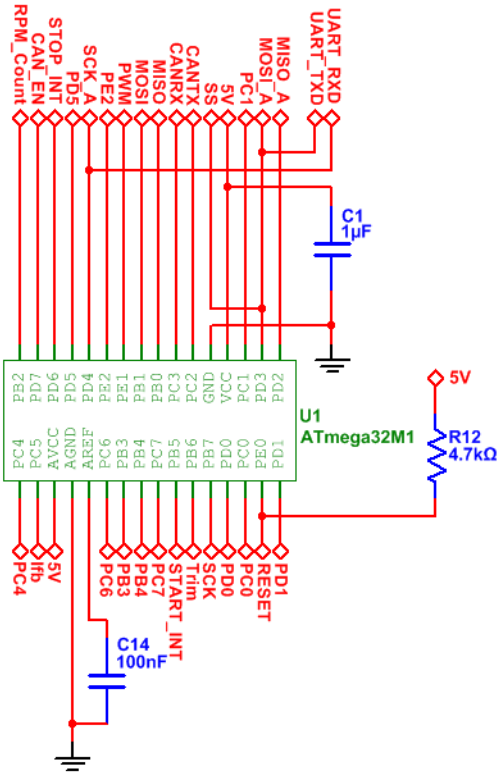

Figure 3.3: Micro controller circuit

The circuitry around the AVR micro controller is made accordingly to the AVR042 application note on Hardware design considerations. The decoupling capacitors are placed physically close to the micro controller to provide sufficient decoupling of all signals.

For better noise performance the AREF pin is connected to GND via a noise reduction capacitor as described in ATmega32M1 datasheet section 21.

3.1.1.3 Switch Mode Step Down Converter

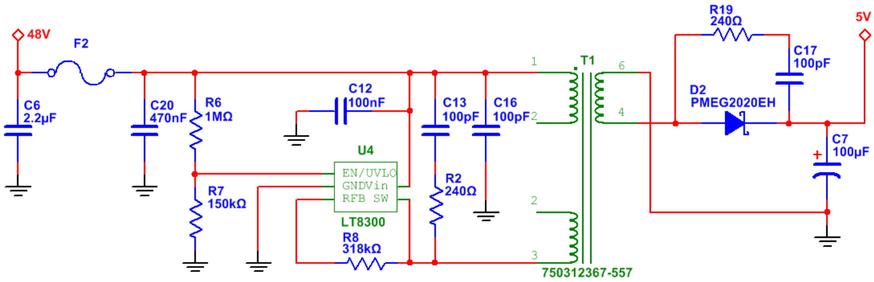

Figure 3.4: Switch Mode Step Down Converter

The voltage step down from the system supply voltage to the control circuit voltage is achieved with at switching mode step down converter. The switching converter provides a significant improvement in efficiency compared to a LDO. The circuit is adapted from the datasheet of the LT8300 controller, and is customized to meet the system specifications. All design details are chosen according to the applications section in the LT8300 datasheet.

To meet the specifications of the dynamic input voltage from 12 V - 75 V the input resistors of the step down converter is chosen as shown in Equation 3.1.

$$R_7 = \frac{V_{Pin} \cdot R_6}{I_{Pin} \cdot R_6 + V_{in} + V_{Pin}} \tag{3.1}$$

Where:
$R_6 = 1\,\text{M}\Omega$
$V_{Pin} = 1{,}239\,\text{V}$
$I_{Pin} = 2{,}5\,\mu\text{A}$
$V_{in} = 12\,\text{V}$
$\Rightarrow R_7 \approx 150\,\text{k}\Omega$

The control circuit is specified to operate at 5 V. This is achieved by calculating the correct value of R_8 as in Equation 3.2.

$$R_8 = \frac{N \cdot (V_{out} + V_f)}{I_{fb}} \tag{3.2}$$

Where:
$N = 6$
$V_{out} = 5\,\text{V}$
$V_f = 0{,}3\,\text{V}$

$I_{fb} = 100\,\mu\text{A}$
$\Rightarrow R_8 \approx 318\,\text{k}\Omega$

This design yields a minimum load current at any given time. The minimum load current is calculated as in Equation 3.3.

