Ball Hopper – Analog Electronics

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Idil Bil, Group Portugal, ECE, University of BC, Vancouver, BC, Canada

Abstract

An electrical hardware system for an autonomous tennis ball gripping robot is designed. The system consists of a microcontroller (ESP32), various peripherals, proximity sensors and a motor driver. Peripherals are used to interface with the user, proximity sensors are used to detect the objects and the destination, while the motor driver is used to control the motor.

In this paper, Section 1 defines the Analog sub-system behavior and identifies the RCGs to achieve that. Section 2 explains the design process for the sub-system including Part Selection, Motor Driver Design and PCB Design using MATLAB and Altium CircuitMaker. Lastly, Section 3 talks about the tests executed to verify if the designs satisfy the RCGs.

Nomenclature

RCG	Requirement, Constraint, Goal
PCB	Printer Circuit Board
cm	centimeter
A	ampere
V	voltage
ms	millisecond
IC	Integrated Circuit
MCU	Microcontroller
PJA	Power Jack
I/O	Input/output
PLD	Programmable Logic Device
DC	Direct Current
OTS	Off the Shelf

MHz Mega Hertz
CPU Central Processing Unit
UART Universal Asynchronous Receiver/Transmitter
SPI Serial Peripheral Interface
CPR Counts per Rotation
DRC Design Rule Checker
PWM Pulse Width Modulation
LED Light Emitting Diode

1. RCG Identification

This project is an autonomous gripper robot. To ensure autonomous functionalities an analog electronic subsystem is designed. The system must have certain peripherals, proximity sensors, a motor to detect and grasp objects. In addition, a microcontroller is needed to use the mentioned devices. For this functionality the following 5 RCGs for the related issues are identified as shown in Figure 1.

Issue	Requirement	Constraint	Goal
Motherboard PCB	Board must fit a 6x8 cm area	All the peripherals need to align with proper mechanical placement in the enclosure box	Minimize board size
Motor Driver PCB	Board must fit a 6x5 cm area	Traces for the motor must hold up to 5 A	Minimize board size
Motor Driver Power Consumption	Must not consume more than 0.3 A at 12 V under no-load conditions	Power consumption can't be smaller than 0.15 A at 12 V	Minimize the power consumption
Motor Driver Response	Step response settle time must be smaller than 200 ms	A minimum of 15% duty cycle is needed for the PWM to generate the response	Minimize the settle time

Homing Circuit	Must be suited for mechanical interaction between the circuit and fingers	Can't be too sensitive, so it doesn't register false homing	Minimize the response time

Figure 1: Analog Electronic RCG's

2. Sub-System Design

In this section, the design choices for the hardware are explained. As a start, the High-Level Hardware Design talks about the overall architecture. Then, Part Selection specifies the electronic components chosen and why. Motor Driver Design explains the chosen IC and the characterization process. After that, Motherboard and the Motor Driver PCB Design explains the respected PCB design processes.

2.1 High-Level Hardware Design

Figure 2 presents the high-level architecture of the hardware. The functionalities of the blocks are as follows.

Power

- **PJA:** Supplies 12 V to the electronics.
- **Power Regulator:** Converts the 12 V input from the power jack into regulated 5V for other devices.

I/O

- **Debug Port:** Used to interface with the microcontroller.
- **Digital Phone Jack:** Used to reset and communicate the state of the gripper.

Sensors

- **Ultrasonic Sensor:** Measure the distance between the gripper and the floor to detect when to grab objects.
- **Hall Sensor:** Detects the destination marker for object collection.

Motor Driver

- **Homing Circuit:** Used to identify the end points of the fingers to start the reset procedure.
- **Motor:** Is the DC motor chosen in the System Identification Report.
- **Control Circuit:** Is the Motor Driver Circuit explained in Section 2.3.
- **Decoder:** Counts the pulses coming from the build-in encoder of the motor.
- **PLD:** Acts as a multiplexer to feed the count bits to the microcontroller.

