SCARA Hardware

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Abstract

Hardware for a SCARA arm is developed. The design makes use of H-Bridge circuits to drive DC motors, digital circuits used to obtain a position from an encoder to relieve stress on a chosen microcontroller, and a power circuit that converts AC to DC. The design also makes use of a buck converter to step down the high DC voltage to a digital level. This design uses only a single daughter board for the microcontroller while the rest of the components were laid out onto a single PCB.

In this paper, Section 1 describes the H-Bridge circuits. Section 2 describes the digital circuits. Section 3 describes the microcontroller selection and connections. Section 4 describes the power circuits. Section 5 describes the PCB layout and wires.

Nomenclature

AWG	American wire gauge
PCB	Printed Circuit Board
PWM	Pulse Width Modulation

1. H-Bridge Circuit

The designed H-Bridge consists of an optocoupler, two P-Channel MOSFETS, two N-Channel MOSFETS and four resistors. The schematic is shown below in Fig.1.

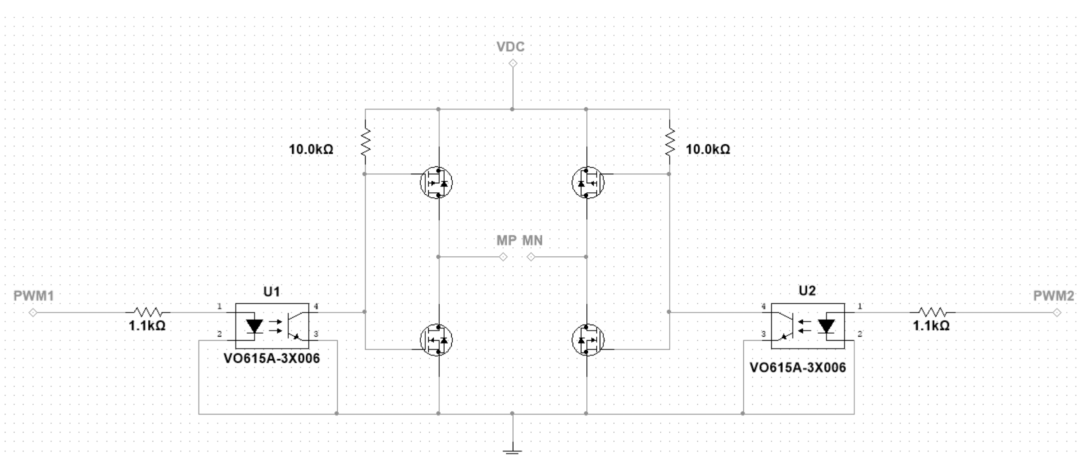


Figure 1 H-Bridge Schematic

The H-Bridge circuit was designed for a motor with a nominal voltage of 24V and the circuit must be capable of handling a continuous current of 12A and a maximum current of 25A. To obtain these results, power MOSFETS were chosen. The P-Channel MOSFETS, both located at the top of the schematic, are IRF9395MPbF [1]. The relevant Parameters from the datasheet are listed in the table below.

	Parameter	**Max.**	**Units**
V_{DS}	Drain-to-Source Voltage	-30	V
V_{GS}	Gate-to-Source Voltage	±20	V
I_D	Continuous Drain Current	-14	A
I_{DM}	Pulsed Drain Current	-110	A

Table 1 - IRF9395MPbF Key Specifications

From these specifications we can see that the MOSFET can handle -14A continuous and

-110A pulsed. This meets the requirements for the circuit. Next, we can look at the selected N-Channel MOSFETS which use the IRF7739L1TRPbF [2]. The relevant Parameters from the datasheet are listed in the table below.

	Parameter	**Max.**	**Units**
V_{DS}	Drain-to-Source Voltage	40	V
V_{GS}	Gate-to-Source Voltage	±20	V
I_D	Continuous Drain Current	46	A
I_{DM}	Pulsed Drain Current	1070	A

Table 2 - IRF7739L1TRPbF Key Specifications

Just as before, these values meet the requirements and much more. Note: While the control system ensures the inrush current from the motors is small, these transistors were selected to be more than capable of handling any large spikes in the case of a system failure.

The MOSFETS are designed such that they operate as switches.

The design also uses VO615 [3] optocouplers which isolate the microcontroller circuit from the higher current and voltages.

The topology works in the following way: The microcontroller sends either a PWM signal or a low signal. If the microcontroller sends a PWM, the optocoupler will amplify the signal such that the P-Channel MOSFET is turned on while the N-Channel is turned off. When the microcontroller outputs a low signal, the N-Channel MOSFET is turned on while the P-Channel is turned off. The following truth table that describes how the circuit will react depending on what the microcontroller outputs.

Input 1	**Input 2**	**Output**
PWM	LOW	Motor goes Right
LOW	PWM	Motor goes Left
PWM	PWM	Motor Stops (Not used)
LOW	LOW	Motor Stops (Not used)

Table 3 - Circuit Truth Table

Next, lets look at the transient response of the motor current and voltage using the Mulltisim's motor model and our motor parameters in Fig. 2 below.

