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DESIGN AND IMPLEMENTATION OF A POWER STAGE FOR DIGITAL COMMAND CONTROL (DCC) SYSTEMS WITH CURRENT MANAGEMENT AND PROTECTION FEATURES

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TÍTULO:	Design and Implementation of a Power Stage for Digital Command Control (DCC) Systems with Current Management and Protection Features
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RESUMEN Y PALABRAS CLAVE

Este estudio propone un nuevo diseño para la etapa de potencia de sistemas de Control de Comandos Digitales (DCC), comparando la eficiencia y adecuación de dos controladores de motores, DRV8873H y L6206D, con el fin de mejorar la seguridad, eficiencia y fiabilidad de las aplicaciones DCC. El diseño consta de dos salidas de 10 amperios y se encarga de modular el formato DCC proporcionado por un microcontrolador Arduino Due en un voltaje de CA de ±18V. Este se aísla galvánicamente del microcontrolador mediante optoacopladores y está protegido por fusibles. Además, la etapa de potencia envía señales de reconocimiento y corriente momentánea de vuelta al microcontrolador para su monitoreo. El objetivo principal es desarrollar un controlador DCC robusto, eficiente y fiable, garantizando un funcionamiento suave, un control de corriente preciso y características de protección.

Diseño Eléctrico-Electrónico, Diseño PCB, Etapa de Potencia, Sistemas DCC, Medidas de Protección

ABSTRACT AND KEYWORDS

This study introduces a novel power stage design for Digital Command Control (DCC) systems, assessing the performance and suitability of two motor drivers, DRV8873H and L6206D, aiming to enhance the safety, efficiency, and reliability of DCC applications. The design comprises two 10-amp outputs and is responsible for modulating the DCC format provided by an Arduino Due microcontroller onto a ±18V AC voltage. It is galvanically isolated from the microcontroller using optocouplers and is fuse-protected. Moreover, the power stage sends acknowledgment signals and momentary current back to the microcontroller for monitoring purposes. The primary aim is to develop a robust, efficient, and reliable DCC controller, ensuring smooth operation, precise current control, and safety features.

Electronic-Electrical Design, PCB Design, Power Stage, DCC Systems, Protection Measures

Abstract

This study introduces a new power stage design for Digital Command Control (DCC) systems, comparing the performance and suitability of two motor drivers, DRV8873H and L6206D, to enhance the safety, efficiency, and reliability of DCC applications.

The design of the power stage consists of two 10 amps outputs and is intended to modulate the DCC format provided by an Arduino Due microcontroller onto a ±18V AC voltage. The designed power stage is galvanically isolated from the microcontroller using optocouplers and protected by fuses. Furthermore, the power stage sends the acknowledge signal and momentary current back to the microcontroller for monitoring purposes.

The primary motivation for this project is to develop a robust, dependable, and efficient DCC controller, ensuring smooth operation, accurate current control, and safety features. The design process involves designing the circuit schematics, selecting appropriate components and assembling them onto printed circuit boards (PCB), designing an enclosure for the PCBs, and integrating the system with the microcontroller. The implemented design is evaluated and validated through a series of experimental measurements and comparisons with the desired objectives.

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Introduction

Thesis Outline

In this thesis, the reader will be guided through the development and implementation of a power stage for DCC systems. The structure of the thesis is as follows:

- A comprehensive background and motivation section that provides the context for the research and highlights the significance of addressing the challenges in designing a power stage for DCC systems.
- A thorough review of the fundamental concepts, including DCC systems, motor driver ICs, power stages, overcurrent protection, current measurement techniques, and galvanic isolation.
- The methodology section outlines the design process, detailing each step involved in developing the power stage, from component selection to circuit design and testing.
- The results and discussion section presents the performance and characteristics of the implemented power stage, addressing the objectives outlined earlier in the thesis.
- Lastly, the conclusion summarizes the findings and contributions of this work and provides recommendations for future research and development in this area.

Background and Motivation

Digital Command Control (DCC) is a standard for controlling vehicles that use digital communication to send commands to individual devices on the network.

One of the components of a DCC system is the power stage, it converts digital signals to higher voltage levels for motor control. Integrated motor driver ICs like DRV8873H and L6206D simplify power stage design by reducing component count and offering advanced features. This thesis designs and implements a 10A dual output power stage for a DCC controller using these ICs, aiming to develop a robust and efficient solution that meets the system's requirements. This work will contribute to the field of DCC systems.

Objectives and Scope

This thesis aims to design and implement a DCC controller power stage with overcurrent protection and current measurement capabilities using motor driver ICs. The objectives are:

1. Investigate power stage requirements for DCC systems, focusing on safety, efficiency, and reliability.
2. Compare DRV8873H and L6206D motor drivers for use in the power stage.