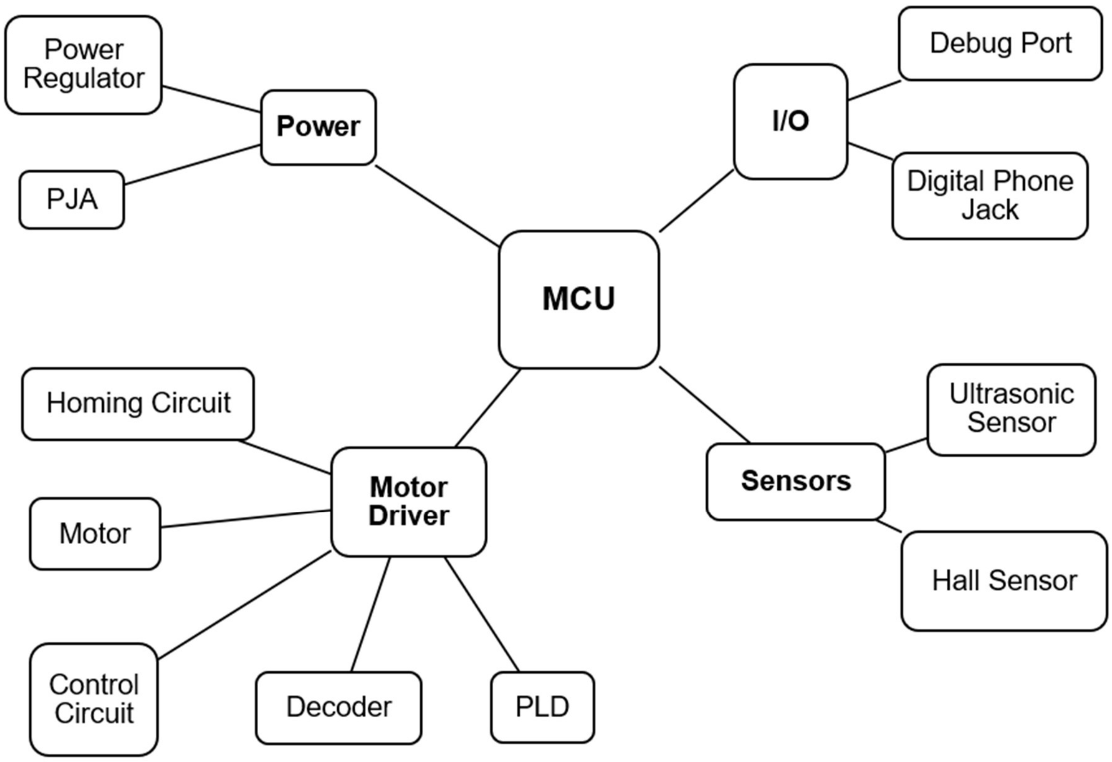

Figure 2: High Level Architecture Diagram

2.2 Part Selection

In order to achieve the functionalities mentioned above the following OTS products are selected and their connections are shown in the schematic prepared with Altium CircuitMaker in Figure 3:

ESP32-DOIT-DEVKIT V1 [1] is chosen as the microcontroller as it has the chip ESP32-D0WDQ6 [2], which provides 4 timers, 19 general purpose I/O and a prebuild debug port. It has a clock frequency between 80 MHz and 240 MHz, this is believed to be enough for our software in our current stage. It also provides dual CPU cores, that can be used for running multiple software simultaneously and supports a high variety of interfaces such as UART, SPI and Ethernet, which can be used for integration.

PJA is a user defined interface, so the device PJ-102A [3] given to us was used. For voltage regulation LM7805CT [4] is used as it provides regulated 5 V given a 12 V input.

Digital Phone Jack is also a user defined interface, so the device SJ1-3544N [5] given to us was used. Debug port is present in the chosen microcontroller.

The Ultrasonic Sensor is chosen as HC-SR04 [6] as it is a widely used and accurate ultrasonic sensor in the market. For the Hall Sensor the SS411P [7] is chosen because it has a build-in pull up resistor making the integration with the microcontroller simpler.

SS-01GLP [8] limit switch is used for the homing circuit as it provides mechanical interface that can be triggers using the fingers of the claw. The motor chosen is from Pololu with the item number 2821 [9]. This motor coming with a build-in encoder, has 64 CPR and needs a 12 V input, which fits our power circuit. Further explanation is in the System Identification Report. The decoder HCTL-2022 [10] is chosen because of reasons explained in the Digital Electronics Report. The Atmel ATF16V88 [11] PLDs are used as 4-1 multiplexers, which is also explained in the Digital Electronics Report. Lastly, the Control Circuit is a Motor Driver IC explained in Section 2.3.