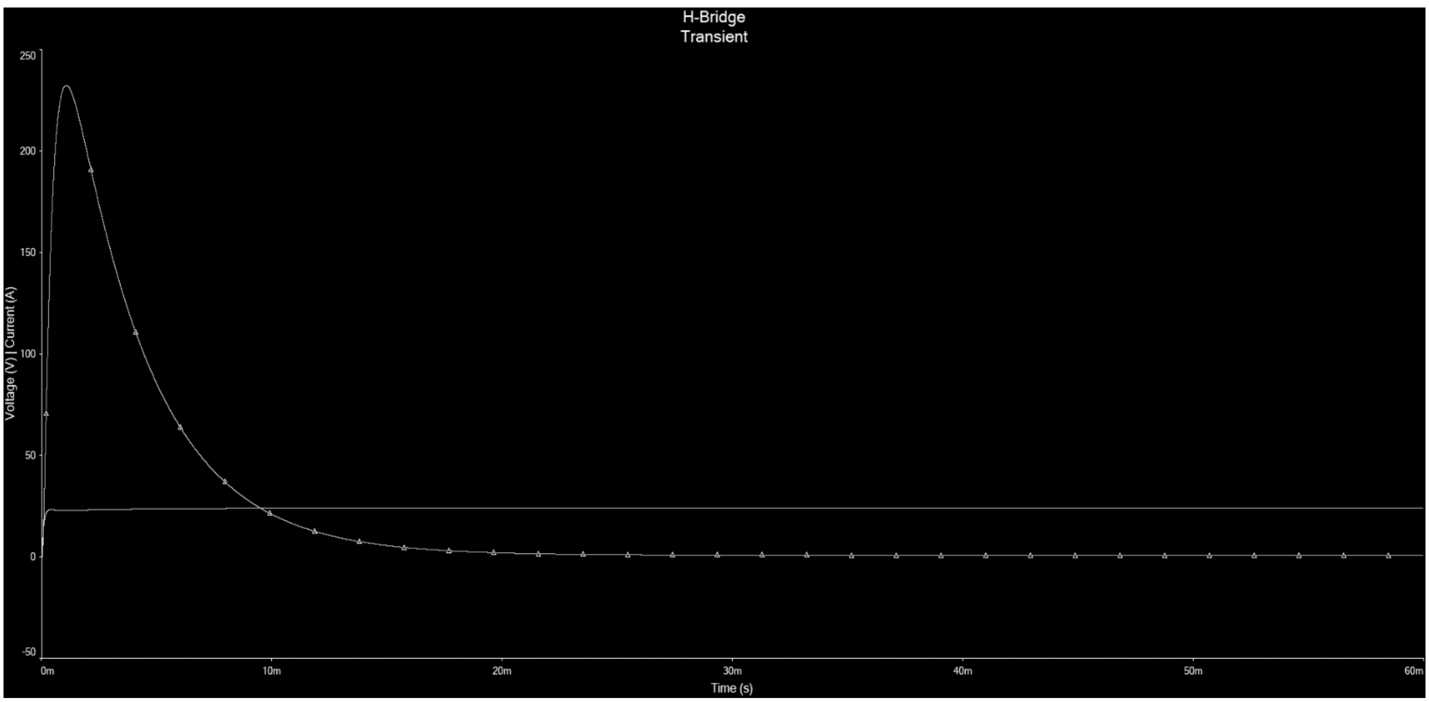


Figure 2 H-Bridge Transient

The transient shows a large spike rising before settling at the no load current of roughly 1A. The voltage settles to the nominal voltage of 24V. This spike of current is the inrush due to the almost instantaneous switch to the “on” state of the driver. This problem is handled by the control system which will never create such a sharp switch thus limiting the inrush. This current waveform can be obtained from the Simulink model and is shown in Fig. 3.