3. Design and implement a 10 Amps power stage with both drivers, incorporating overcurrent protection, current measurement capabilities, and galvanic isolation.
4. Evaluate the implemented power stage's performance using both drivers through testing and comparison with existing solutions.

The scope is limited to the power stage design, assuming an existing Arduino microcontroller that generates DCC signals. Alternative solutions may be explored, but the project does not cover other DCC system aspects.

Literature review

Overview of DCC Systems

Digital Command Control (DCC) is a standardized protocol for independent control of model railway vehicles and accessories, introduced by the National Model Railroad Association (NMRA) in the 90s. In DCC systems, digital packets with commands are sent via a modulated AC signal through tracks or accessory wiring to decoders in each vehicle or accessory. This facilitates unique control over numerous locomotives on the same track, enabling complex operations like consisting and speed matching.

A typical DCC system consists of the following components:

- DCC Controller: The central unit that generates the DCC command packets and modulates the AC voltage signal. It can be operated by a computer or microcontroller, such as an Arduino.
- Power Stage: A circuit that amplifies the modulated DCC signal generated by the controller, providing sufficient voltage and current.
- Decoders: Electronic devices installed in the locomotives and accessories that receive the DCC command packets.
- Wiring: The physical infrastructure that carries the DCC signal.
- Accessories: The devices that are controlled by the DCC system.

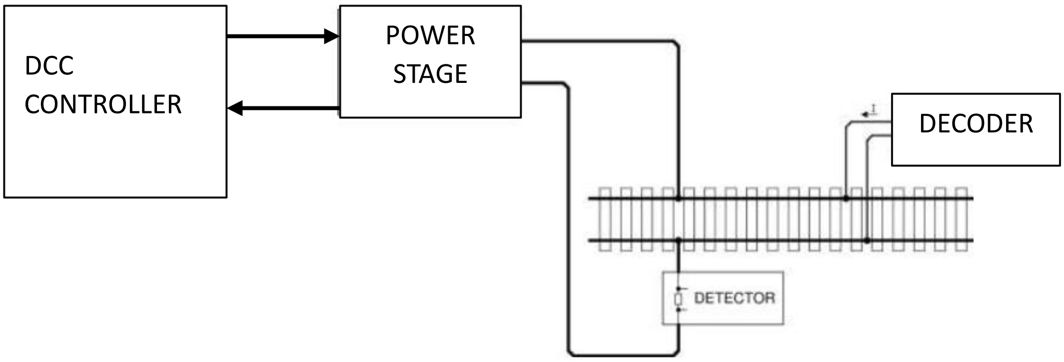

Figure 1 DCC Block Diagram based on (NMRA, 2023)

DCC Signal and Protocol

The DCC signal consists of a bipolar AC voltage waveform modulated with digital packets containing the command information. The voltage level typically ranges from 12V to 24V, depending on the scale and power requirements of the layout. The digital packets follow a specific format defined by the NMRA DCC standard, which includes a preamble, address, instruction, data, and error checking fields.

The DCC packets can contain several types of commands, such as speed and direction control, function activation, accessory control, and programming instructions. The packets are addressed to specific decoders using a unique address, which can be either a short (7-bit) or long (14-bit) format, allowing for up to 128 or 16,384 unique addresses, respectively.

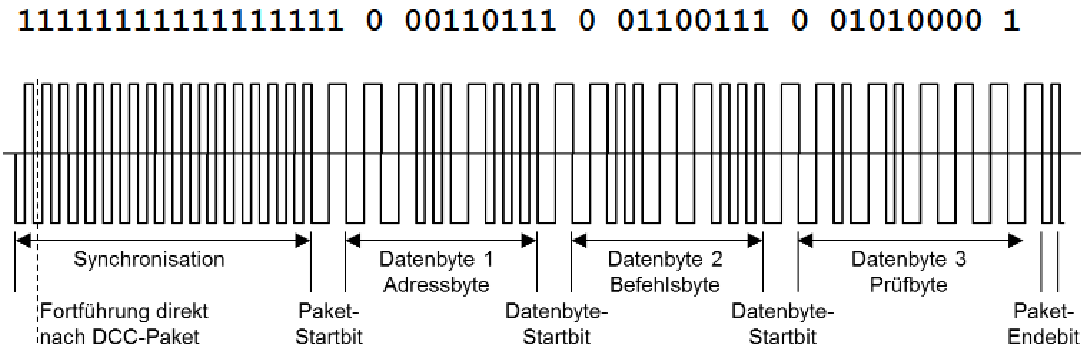

Figure 2 Example of a DCC packet with three bytes (1 address byte, 1 command byte, 1 check byte), coded for address 55 and driving forward with speed 14 (Rail Community, 2023).