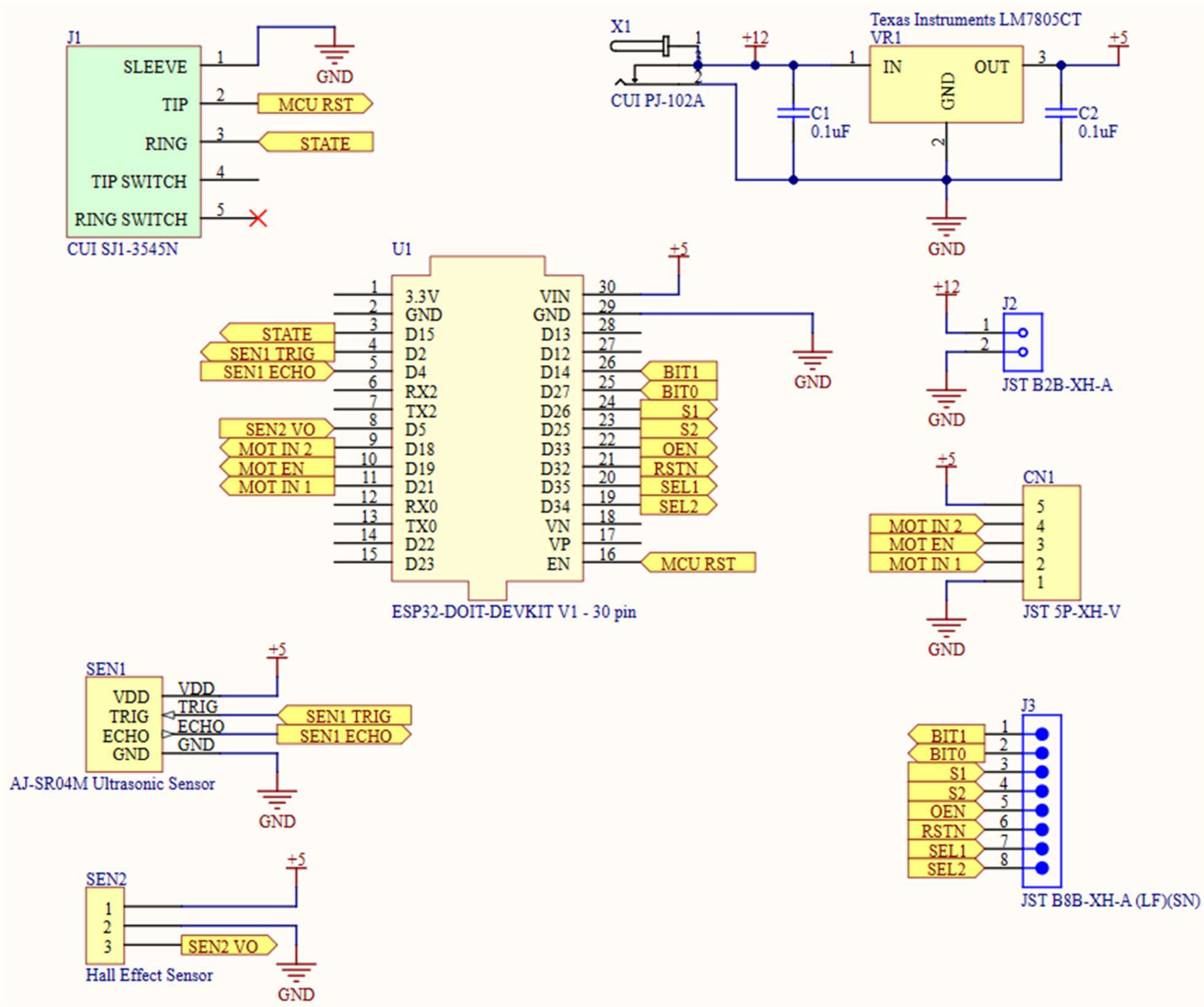

Figure 3: Motherboard Schematics

2.3 Motor Driver Circuit Design

The chosen motor driver being used is L298 Dual Full-Bridge Driver [12]. It’s block diagram obtained from the datasheet is shown on Figure 4. On the diagram, pin VS and VSS are respectively supply voltage and logic supply voltage. Pin numbered 8 is ground, pins labelled In1 and In2 are input signals for one H-bridge. Pin labelled EnA is the enable pin for the H-bridge of one motor. Out1 and Out2 are the output pins of that H-bridge and they connect to the motor chosen. Rest of the pins are not used as they are for a second motor which is not used in this project.

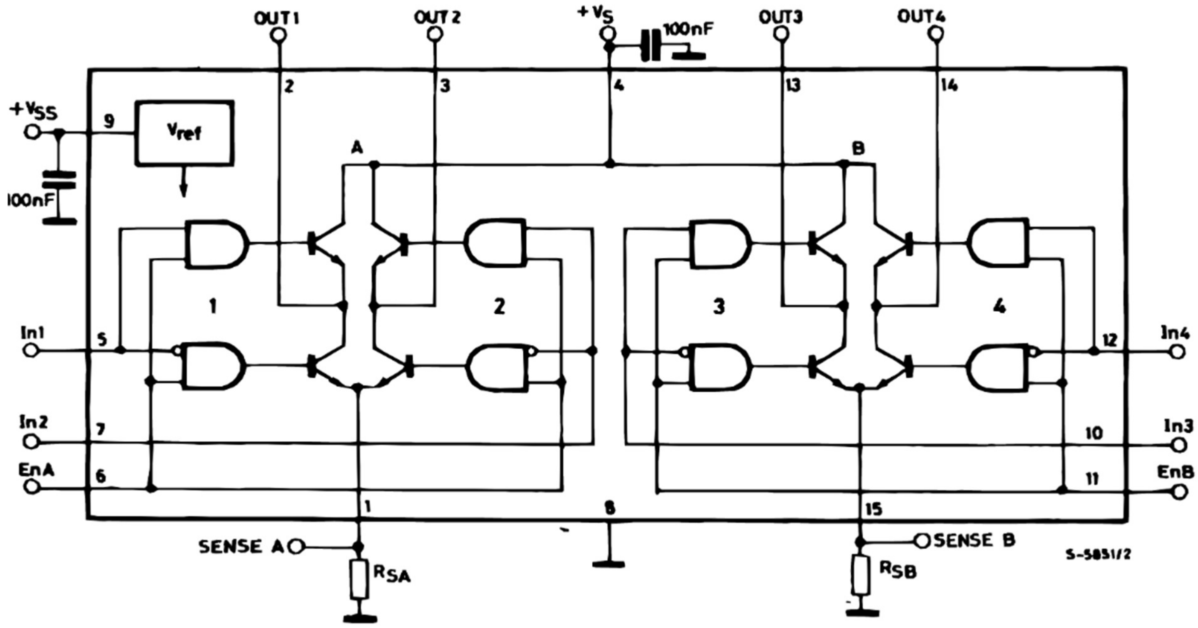

Figure 4: Motor Driver Block Diagram

The schematic for the motor driver (Figure 5) is prepared by referring to the Bidirectional DC Motor Control Diagram found in the datasheet [12] (Appendix A). To provide a path for the current to dissipate when the motor switches from on to off, 4 fly-back diodes are placed.