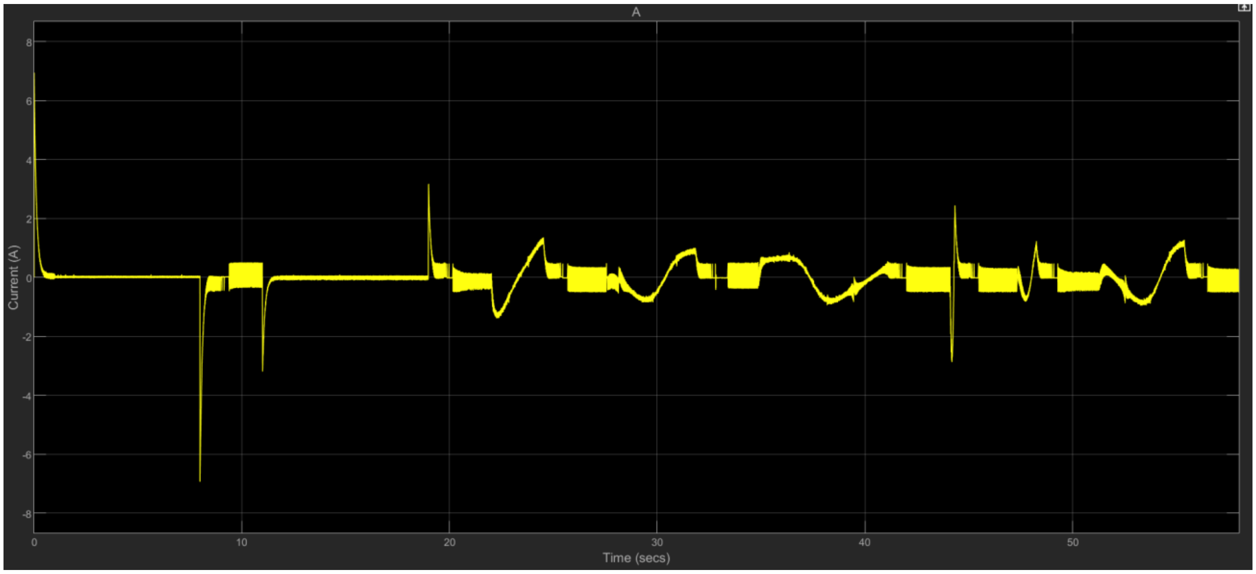


Figure 3 - Motor Current from Simulink

We can see from Fig. 3 that the maximum spike of current is only around 7A.

2. Digital Circuit

Let’s start of with the RCG’s for this section which are described in the table below

Specification	Requirement	Constraint	Goal
Sensor Resolution	0.001°	-	Max
Number of Pins	-	64	-
Encoder Shaft	8mm	-	-

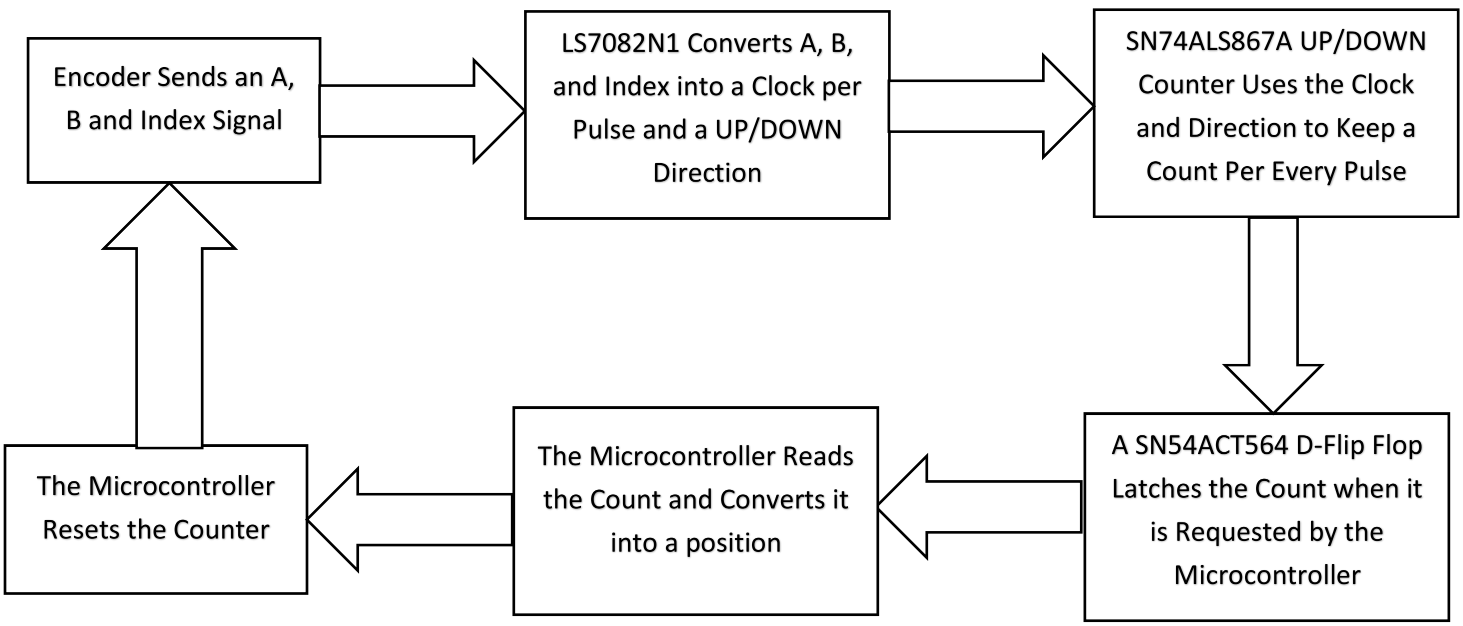
Table 4 – Sensor RCG’s

The following encoder was chosen to best fit the specifications: E6 Rotary Encoder [4]

This encoder has a PPR of 20,000 and a shaft of 8mm. With our gear ratio of 20:1, this gives us a resolution which was calculated in the following way:

$$Resolution = \frac{360}{(PPR)(20)} = 0.0009°$$

Perfect! Now, with a suitable sensor, a digital circuit was created to ensure the microcontroller can prioritize processing the control system. Let's start with a block diagram to that describes the circuit.