ACK Detection

Whenever information is transmitted to various devices within the system, each device's decoder must be capable of sending back a confirmation signal. This enables the microcontroller to ascertain whether the information has been successfully received or not.

According to the RCN-216 Norm (Rail Community, 2023), the decoder confirms successful programming by increasing its current consumption by at least 60 mA for 5-7 ms (8). The current pulse only occurs once the programming command, including data storage, is processed. All write commands must be confirmed. The time window for the current pulse starts with the first data packet's end bit and lasts at least 100 ms (5) for write commands and 50 ms for read commands. The current must return to its previous value before the time window ends. After the time window or an acknowledgement, the read or write cycle is complete. Afterward, a new operation can commence immediately, or data packet transmission can stop, and the voltage can be switched off after another 100 ms.

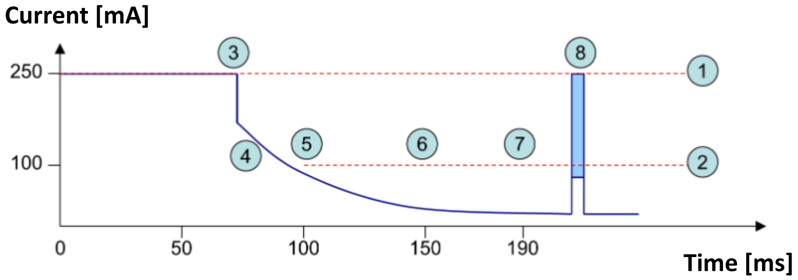

Figure 3 Example of a current curve when switching on the programming track (Rail Community, 2023).

The numbers in *Figure 3* have the following meanings:

1. Current limitation at 250 mA
2. Short-circuit detection threshold at 100 mA starting from 100 ms after power-on
3. The decoder recognizes programming mode and switches off all loads. Until then, the programming track current is limited to 250 mA.
4. Some (smaller) capacitors continue charging, as they cannot be switched off.
5. After 100 ms, the current must have fallen below 100 mA.
6. After 150 ms, the current consumption must have stabilized.
7. After 190 ms, the transmission of the 25 reset packets is complete. Commands for reading and writing configuration variables can be sent from this point.
8. The decoder responds to a command with a current pulse. The current can be below the 100 mA threshold or even above it. It is limited to 250 mA by the programming track's current limiter.

Motor Driver ICs and Power Stages

Overview of Motor Driver ICs

Motor driver ICs are electronic components for efficient motor control in various applications. They offer accurate control of speed, direction, and torque by converting digital signals into electrical power. Available types include H-bridge, half-bridge, and full-bridge drivers for diverse motor setups and power needs.

H-Bridge Motor Drivers

H-bridge motor drivers are commonly used in DCC systems due to their ability to control the speed and direction of DC motors using a single power supply. An H-bridge driver consists of four electronic switches (usually MOSFETs or transistors) arranged in an "H" configuration, with the motor connected between the two middle switches.

By controlling the states of these switches, the motor driver can apply voltage across the motor terminals in either polarity, resulting in forward or reverse rotation.

Figure 4 shows the configuration of an H-bridge driver, where V_{bat} is the power supply, Q1 to Q4 are the switches (MOSFETs) and M is the load.

Some popular H-bridge motor driver ICs for DCC applications include the L6206D, DRV8873H, and L298N. These ICs offer features such as overcurrent protection, thermal shutdown, and current sensing, which can help improve the reliability and safety of the DCC power stage.

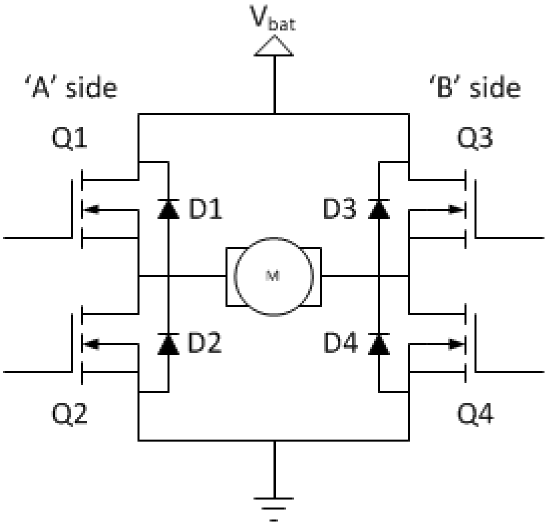

Figure 4 Schematic of an H-bridge (Modular circuits, 2023)

Power Stages

The power stage is a critical part of a DCC system, as it amplifies the modulated DCC signal generated by the microcontroller and provides sufficient voltage and current to power the vehicles and accessories. In the context of motor driver ICs, the power stage refers to the external circuitry required to support the motor driver, including the MOSFETs, capacitors, diodes, and resistors.