$$I_{Loadmin} = \frac{L_{Pri} \cdot I_{sw} \cdot f_{min}}{2 \cdot V_{out}} \tag{3.3}$$

Where:
$L_{Pri} = 300\,\mu\text{H}$
$V_{out} = 5\,\text{V}$
$I_{sw} = 52\,\text{mA}$
$f_{min} = 7{,}5\,\text{kHz}$
$\Rightarrow I_{Loadmin} \approx 610\,\mu\text{A}$

In order to reduce the ringing on the output diode an RC snubber is implemented on the primary side of the transformer. An additional snubber is designed on the secondary side so that the PCB is ready for implementation, this one is not implemented. The calculations is done as in Equations 3.4, 3.5 and 3.6. The timing parameters are measured on the actual circuit to provide the most optimum snubbing.

$$C_{parasitic} = \frac{C_{17}}{(\frac{T_{periodsnub}}{T_{period}})^2 - 1} \tag{3.4}$$

$$L_{parasitic} = \frac{T_{period}^2}{C_{parasitic} \cdot 4 \cdot \pi^2} \tag{3.5}$$

$$R_{19} = \sqrt{\frac{L_{parasitic}}{C_{parasitic}}} \tag{3.6}$$

Where:
$T_{period} = 60\,\text{ns}$
$T_{periodsnub} = 112\,\text{ns}$
$C_{17} = 100\,\text{pF}$
$\Rightarrow R_{19} \approx 240\,\Omega$

The switch mode step down converter has an additional overcurrent and short circuit protection via a fuse rated $250\,\text{V}@200\,\text{mA}$.

3.1.1.4 Power Output and Feedback Circuit

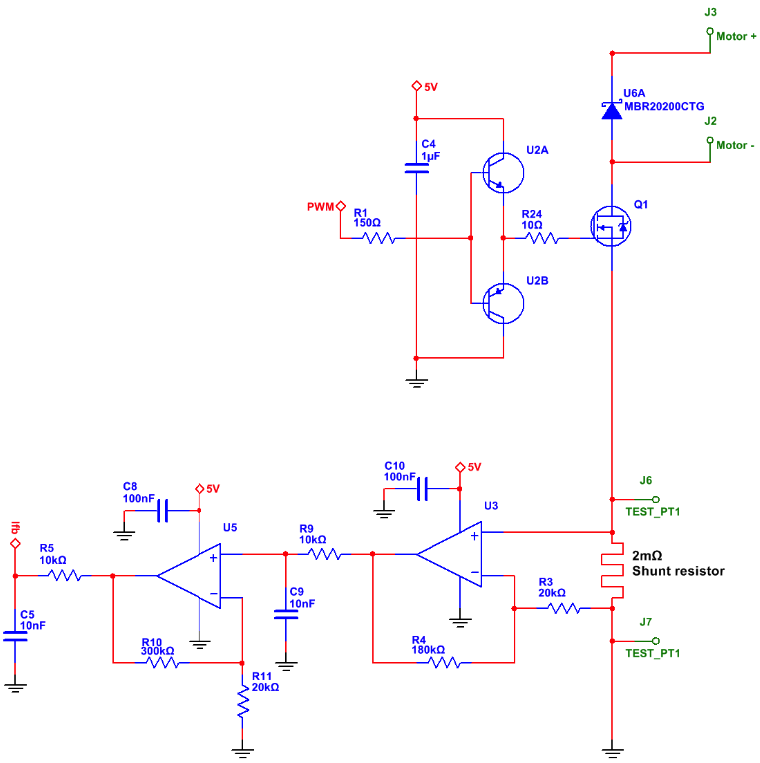

Figure 3.5: Power output stage at current feedback circuit

The power output for the DC motor is made as a simple on switch chopper PWM control. The motor controller is thereby only able to control the DC motor in the first quadrant. To minimize switch losses a two transistor gate driver is implemented. These two Bipolar junction transistors is able to charge the gate of the MOSFET with a current of approximately 500 mA. The gate current is limited by R_{24} to minimize high frequency ringing on the gate. A flyback diode is coupled parallel to the DC motor terminals to ensure at current path when the MOSFET is turned of.