First let's describe how each component works starting with the LS7082N1 [5]. This chip is a quadrature clock converter which takes the encoder signals and outputs a falling edge up clock and down clock as well as a direction signal to the UP/DOWN counter. The chip is wired in the following way

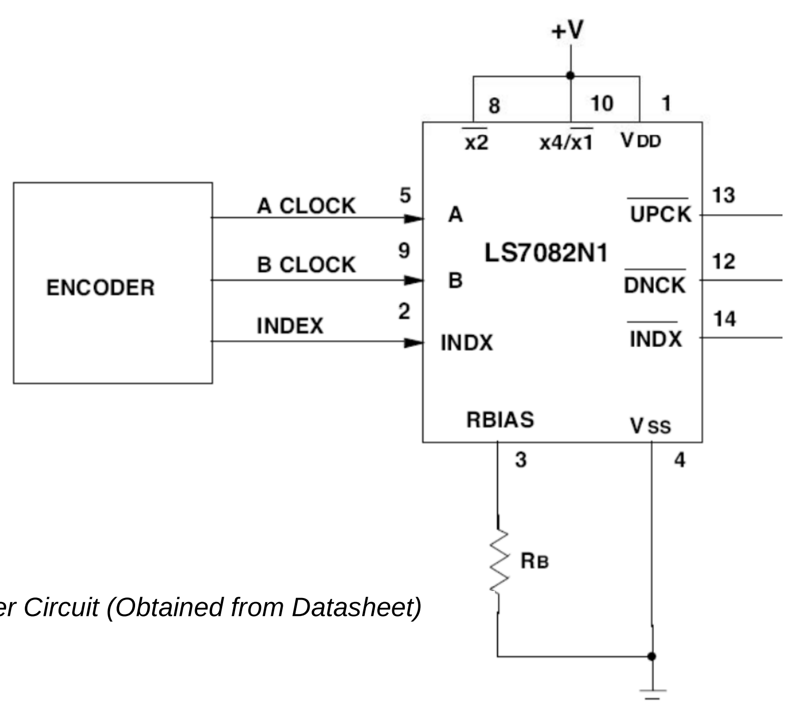


Figure 4 Clock Converter Circuit (Obtained from Datasheet)

Here, the R_B was selected to be 100kΩ. Next, these outputs must be connected to the SN74ALS867A [6] UP/DOWN counter. Let's start with the falling edge clocks. Our counter

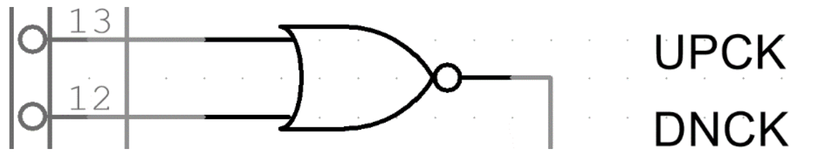


Figure 5 Nor Gate Configuration

needs only a single positive edge clock so in order to obtain this a 4001BD [7] nor gate was attached to these signals which can be seen in Fig. 4. This is then used as the clock signal for the SN74ALS867A. The full connections for the counter are described in Fig. 5.

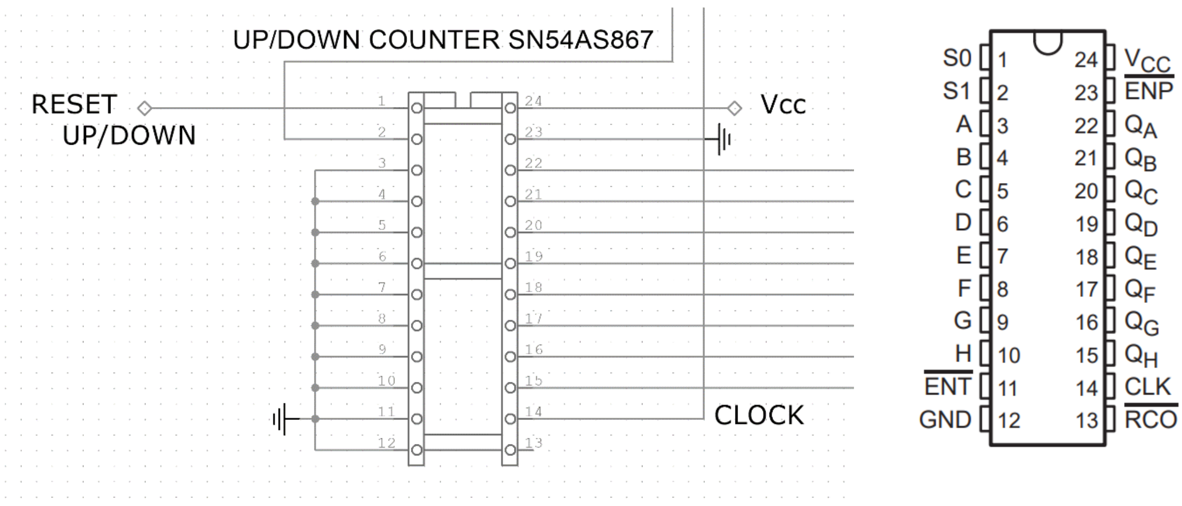


Figure 6 - SN54AS867 Schematic (Right Image from Datasheet)

To better understand these connections let's look at the truth table for S0/S1.