Overcurrent Protection, Current Measurement and Galvanic Isolation

Overcurrent Protection

Overcurrent protection is an essential safety feature in DCC systems that prevents damage to the power stage and connected devices, due to excessive current flow. For this project, the following techniques were used:

Fuses: Fuses are the simplest and most usual form of overcurrent protection. They consist of a thin wire or strip that melts and breaks the circuit when the current exceeds a predefined threshold. Fuses can be either one-time use (non-replaceable) or replaceable.

Electronic overcurrent protection: This method involves monitoring the current flow using current-sensing techniques and implementing a control mechanism to limit or interrupt the current flow when it exceeds a predefined threshold. Electronic overcurrent protection can be integrated into motor driver ICs, such as the DRV8873H and L6206D, or implemented using discrete components like comparators and MOSFETs.

Current Measurement Techniques

Current measurement is used in DCC systems for monitoring the power stage's performance, detecting overcurrent conditions, and providing feedback to the microcontroller for closed-loop control. In this case, the following technique was used:

Integrated current sensing: Some motor driver ICs, such as the DRV8873H and L6206D, have built-in current sensing capabilities using internal sense FETs or resistors. The sensed current is often output as a voltage proportional to the current, which can be fed directly into the microcontroller's ADC for processing.

Galvanic Isolation

Galvanic isolation is key in separating electrical circuits to prevent unwanted current flow while enabling data and power transfer. Various methods exist, with optocouplers being efficient for digital signal transfer in DCC systems, providing isolation between the microcontroller and power stage. Optocouplers, with an LED and a photodetector in a single unit, allow signals to cross isolation barriers without direct electrical connections.

This protects the microcontroller from potential damage due to voltage spikes, noise, and ground loops, crucial when dealing with high-power devices like motor drivers.

System Overview and Design Requirements

System Architecture

This section discusses the overall system architecture for the power stage designed, focusing on the integration of the DRV8873H and L6206D motor drivers. The system architecture serves as a blueprint for the development and implementation of the power stage, ensuring seamless operation with the existing microcontroller.

The system architecture can be divided into three key components:

- DCC Controller: The DCC controller, implemented using an Arduino microcontroller, generates the DCC signal in TTL format, which serves as the input for the power stage. It also processes feedback from the current measurement system and communicates with the power stage for control and monitoring purposes.

- Power Stage: The power stage is responsible for amplifying and modulating the DCC signal, converting the TTL input into a ± 18V AC voltage. The power stage is designed with both DRV8873H and L6206D motor drivers, allowing for a comparative analysis of their performance and suitability for the application. Overcurrent protection, current measurement capabilities, and galvanic isolation are integrated into the power stage to enhance safety, enable real-time monitoring of the system's performance, and ensure that any electrical disturbances or faults in the power stage do not affect the microcontroller or other sensitive components in the system.

- Communication and Feedback: The system architecture includes provisions for communication between the microcontroller and the power stage, allowing for control, monitoring, and feedback. This includes the transmission of the DCC signal, as well as the reception of current measurement data and other relevant information from the power stage.

Design Requirements and Specifications

This section outlines the design requirements and specifications for the power stage. These requirements and specifications aim to ensure that the power stage meets the desired performance, safety, and reliability goals while enabling a comparative analysis of the two motor drivers.

Dual Output: The power stage must provide two independent output channels, each capable of delivering up to 10A of current to accommodate the requirements of the system.

Overcurrent Protection: The design must incorporate overcurrent protection features to safeguard the power stage, motor drivers, and connected devices from damage due to excessive current draw.

Current Measurement: The power stage must be capable of measuring the output current of the main channel, enabling real-time monitoring and feedback to the microcontroller.

Galvanic Isolation: Optocouplers must be used to achieve galvanic isolation between the power stage and the microcontroller, ensuring that the two circuits are electrically separated to prevent interference, noise, and potential damage.

Voltage Conversion: The power stage should be capable of modulating the DCC signal provided by the microcontroller in TTL format onto a ± 18V AC.

Power Supply and Protection: The power stage must be powered by an 18V power source and include appropriate fusing to protect the circuitry from overcurrent and short-circuit conditions.

Communication and Feedback: Provisions for bidirectional communication between the microcontroller and the power stage must be included, enabling the transmission of the DCC signal and the reception of current measurement data and other relevant information.

Design and Implementation

Motor Driver ICs Implementation

- For DRV8873H:

The schematic from *Figure 5* has been used as a starter point for the final design.