The main current feedback is maintained via a 2 mΩ shunt resistor in the main power line. The shunt is realized as a specific piece of PBC wire and calculated as shown in Equation 3.7.

$$R_{Shunt} = \frac{\rho \cdot length}{Area} \tag{3.7}$$

Where:
$\rho = 17{,}5\,\mathrm{n\Omega\,m}$
$length = 4\,\mathrm{cm}$
$Area = 35\,\mathrm{\mu m} \cdot 1\,\mathrm{cm}$
$\Rightarrow R_{Shunt} \approx 2\,\mathrm{m\Omega}$

A the voltage across the shunt resistor is measured via a second order buffered low pass filter with sufficient gain. The voltage is proportional to the DC motor current. The filter gain is calculated to fit the control voltage range when the current is lower or equal to the maximum rating for the system. The gain is calculated for each filter as in Equations 3.8. The cut off frequency for each of the filters is calculated as in Equation 3.9.

$$A = \frac{R_4}{R_3} + 1 \tag{3.8}$$

Where:
A = Gain
R_3 = Ground Resistor (Will be R_{11} for the second filter in Figure 3.5)
R_4 = Feedback Resistor (Will be R_{10} for the second filter in Figure 3.5)

$$f_c = \frac{1}{2 \cdot pi \cdot R \cdot C} \tag{3.9}$$

Where:
f_c = Cut Off Frequency
R = Resistor in RC low pass filter
C = Capacitor in RC low pass filter

3.1.1.5 Analog and Digital Interfacing

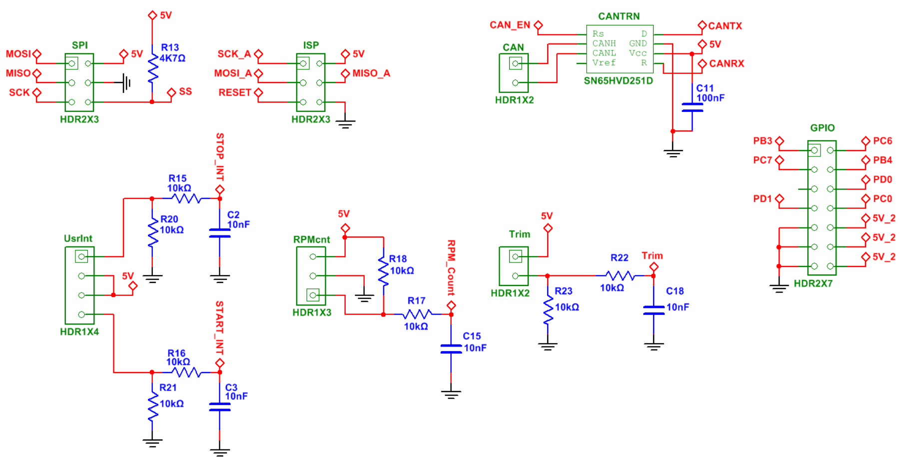

Figure 3.6: Interfacing circuits

The system interfaces includes the following types.

- Drivetrain Speed Feedback
- Additional Analog Interfaces
- CAN Interface
- SPI Interface
- UART Interface
- User Interface

Drivetrain Speed Feedback
The drivetrain speed feedback is implemented as a Hall effect sensor in the drivetrain. This sensor triggers an interrupt on the micro controller.

Additional Analog Interfaces
A number of general purpose In/Out ports is connected to accessible solder pads for additional and "on the fly" extensions.

CAN Interface
The system and the PCB layout is prepared for CAN interfacing.

SPI Interface
The SPI interface is used to log data form the motor controller on an SD card placed on a breakout board with a level converter.

UART Interface
The UART is used for accessing and monitoring internal software parameters.

USER Interface
The User interface consists of a number of buttons in the user controls. The user is able to control the system functions via these buttons.

Each interface includes protocol specific hardware such as pull-up resistors, decoupling capacitors and analog low pass filters.

A seven point turn switch is placed in the cabin to make the driver able to adjust parameters in the cruise control while driving. The turn switch in implemented as a simple voltage divider, shown in Figure 3.7 and connected to an analog to digital converter in the micro controller.