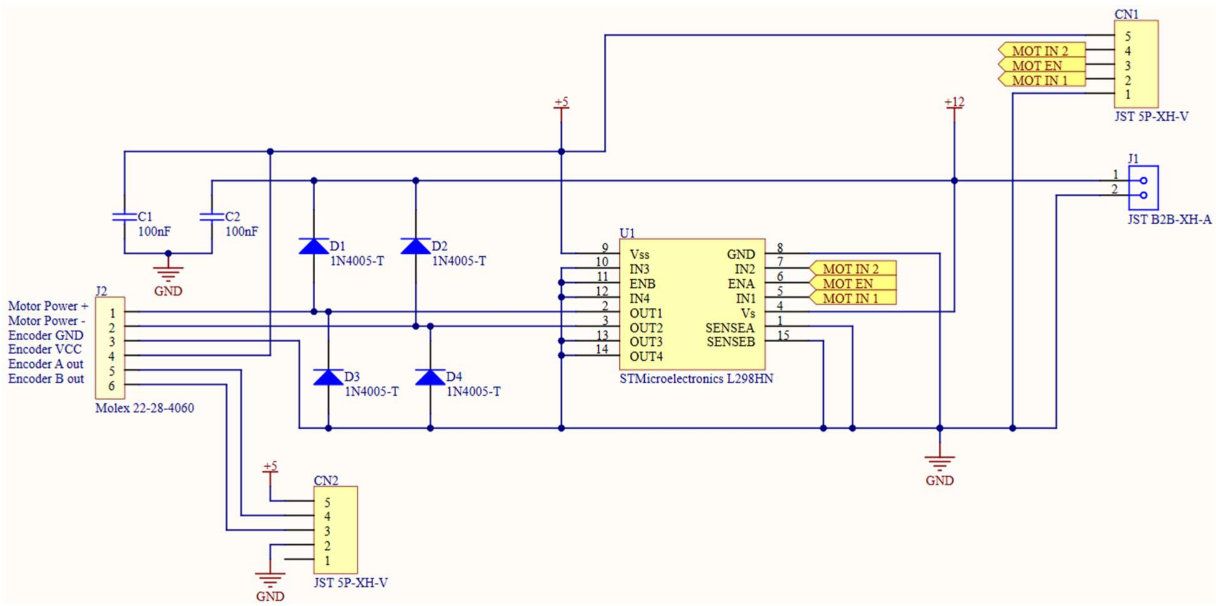

Figure 5: Motor Driver Schematics

The characterization of the motor is done by collecting data from the oscilloscope to be used by Optimal Control. 5 V was given to In1 and In2 of the motor driver to get the step response seen in Figure 6.

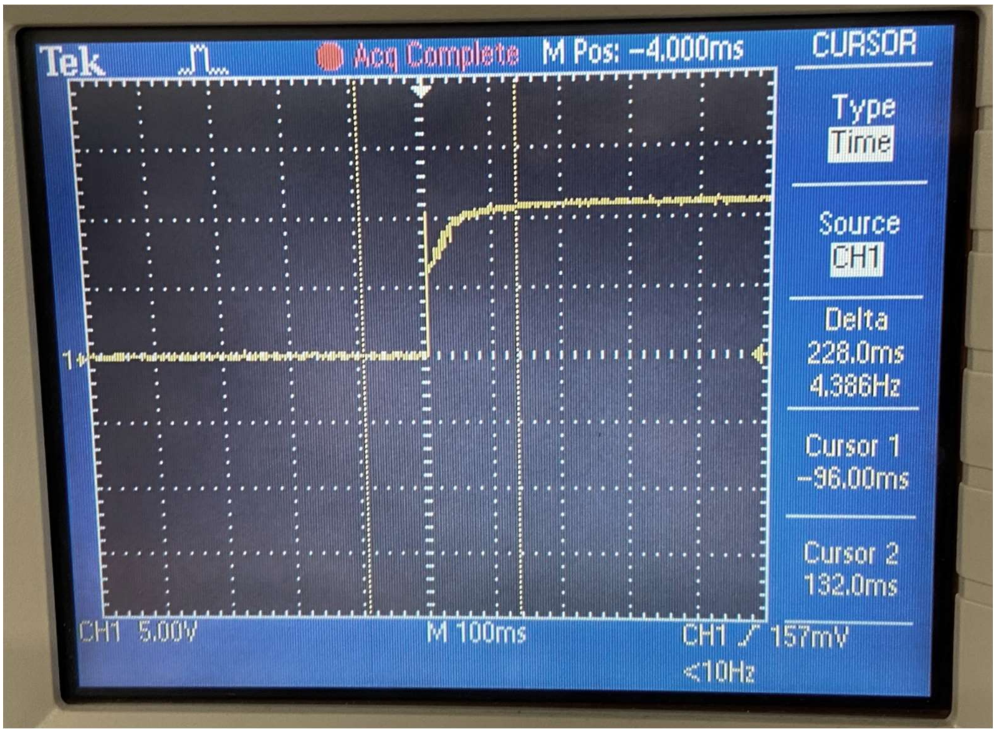

Figure 6: Step Response of the Motor Driver

This data acquisition is done multiple times to calculate the approximate settle time as 130 ms and the MATLAB code found in Appendix B is used to calculate the transfer function in Figure 7 and the step response in Figure 8. The settle time was lower than 200 ms and it was only consuming around 0.21 A at 12 V. Since these satisfies the RCGs and the step responses looked similar this driver was chosen.

```
       8748
-----------------
s^2 + 54 s + 729
```