S1	**S0**	**Function**
L	L	Clear
L	H	Count Down
H	L	Load
H	H	Count Up

Table 5 - Counter Truth Table

A signal "RESET" is sent from the microcontroller. When it is high the counter will count depending on the UP/DOWN direction signal and the clock. When the count needs to be reset, S0 is set low the count will be cleared. In the case where the UP/DOWN direction is high when a reset is requested, the A-H signals are all set to low which will result in a load of zero, effectively clearing the output regardless of the state of S1. Next, we simply need to latch this count whenever it is requested by the microcontroller which is done using an SN54ACT564 chip. The connections are shown in Fig. 6 below.

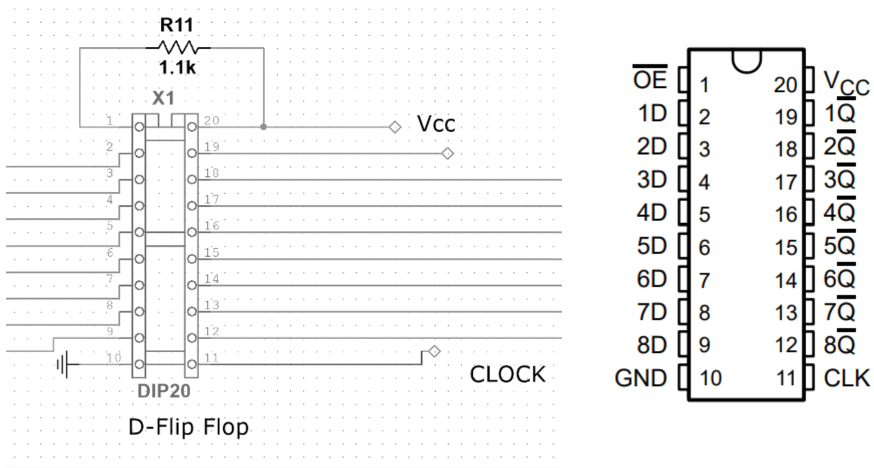


Figure 7 D-Flip Flop Schematic (Right is From Datasheet)

The D inputs in the latch are arriving from the UP/DOWN counter and the Q outputs go directly to the microcontroller. We also have a clock signal generated by the controller to latch and read the output. We will need a total of three of these circuits and encoders for the three motors on our SCARA arm which will take up 28 pins: 24 count pins, 1 clock pin and 3 reset control pins. This meets our constraint for number of pins.

To summarize, an encoder rated for our RCG's sends out signals that are converted into a count which is continuously latched and processed by the microcontroller to obtain a position.

3. Microcontroller Selection

Once again, lets start with the RCG's

Specification	Requirement	Constraint	Goal
Number of Pins	40	-	-
Clock Frequency	100MHz	-	Max
Storage	1GB	-	-
PWM Outputs	6	-	-
Price	-	< $50	$20

Table 6 – Microcontroller RCG's

The Teensy 3.5 [8] was an excellent choice for the design. It has a total of 64 input/output pins and 20 can be used as PWM signals. The microcontroller works at 120MHz which is important for the control system. For storage, the board has a built in SD card slot which can be used to meet the minimum requirement of storage. This storage will be used to save large custom arm path files. Lastly, while the microcontroller does not meet the price goal, it comes close at a price of $25.

Next let's look at the connections on the board. The table below describes the connections for the board.

Pins	Connection
2-5, 29,30	PWM
16-23 [0:7]	250W Motor Count
15,39-33 [0:7]	200W Motor Count
12,24-28,31-32 [0:7]	150W Motor Count
0	150W Motor Reset
6	200W Motor Reset
9	250W Motor Reset
10	Clock

Table 7 – Microcontroller Connections

On top of this 5V will be connected to power the microcontroller. The power will be discussed in the next section.

4. Power Circuit

Starting with the RCG's

Specification	Requirement	Constraint	Goal
V_{Ripple}	-	< 0.5	0.1
Power	700W	-	-

Table 8 – Power RCG's

The power circuit steps down an AC source using a transformer. It then takes this AC signal and uses a full bridge wave rectifier to convert the signal to DC. Using a smoothing capacitor, we have a DC source used to source each H-Bridge driver. On top of this we

need a buck converter to change this 24V signal into 5V which will be used for powering the microcontroller and digital chips. Let's take a look at the schematic for the AC/DC converter first on the following page.