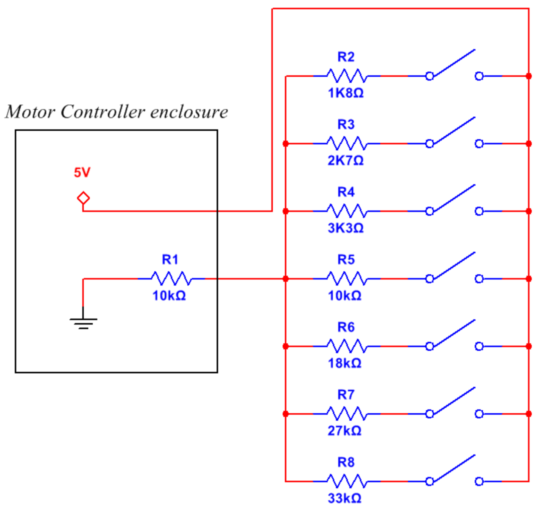

Figure 3.7: Turn switch circuit for adjusting cruise parameters.

3.1.2 Software

The software in implemented to match the state machine shown in Figure 3.8. The input parameters for the software is the speed of the drivetrain, the current through the DC motor and driver inputs from the controls in the steering rods. Furthermore the driver is able to adjust the setpoint for the driving style via a turn switch in the cabin.