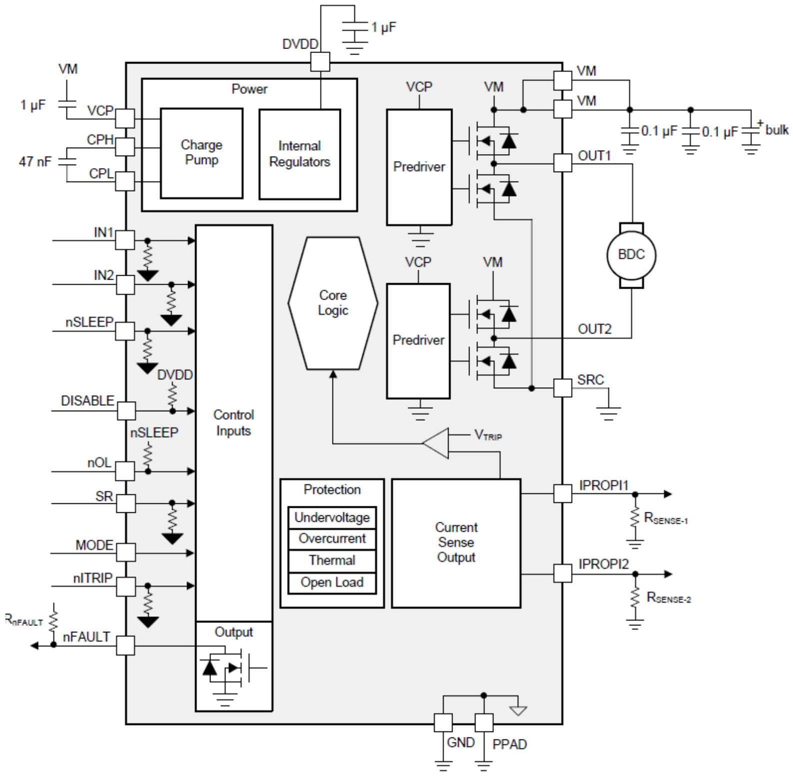

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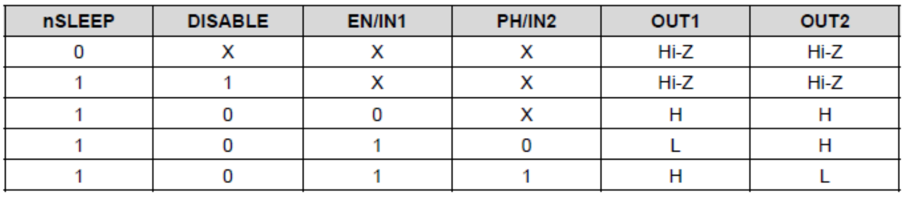
Figure 5 DRV8873H Device Block Diagram provided by the manufacturer (Texas Instruments, 2023)

The DCC output of the microcontroller goes through the optocoupler to the IN2 input, the IN1 is always High connected to a 5V source. MODE pin is connected to ground to configurate the driver as “Phase and Enable” mode, DISABLE pin is connected to ground and nSLEEP to 5V to achieve oscillating ±18V output, as required by the manufacturer *Figure 6*.



nSLEEP	DISABLE	EN/IN1	PH/IN2	OUT1	OUT2
0	X	X	X	Hi-Z	Hi-Z
1	1	X	X	Hi-Z	Hi-Z
1	0	0	X	H	H
1	0	1	0	L	H
1	0	1	1	H	L

Figure 6 Truth Table for the DRV8873H provided by the manufacturer (Texas Instruments, 2023)

SR pin is connected to DVDD pin to achieve a Slew Rate of 2,6V/µs as required by the norm, nFAULT is connected to the microcontroller to monitor any faults in the driver, nITRIP (Internal Control-Regulation Control) and nOL (Open Load Diagnosis) are connected to DVDD to disable them.

OUT1 and OUT2 are the outputs that go to the load.

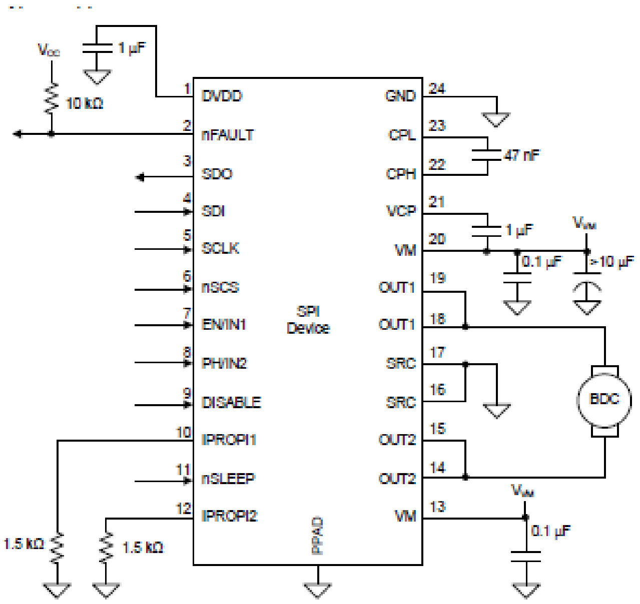


Figure 7 Values provided by the manufacturer for a typical application (Texas Instruments, 2023)

- For L6206D:

The schematic from *Figure 8* has been used as a starter point for the final design, this configuration allows the L206D motor driver to achieve a 5,6A_{RMS} load current maximum or 11,2A_{OCD} threshold.