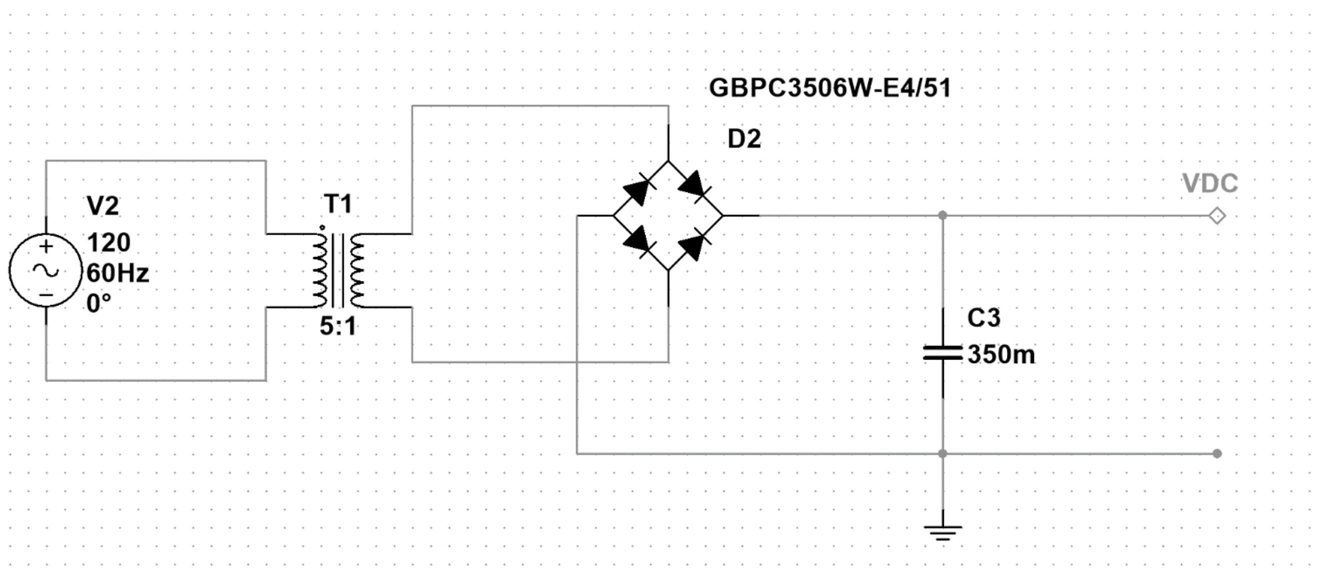


Figure 8 - AC/DC Converter Schematic

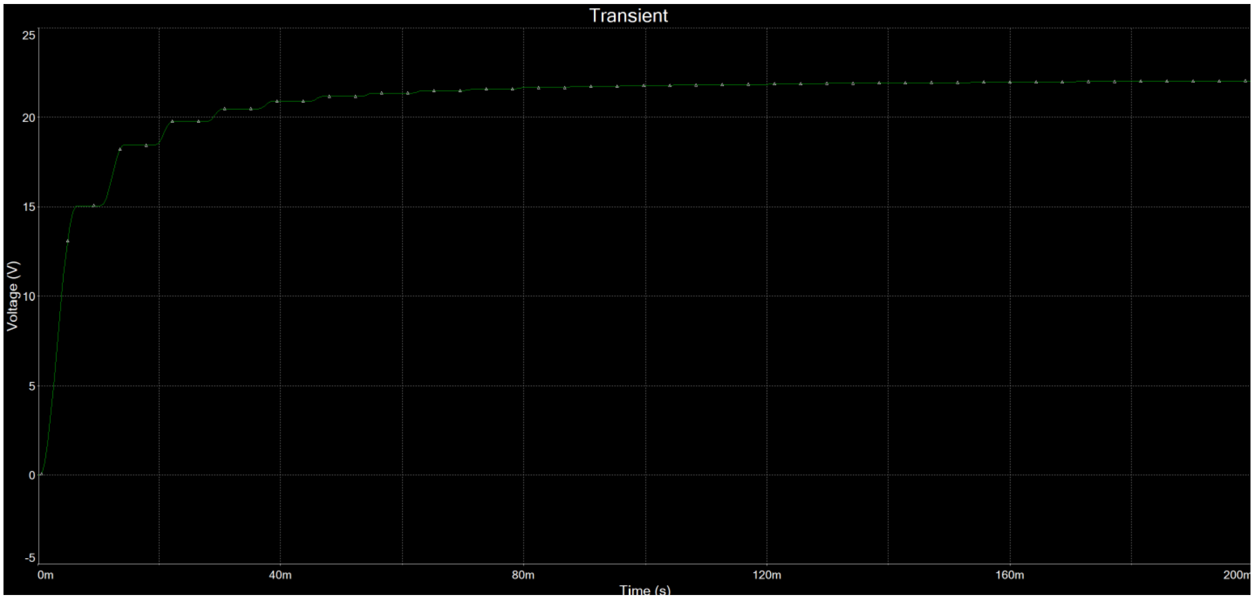


Figure 9 - Power Circuit VDC Transient

The transient in the figure above shows the voltage “VDC”. We can see from the transient that it settles at approximately 200ms at around 24V. This happens because a step-down transformer was used with a 5:1 ratio which gives us the following equation:

$$V_s = \frac{n_2}{n_1} V_p = \frac{120V}{5} = 24V$$

A large capacitor was chosen to minimize the ripple voltage which can be found using the following formula:

$$I_D = I_{Motor1Max} + I_{Motor2Max} = 10.8 + 10 = 20.8A$$

$$V_{Ripple} = \frac{I_D}{2fC} = \frac{20.8}{(2)(60Hz)(350m)} = 0.495V$$

This meets the constraint but unfortunately it is nowhere near the goal.