Figure 7: Motor Driver Transfer Function

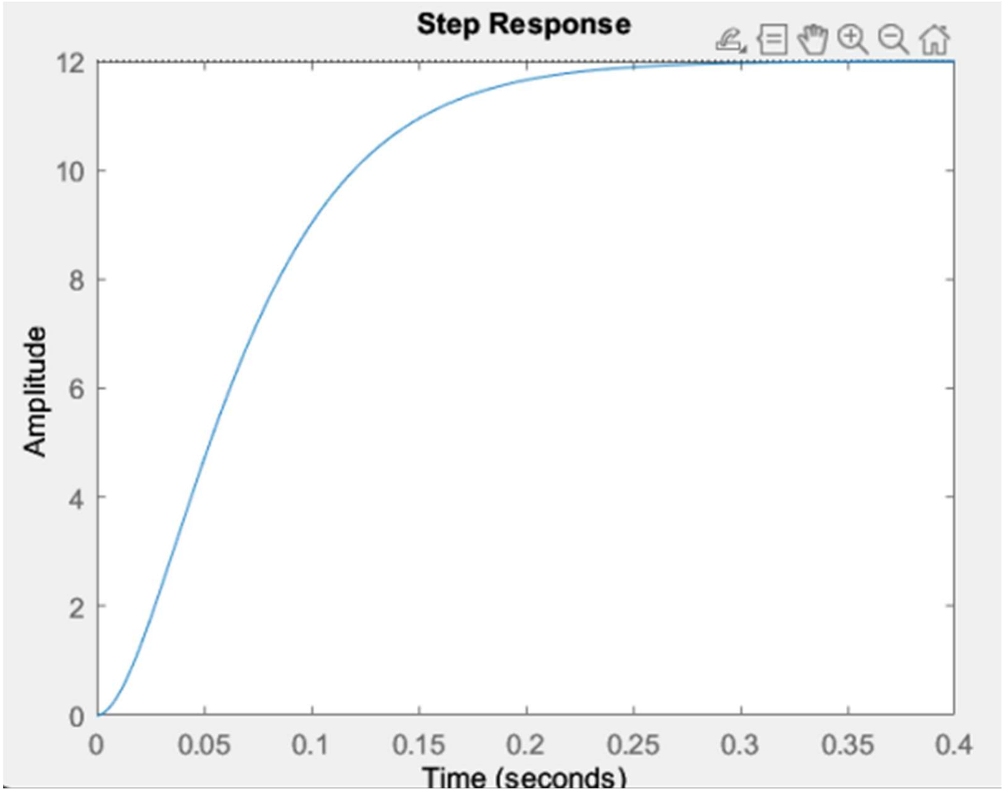

Figure 8: Motor Driver Step Response

2.4 Motherboard and Motor Driver PCB Design

Using Altium CircuitMaker, a Motherboard for the Microcontroller and the peripherals, as well as, a Daughterboard for the Motor Driver Circuit are designed. The boards are 2-layered with no ground plane. Each board has dedicated XH-connecters for board-to-board connections. All the components are properly named, and their labels can be seen on the silkscreens. Figure 9 and 11 show the PCB schematics, while Figure 10 and 12 show the 3D view of the PCBs.

To meet the size RCG, the PLDs and the decoder were put on a different Daughterboard that is explained in the Digital Electronics Report.