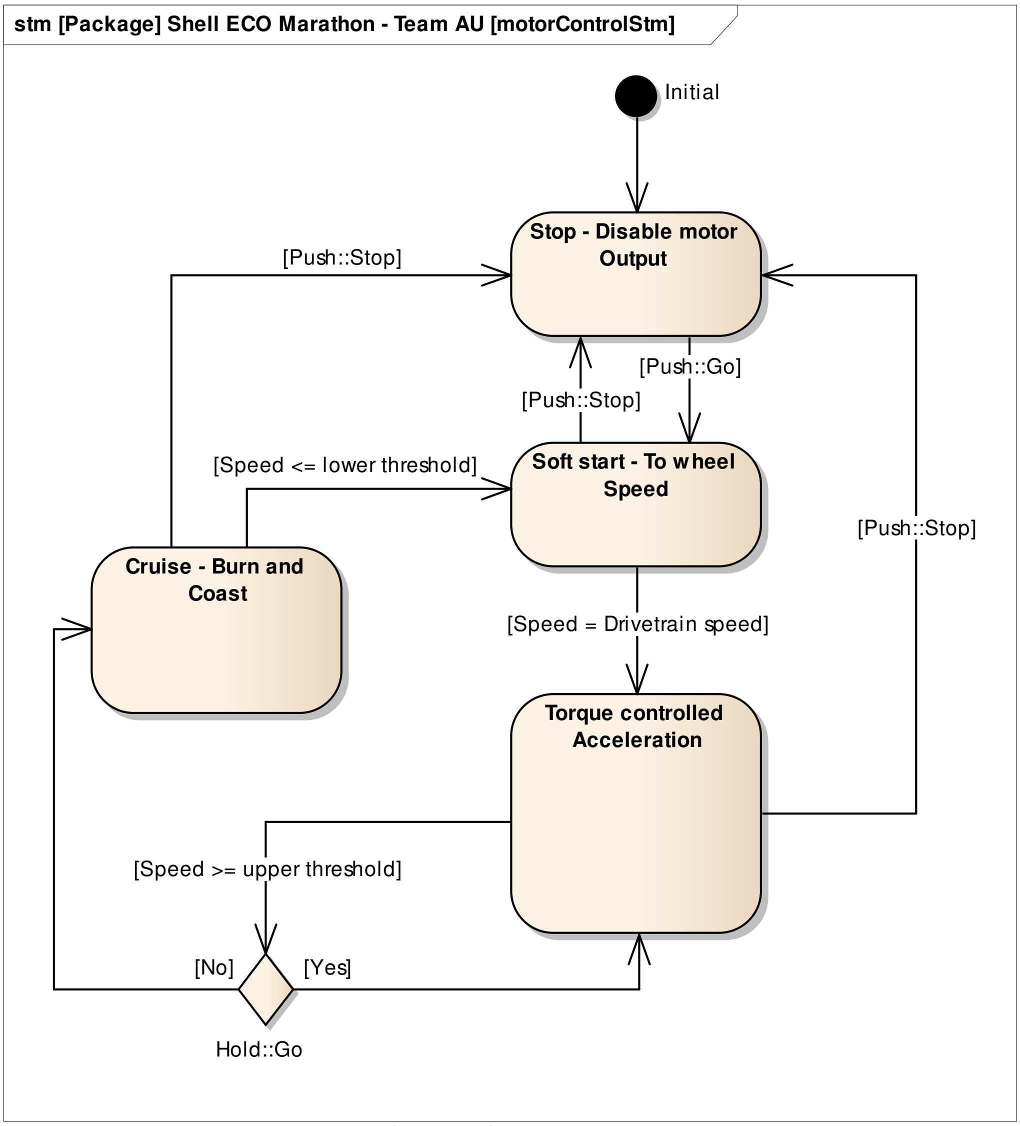

Figure 3.8: *System functionality state machine*

The software in the motor controller is based on a state machine with four states; "Stop", "Soft start - to wheel speed", "Torque controlled acceleration" and "Cruise - Burn and Coast". Shown in Figure 3.8

In "Stop" the output PWM to the motor is set to zero and the PWM timer is disabled to save energy. The "Stop" state is activated when the controller starts up or if the driver presses the stop button or one of the brake handles. The input from the brakes and the stop button are connected in a series connection to one interrupt pin on the micro controller.

When the driver presses start the state is shifted to "Softstart - to wheel speed" were a PWM ramp is started. It ramps from 0-100% PWM in 8-10 seconds. When the wheel speed starts to increase is the flywheel and the wheel at the same speed. Then the "Torque controlled acceleration" is started.

The speed is measured by an a hall-sensor tricking at six magnets mounted at the brake disc. The input from the hall-sensor is connected to a interrupt pin on the micro controller.

When a interrupt occurs, a timer value is copied to the memory and the timer is set to zero. To compensate for the possible misalignment of the magnets on the brake disc, the time from the last six speed interrupts is saved in the memory an a average is used to determine the speed.

In "Torque controlled acceleration" state is the microcontroller adjusting the motor current. It will adjust the current dependent on a ramp function describing where the motor is most efficient at a certain speed. The current adjustment is done with a PI regulator on the motor PWM. And the motor current is measured with a ADC. When the speed exceeds the upper speed limit in the "Burn n Coast function" the state is shifted to "Cruise - Burn and Coast" unless the driver holds the start button. Then the motor will keep acceleration to the top speed limit where it will shift to "Cruise - Burn and Coast".

In "Cruise - Burn and Coast" is the motor PWM is disabled and the speed is monitored. When the speed is under the lower speed limit the state is shifted to "Softstart - to wheel speed" where a new acceleration will begin. This continues to the driver presses stop or brakes.

To minimize the risk of connecting the motor to the controller while the controller is at 100% dutycycle at the motor PWM, a protection function is added. It checks if the dutycycle is above 80% and the wheel speed remains slow, if that is the case, the state is shifted to "Stop". The stop input from the driver is detected by interrupt, but if the stop button or one of the brakes is activated and hold down when the controller is turned off and the controller then is turned on with the button or brake still activated, the controller will never get a positive flank on the input pin. The protection function will check if the stop button or brake is hold down and shift to stop state. It will not be possible to start the car before the stop button or brake is released. The complete class diagram of the software is shown in Figure 3.9.