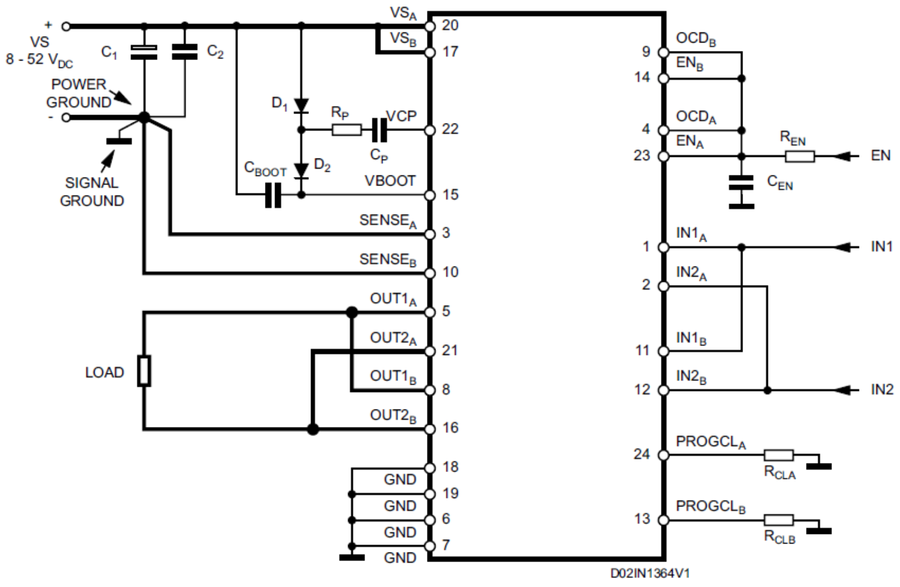
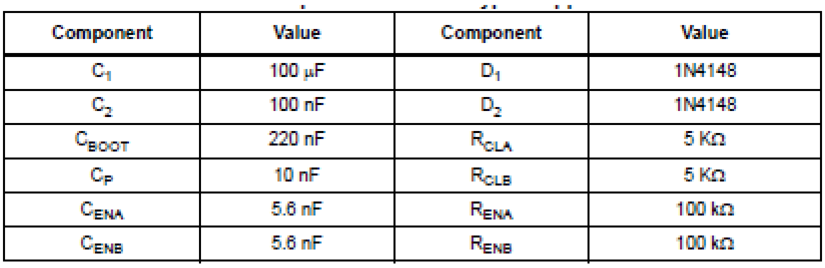


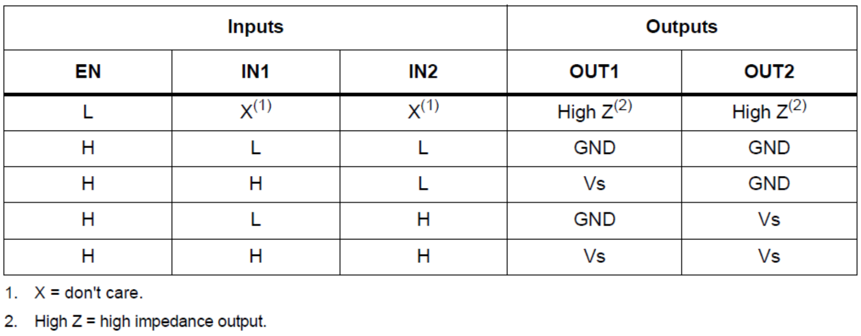
Figure 8 Typical Schematic for Parallel Operation provided by the manufacturer (ST life.augmented, 2023)



Component	Value	Component	Value
C_1	100 µF	D_1	1N4148
C_2	100 nF	D_2	1N4148
C_{BOOT}	220 nF	R_{CLA}	5 KΩ
C_P	10 nF	R_{CLB}	5 KΩ
C_{ENA}	5.6 nF	R_{ENA}	100 kΩ
C_{ENB}	5.6 nF	R_{ENB}	100 kΩ

Figure 9 Values provided by the manufacturer for a typical application (ST life.augmented, 2023)

EN pin is an input from the microcontroller, IN1 and IN2 signal comes from the optocoupler from the DCC provided by the microcontroller, IN2 must be inverted to achieve an oscillating ±18V output as required by the manufacturer, *Figure 10*.