As for power a 700W transformer needs to be selected. This value is calculated from the three motors which use 250W + 200W +150W = 600W. An extra 100W is needed for power dissipation in the MOSFETS and the digital circuits. Now that we have a 24V DC supply for our H-Bridges, we also need to step down this voltage to 5V for our digital logic power supply. This is done using an LM2567 [9] Simple Switcher. The circuit is wired in the following way which is provided by the datasheet:

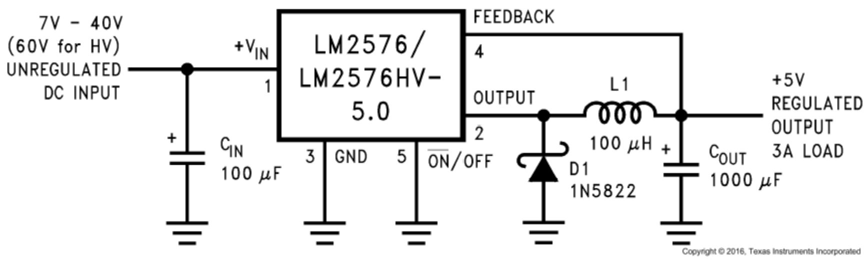


Figure 10 - Buck Converter Schematic (From Datasheet)

Now we have an efficient step-down DC/DC converter that provides 5V to power each of the digital chips and the Teensy 3.5. Next, we will discuss the layout of the PCB.

5. PCB Layout and Wires

Starting with the PCB RCG's.

Specification	Requirement	Constraint	Goal
Size	150mmx90mm	-	-

Table 9 - PCB RCG's

The PCB was created by starting with a 150mm by 90mm. There is only one daughter board which is the microcontroller, while everything else is on one PCB. This decision was made to save space and any extra area costs. Next the components were all laid out onto the board.

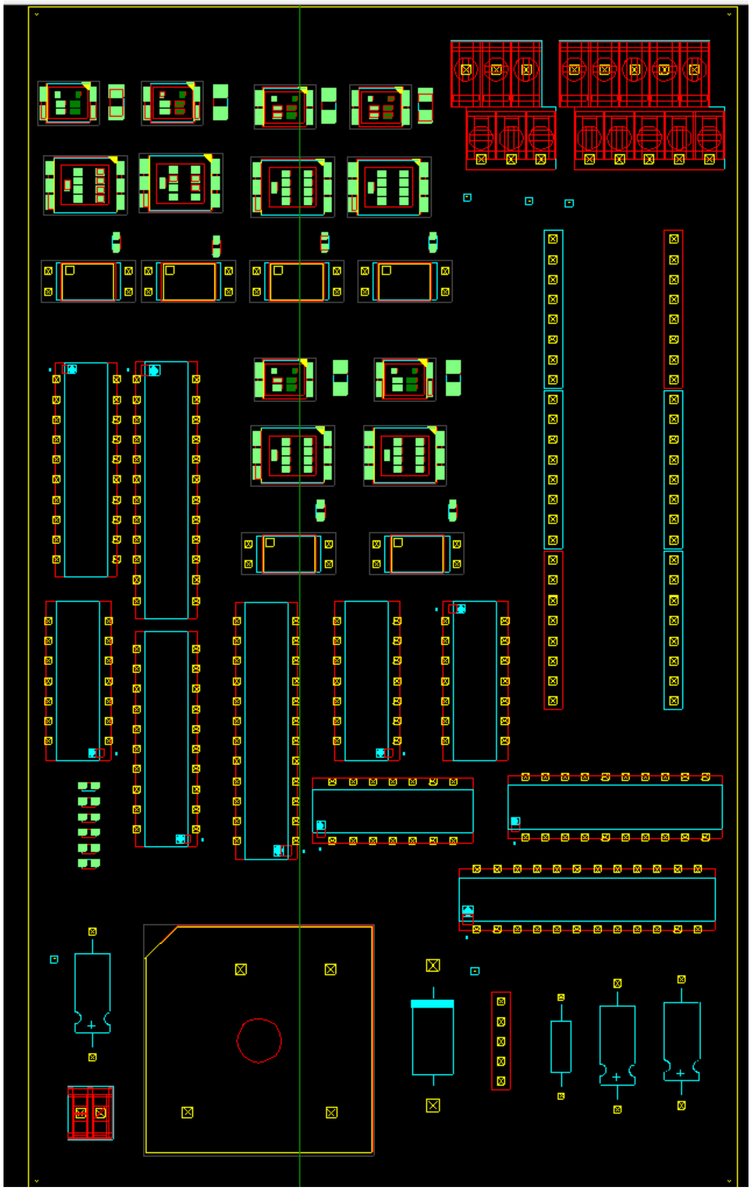


Figure 11- Bird Eye View PCB

In the bird's eye view of the PCB, we can see the placement of each of the components. The top right of the PCB has two terminal blocks. Of these terminal blocks, the one on the right takes in the encoder outputs and the one on the left takes in the motor outputs. Since the motor needs to handle up to 25A as mentioned in section one, 10AWG wires must be used which can handle up to 30A. Next, we can see the header pins for where the microcontroller will attach along the middle right. It is important that we keep the H-Bridges as close to this section as possible as the PWM signal is one of the only signals with frequency. For this reason, two of the H-Bridges are located at the top of the board and one is directly in the middle. This is also why the PWM signals were chosen to be on the left side of the board to further decrease the distance it travels. The digital circuits are scattered along the middle of the PCB and are clearly seen as they all have the DIP packaging. Lastly, the power circuits are all along the bottom of the board with the AC/DC converter on the left side along with terminal blocks that connect the transformer to the circuit and the DC/DC converter on the bottom right. A last note is that at each corner of the PCB, small yellow circular symbols can be seen. These are mounting holes for screwing the board to the mechanical design. The board uses four layers and can be seen in the wired in the following figure.