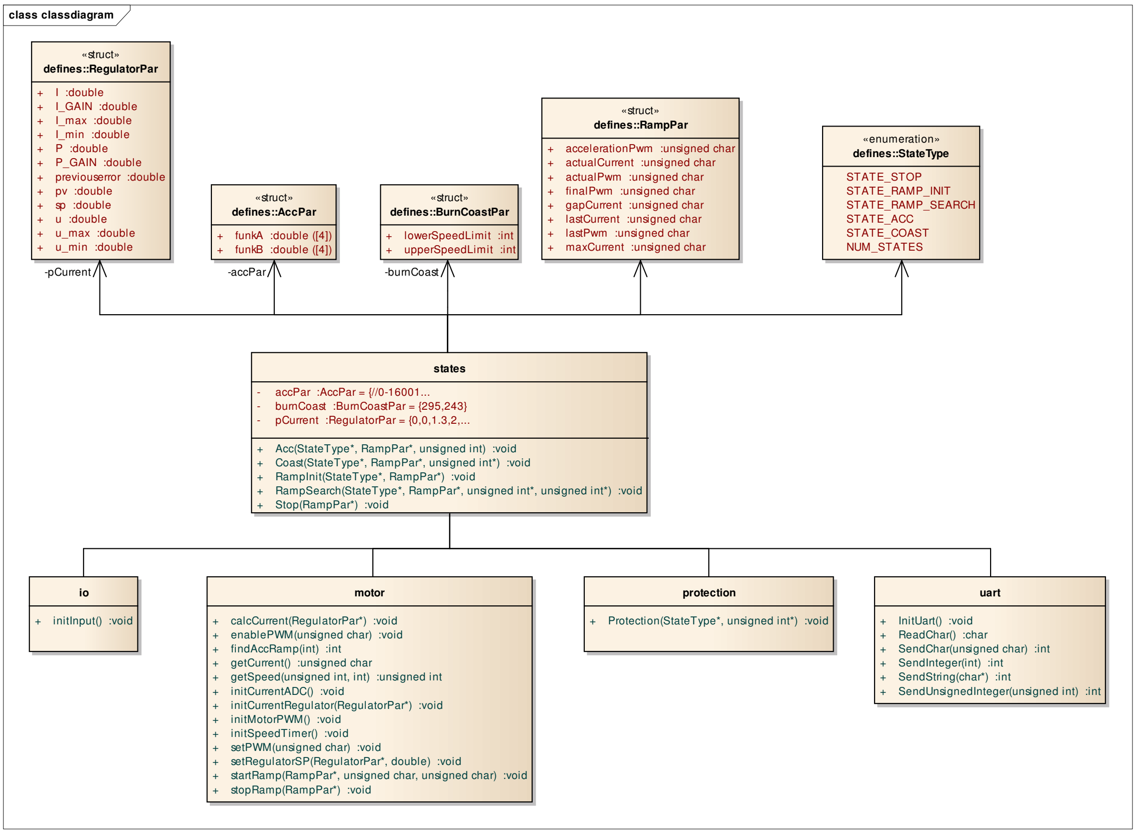

Figure 3.9: *Software Class Diagram*

4 Conclusion

The project has turned out successful in most of its aspects. The general thought of simplicity and agility of the motor controller has turned out to be a real force of the system. Along the way many challenges and minor changes were able to be fixed by simply re-programming the system with updated software. The key-functionality of the motor controller such as the regulation system, the motor feedback and the diving algorithm is implemented, and is fully functional. For the Shell Eco Marathon less important functionalities such as CAN-communication and internal data collection are not implemented, but the motor controller is physically prepared for these features.

To optimize the motor controller for further participation better testing facilities has to be made. To reach the peak efficiency a DC-motor test bench would be a possible way of adjusting the regulation system to its optimum. CAN-communication as well as internal data collection has to be implemented as well.

Despite numerous challenges during design an implementation as well as during the Shell Eco Marathon. Zenith 33 with its motor controller, drivetrain, from time to time reliable mechanics and persistent team spirit managed to clock a 5^{th} ***position in its class in the annual Shell Eco Marathon with the result 815 km/kWh.***