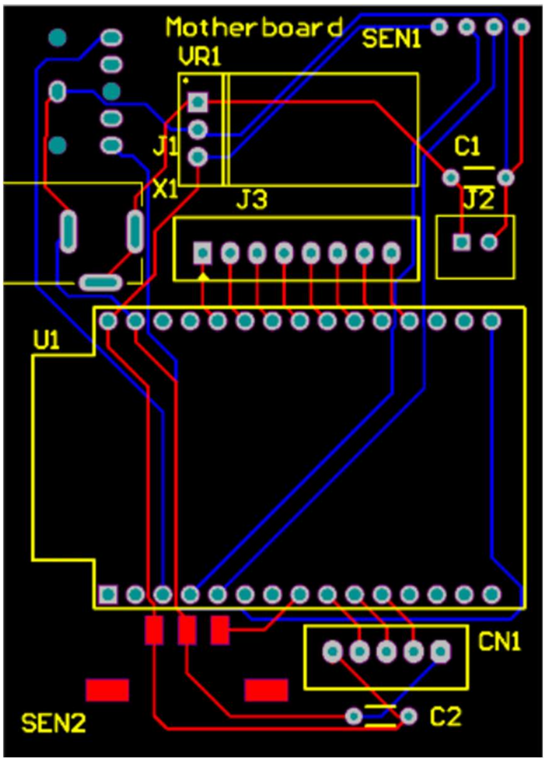

Figure 9: 2D View of the Motherboard PCB

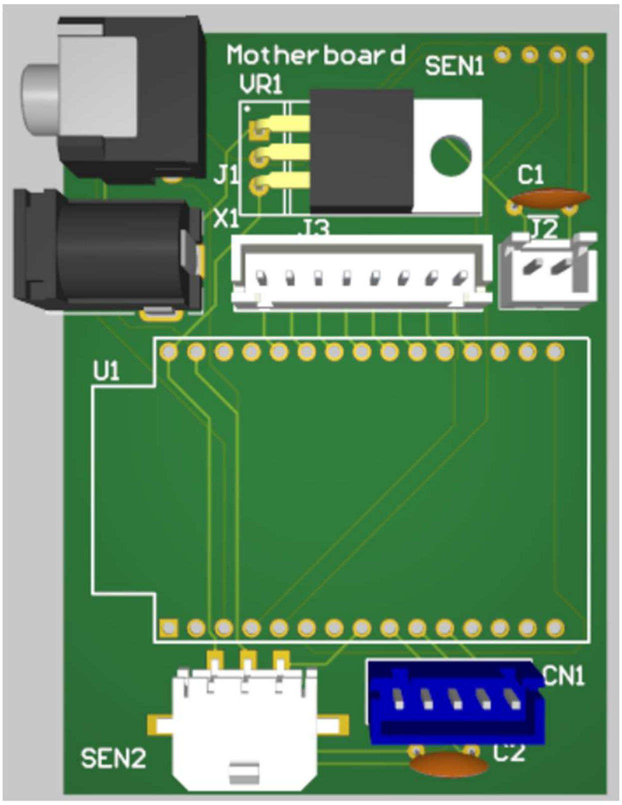

Figure 10: 3D View of the Motherboard PCB

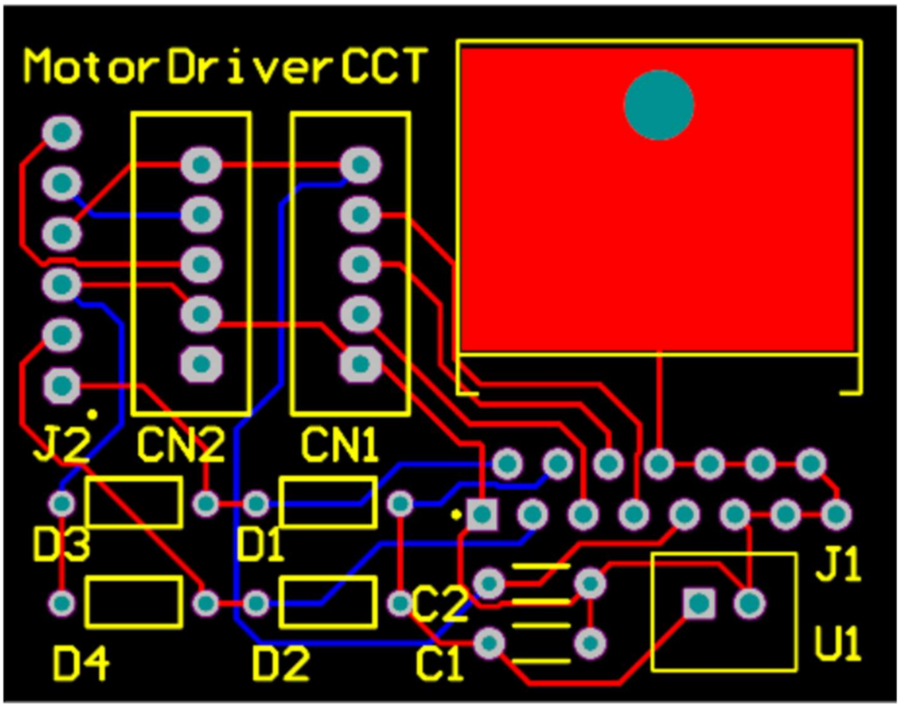

Figure 11: 2D View of the Motor Driver PCB

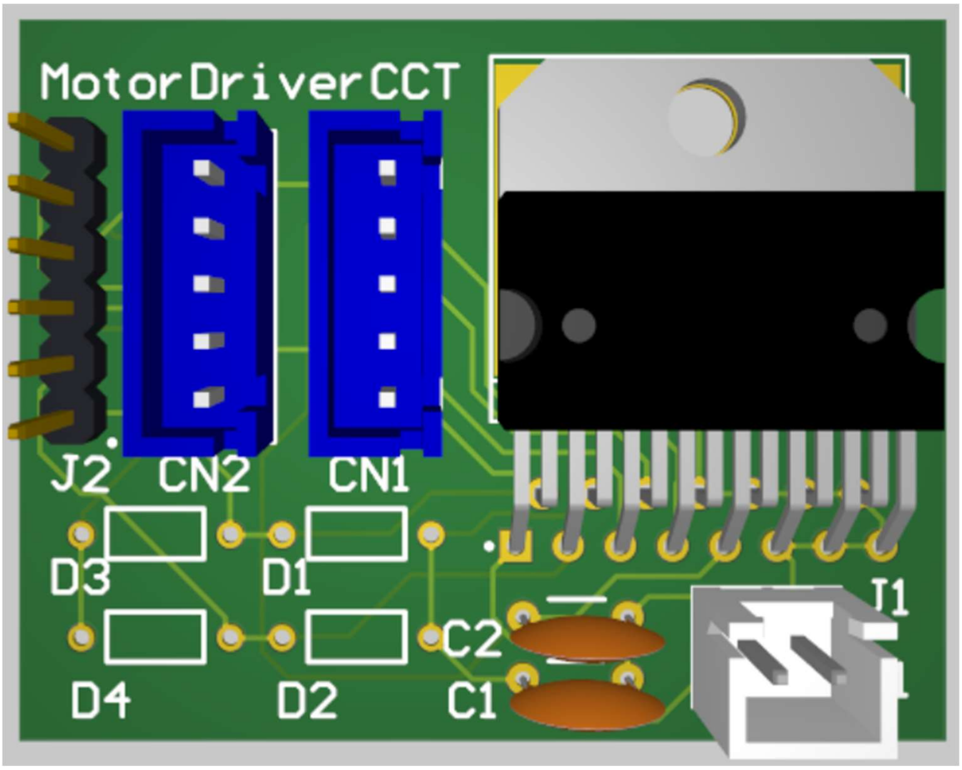

Figure 12: 3D View of the Motor Driver PCB

3. Testing of the Design

The 5 RCGs listed in Section 1 are either individually tested or considered in the design process. The tests executed, and their results are explained below.