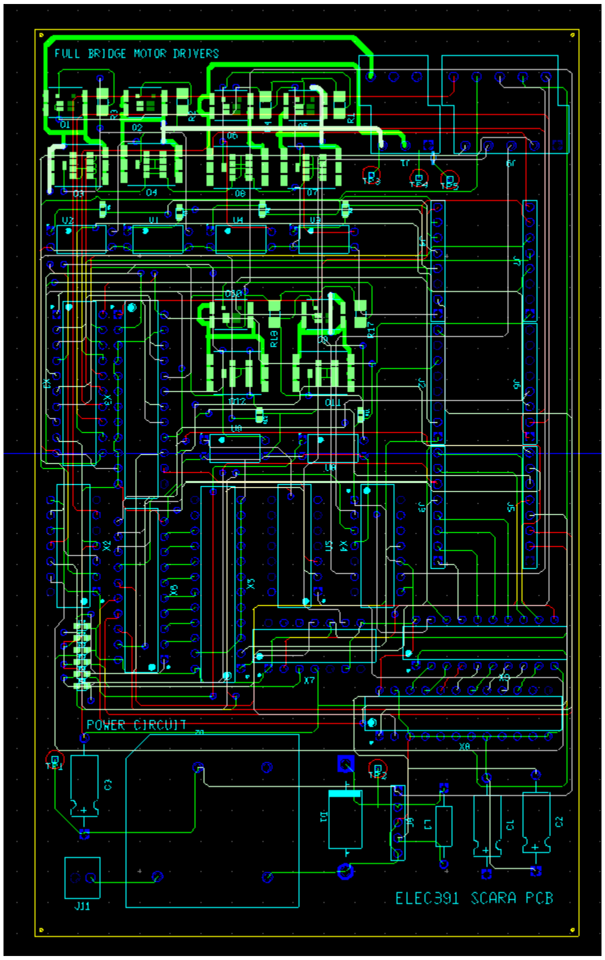


Figure 12- PCB Layout

Since this is a large schematic, we can try to break down the key points. Most right angles were minimized, there are 58 vias and a total of 62 parts. Another important note is some traces are clearly thicker than others. These are to handle the higher current that will be going through the motor drivers. There are also a total of five test points. Two of these are at the bottom and connect to the 24 DC output and the 5V DC output. Three of these connect to the motor terminals. Lastly, since the packaging for the digital circuits was a DIP, it is very easy to probe the signals for any debugging required.

Finally, the final PCB model view can be seen in the figure below.

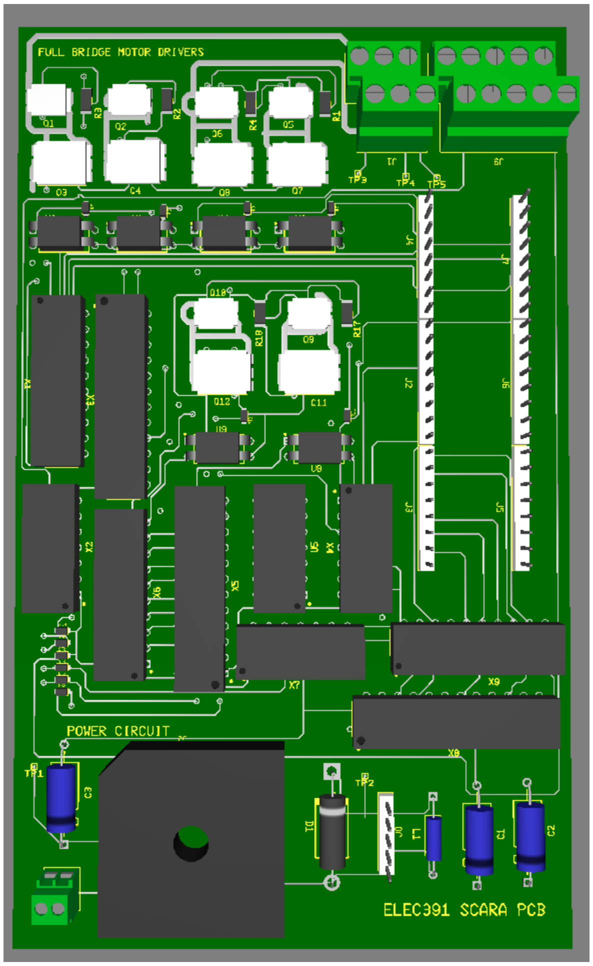


Figure 13 - SCARA PCB

There are labels for each circuit and component and none of the top layer wires cross these labels. This is the completes the SCARA hardware design.

References

[1] Infineon https://www.infineon.com/dgdl/irf9395mpbf.pdf?fileId=5546d462533600a40153561198461db7

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