Appendices 5

5.1 Appendix A - System BDD

System Block diagram

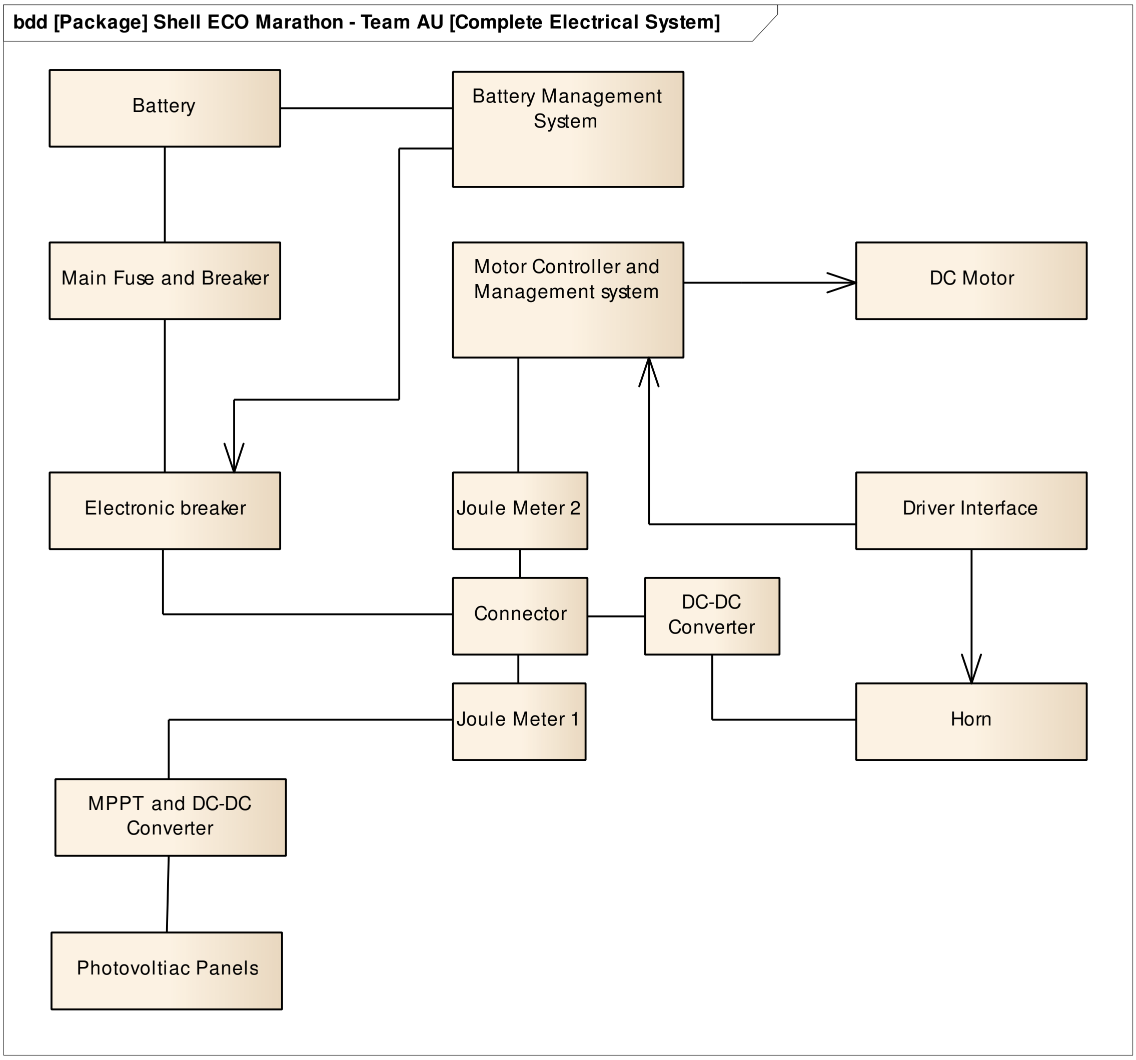

Figure 5.1: System Block Definition Diagram

5.2 Appendix B - Current and Wire Gauge

Maximum Ampere according to wire size

AWG gauge	Diameter [mm]	Ohms per km	Maximum amps for chassis wiring
0	8.25246	0.322424	245
1	7.34822	0.406392	211
2	6.54304	0.512664	181
3	5.82676	0.64616	158
4	5.18922	0.81508	135
5	4.62026	1.027624	118
6	4.1148	1.295928	101
7	3.66522	1.634096	89
8	3.2639	2.060496	73
9	2.90576	2.598088	64
10	2.58826	3.276392	55
11	2.30378	4.1328	47
12	2.05232	5.20864	41
13	1.8288	6.56984	35
14	1.62814	8.282	32
15	1.45034	10.44352	28
16	1.29032	13.17248	22
17	1.15062	16.60992	19
18	1.02362	20.9428	16
19	0.91186	26.40728	14
20	0.8128	33.292	11
21	0.7239	41.984	9
22	0.64516	52.9392	7
23	0.57404	66.7808	4.7
24	0.51054	84.1976	3.5
25	0.45466	106.1736	2.7
26	0.40386	133.8568	2.2
27	0.36068	168.8216	1.7
28	0.32004	212.872	1.4
29	0.28702	268.4024	1.2
30	0.254	338.496	0.86
31	0.22606	426.728	0.7
32	0.2032	538.248	0.53