3.1 Motherboard PCB

The “Run DRC” feature in Altium CircuitMaker is used to verify the PCB design made, refer to Appendix C for the “DRC Report”. The size requirement was kept in mind while designing the board for the first iteration. Iterations following that focused on minimizing the board size. Current board size is 5x7 cm, the RCG has been met.

3.2 Motor Driver PCB

Same approach as the Motherboard is used when designing the PCB for the Motor Driver. The “Run DRC” feature in Altium CircuitMaker is used to verify the PCB design made, refer to Appendix D for the “DRC Report”. First iteration was made while keeping the size requirement in mind and the following iterations minimized the board size. Current board size is 4.5x3.5 cm, the RCG has been met.

3.3 Motor Driver Power Consumption

Multiple tests where the Motor Driver was connected to a 5 V input were run. Figure 13 shows the power supply photo where the current was as low as 0.18 A. However, on average the power consumption under a no-load case was found to be 0.21 A at 12 V. These numbers meet the RCGs identified.

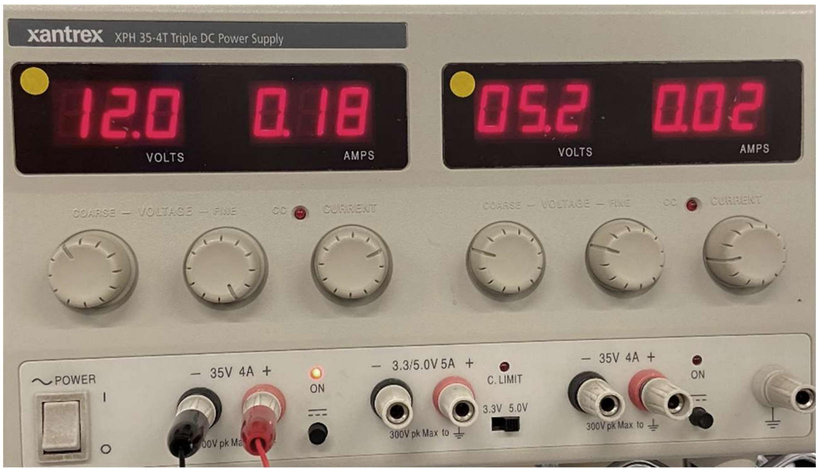

Figure 13: Power Supply Data for the Motor Driver

3.4 Motor Driver Response

As seen in Section 2.3 the Motor Driver has a settle time of 130 ms. Other tests were run with a custom build H-bridge, which also consumed 0.2 A at 12 V under no-load conditions. However, it had a settle time of 180 ms, so due to the lower settle time of the IC, L298 was chosen as the Motor Driver. Refer to Appendix E for the step response of the H-bridge.

The video "Motor-Driver-Response-to-PWM Signals" (https://drive.google.com/file/d/1h0WLaYGfkV7tp02XX7nt_eYF0rJrJksn/view?usp=sharing) shows the Motor Driver operating under different PWM duty cycles. When the duty cycle is doubled the speed also approximately doubled. This data can be seen on the proof of concept video.

3.5 Homing Circuit

A straightforward test circuit was prepared for the limit switch. By clicking the switch, the circuit was complete, and the LED was lit. Since this mechanical interface can be used with the fingers of the gripper, this component can be used as the Homing Circuit and the RCG is met. Refer to the video “Homing-Circuit” (https://drive.google.com/file/d/1XPwnbltA7bYrDxhqjHbavb2MQuFamWF6/view?usp=sharing) to see the test being run.