Inputs			Outputs	
EN	**IN1**	**IN2**	**OUT1**	**OUT2**
L	X(1)	X(1)	High Z(2)	High Z(2)
H	L	L	GND	GND
H	H	L	Vs	GND
H	L	H	GND	Vs
H	H	H	Vs	Vs

1. X = don't care.
2. High Z = high impedance output.

Figure 10 Truth Table for the L6206D provided by the manufacturer (ST life.augmented, 2023)

Overcurrent Protection and Current Measurement Implementation

- **Overcurrent Protection**

Fuses are integrated into the power stage as a layer of protection. The fuses are rated to handle the maximum continuous current required by the system, 10A, plus a margin to account for transient overcurrent events. Fuses are placed in series with the power supply input of 18V, protecting the power stage from excessive current draw and potential damage.

An IRF3710 MOSFET Diode is also implemented in parallel with the power supply of 18V to prevent a possible polarity change.

➢ For DRV8873H:

The DRV8873H has an integrated overcurrent protection feature, which helps limit the output current to a safe level. If the current in any FET exceeds the 10A limit for longer than 4µs, all FETs in the half bridge are disabled and the nFAULT pin is driven low.

➢ For L6206D:

The L6206D has an integrated overcurrent protection circuit as shown in *Figure 11*, this circuit can be used to provide protection against a short-circuit to ground or between two phases of the bridge as well as a roughly regulation of the load current.

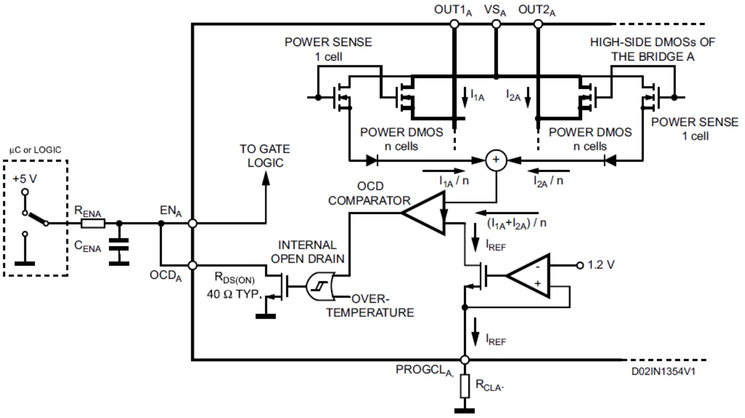


Figure 11 L6206 Overcurrent Diagram

- **Current Measurement**

➢ For DRV8873H:

The DRV8873H has an integrated current-sense amplifier that provides an analog output voltage proportional to the output current. The IPROPI1 and IPROPI2 pins are connected to the current-sense amplifier outputs for OUT1 and OUT2, respectively. The voltage at these pins can be measured using the microcontroller thought a R_{SENSE} resistor (R5) in parallel to ground as shown in the *Figure 12* on the right.

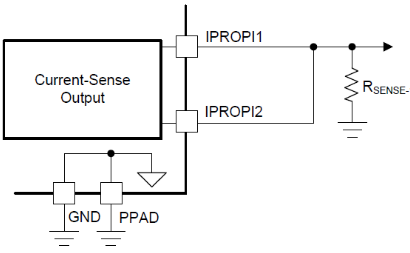


Figure 12 DRV8873H Current Sense Output

The equation to introduce into the microcontroller to know the exact current measured is:

$$I_{measured} = \frac{V_{measured}}{R_{sense}} \cdot 1100$$

Equation 1 Relation between Current and Voltage measured for the DRV9973H.

- For L6206D:

The L6206D has an integrated current-sense amplifier that provides an analog output voltage proportional to the output current. The current from the SENSEA pin can be measured using the microcontroller thought a R_{SENSE} resistor (R13 and R14) in parallel to ground.

Isolation Implementation

The 6N137 optocoupler is a high-speed, high-performance device that can maintain signal integrity while providing galvanic isolation between the input and output stages.

- Implementation:

The DCC signal output from the Arduino microcontroller is connected to the anode of the 6N137 optocoupler's internal LED through a current-limiting resistor of 220 Ω, which helps to set the LED current. The cathode of the LED is connected to the ground of the microcontroller.

The 6N137 optocoupler is powered by 5V provided by the L7805CV voltage regulator.

The output signal, now isolated, is connected to the IN1 and IN2 pins of the DRV8873H and L6206D motor drivers.