Table 5.1: Part selection of AWG gauge current table

Source: `https://www.eol.ucar.edu/rtf/facilities/isff/LOCAL_access_only/Wire_Size.htm`

5.3 Appendix C - System Cable Diagram

Detailed vehicle cable diagram

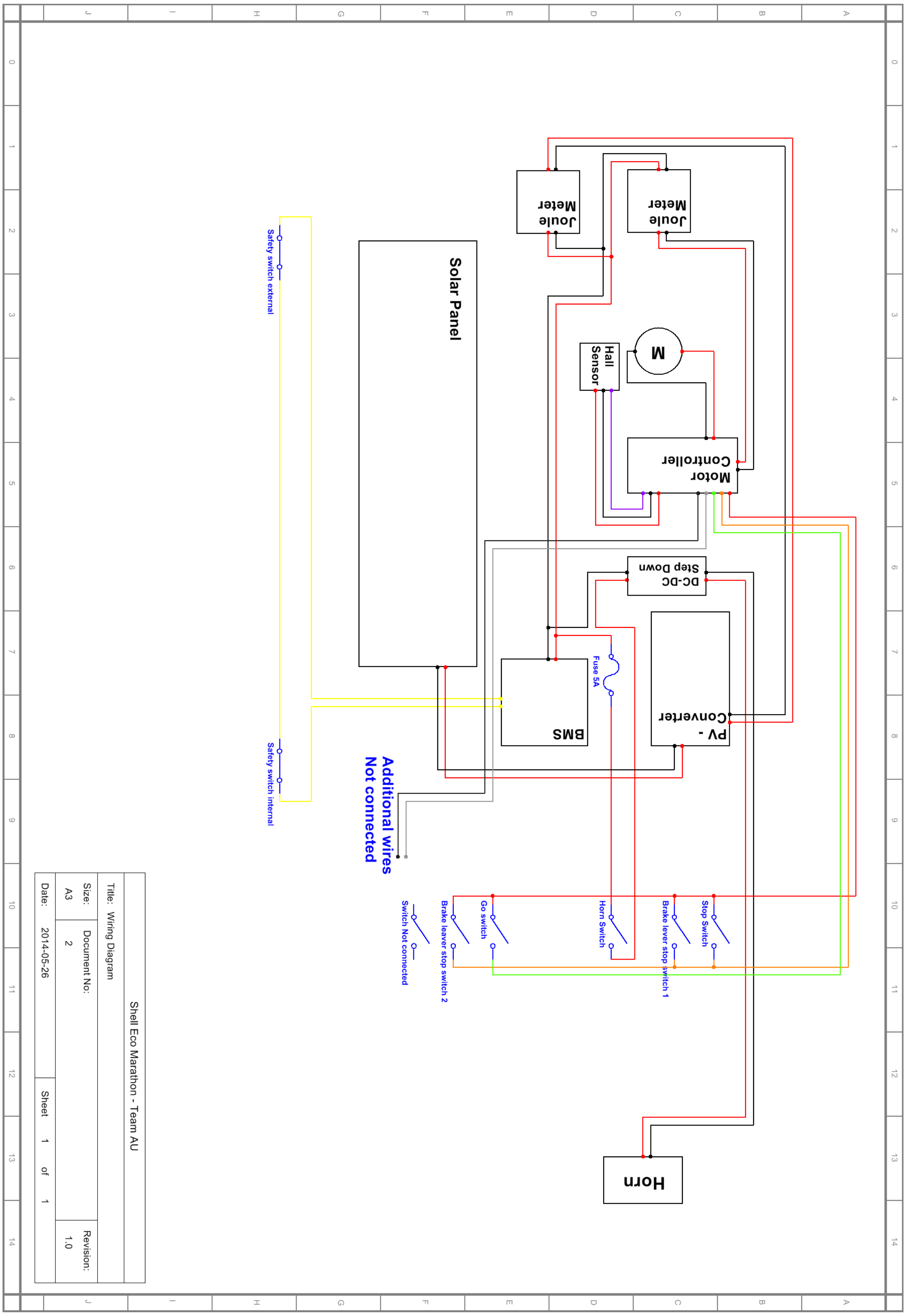

Figure 5.2: System Cable Diagram