References

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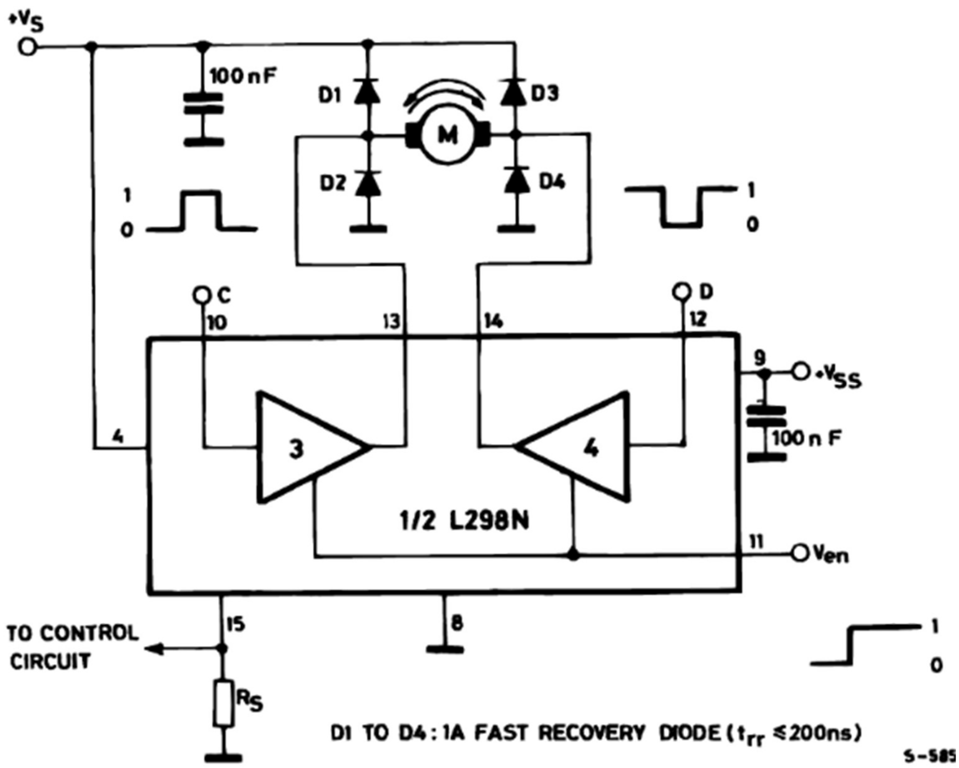
[12] "Dual full-bridge driver," . Retrieved March 19, 2023, from https://www.sparkfun.com/datasheets/Robotics/L298_H_Bridge.pdf

Appendix

A: Bidirectional DC Motor Control Block Diagram



B: MATLAB Code for the Transfer Function

```
function naturalFrequency = getSettleTimeNaturalFrequency(settleTime, dampingCoefficient, timeConstantMultiplier)

    naturalFrequency = fraction(timeConstantMultiplier, (dampingCoefficient * settleTime));

end

timeConstantMultiplier = 5

dampingCoefficient = 1

function transferFunction = getTransferFunction(naturalFrequency, gain, dampingCoefficient)

    transferFunction = minreal(tf((((naturalFrequency)^2) * gain), [1 (2 * dampingCoefficient * naturalFrequency) ((naturalFrequency)^2)]));

end
```

C: DRC Report for the Motherboard

ALTIUM
CIRCUITMAKER

Design Rule Verification Report

Date:	19-Mar-23		
Time:	9:18:32 PM	**Warnings:**	0
Elapsed Time:	00:00:01	**Rule Violations:**	0
Filename:	motherboard.CMPcbDoc		

Summary

Warnings	Count
Total	**0**

Rule Violations	Count
Clearance Constraint (Gap=0.254mm) (All),(All)	0
Short-Circuit Constraint (Allowed=No) (All),(All)	0
Un-Routed Net Constraint ((All))	0
Modified Polygon (Allow modified: No), (Allow shelved: No)	0
Width Constraint (Min=0.254mm) (Max=0.254mm) (Preferred=0.254mm) (All)	0
Power Plane Connect Rule(Relief Connect)(Expansion=0.508mm) (Conductor Width=0.254mm) (Air Gap=0.254mm) (Entries=4) (All)	0
Hole Size Constraint (Min=0.025mm) (Max=2.54mm) (All)	0
Hole To Hole Clearance (Gap=0.254mm) (All),(All)	0
Minimum Solder Mask Sliver (Gap=0.254mm) (All),(All)	0
Silk To Solder Mask (Clearance=0.254mm) (IsPad),(All)	0
Silk to Silk (Clearance=0.254mm) (All),(All)	0
Net Antennae (Tolerance=0mm) (All)	0
Height Constraint (Min=0mm) (Max=25.4mm) (Prefered=12.7mm) (All)	0
Total	**0**

D: DRC Report for the Motor Driver

ALTIUM
CIRCUITMAKER

Design Rule Verification Report

Date:	19-Mar-23		
Time:	9:16:59 PM	**Warnings:**	0
Elapsed Time:	00:00:02	**Rule Violations:**	0
Filename:	DriverCCTPCB.CMPcbDoc		

Summary

Warnings	Count
Total	**0**

Rule Violations	Count
Clearance Constraint (Gap=0.254mm) (All),(All)	0
Short-Circuit Constraint (Allowed=No) (All),(All)	0
Un-Routed Net Constraint ((All))	0
Modified Polygon (Allow modified: No), (Allow shelved: No)	0
Width Constraint (Min=0.254mm) (Max=0.254mm) (Preferred=0.254mm) (All)	0
Power Plane Connect Rule(Relief Connect)(Expansion=0.508mm) (Conductor Width=0.254mm) (Air Gap=0.254mm) (Entries=4) (All)	0
Hole Size Constraint (Min=0.025mm) (Max=2.54mm) (All)	0
Hole To Hole Clearance (Gap=0.254mm) (All),(All)	0
Minimum Solder Mask Sliver (Gap=0.254mm) (All),(All)	0
Silk To Solder Mask (Clearance=0.254mm) (IsPad),(All)	0
Silk to Silk (Clearance=0.254mm) (All),(All)	0
Net Antennae (Tolerance=0mm) (All)	0
Height Constraint (Min=0mm) (Max=25.4mm) (Prefered=12.7mm) (All)	0
Total	**0**

E: Step Response of the Custom Build H-Bridge