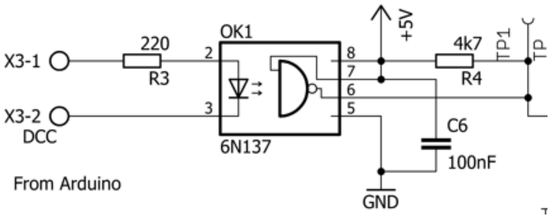


Figure 13 Schematic of the 6N137 Optocoupler

Acknowledge Signal Detection Implementation

As RP 9.2.3 (NMRA, 2023), a service mode locomotive decoder should send an acknowledgement, achieved by briefly increasing current by 60mA. This causes a voltage drop at the programming port's SENSE/IPROPI pins (depending on the motor driver IC used) directed to two RC circuits. Usually, the comparator's negative input voltage is about 11mV higher. With a voltage change, the lower circuit takes longer to follow, causing the comparator to detect a short positive pulse. This pulse initiates a low-active interrupt in the processor. This circuit is simulated through Proteus and results are discussed in page 21 *Figure 19.*

To achieve this, the following circuit on *Figure 14* is used.

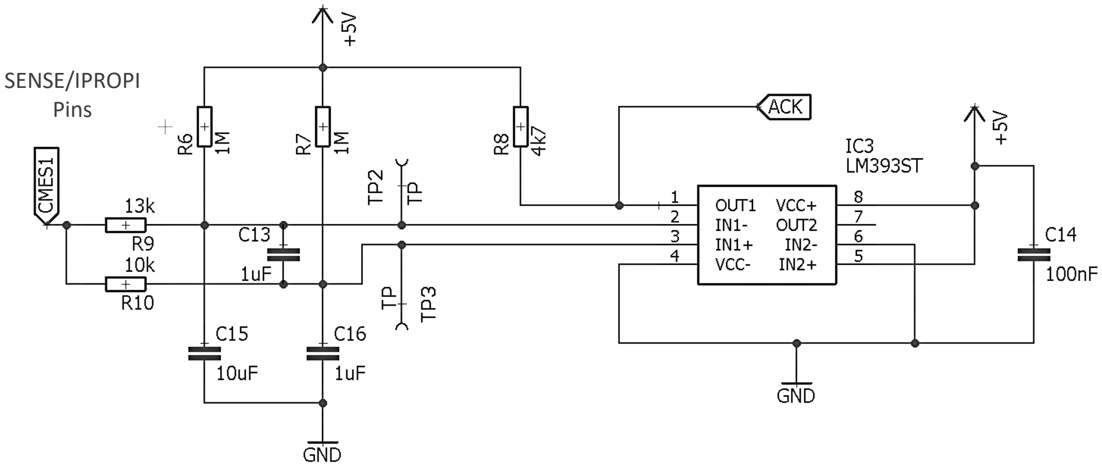


Figure 14 Schematic of the Acknowledge Detection Signal

Component Selection

This section discusses the components selected for the power stage of the DCC system, considering the design requirements and specifications from *Design Requirements and Specifications.*

- Motor Drivers: DRV8873H and L6206D were chosen for their unique features, allowing for a comparative analysis of their performance and suitability for the DCC system.
- Optocouplers: 6N137 high-speed optocouplers.
- Comparators: LM393 voltage comparators for comparing the current measurement signals from the motor driver with a reference voltage.
- Power Supply: An 18V power source provides power to the power stage.
- Voltage Regulator: L7805CV voltage regulator to supply a stable 5V to low-voltage components.
- Screw Connectors: 2 and 3 pin screw connectors for easy connections between the power stage, motors, and other external components.
- Protection Components: 10 Amp single-use fuses.
- Passive Components: SMD 1206 Package Resistors and capacitors chosen based on their suitability for specific functions within the design.

Passive Components values:

- Decoupling capacitors of 100nF have been inserted as close as possible to the integrated circuits to minimize high-frequency electrical noise.
- For the pull-up circuits, resistors of 4k7Ω or 10kΩ values have been used, which are standard values used in these circuits.
- Other Passive Components: values specified by the manufacturer in their datasheet.
- Bulk Capacitance: as specified by the manufacturer in their datasheet.

Design and Assembly

- Design:

Detailed Circuit Schematics for both the DRV8873H and L6206D motor drivers and PCB Layouts are provided in *Appendix A: Circuit Schematics* and *Appendix B: PCB Layout, Design Files*.

An enclosure has been designed with designated perforations to facilitate both the mounting of the PCB within the casing and the insertion and extraction of cables assigned to the device's inputs and outputs. This enclosure is ready for 3D printing with PLA material. The .ipt (designed 3D models) and .stl (3D models ready for printing) files can be found in the project folder under the folder name *3D Case*, while images of the enclosure are in *Appendix C: Cases for the PCBs*.

- Issues encountered and resolved prior assembly:

The assembly phase revealed several complications with the L6206D PCB which required remediation.

- ➢ Issue: The track for the CSENS was inadvertently linked to N$4 (EN1).
  - ✓ Resolution: The track to N$4 was severed and a resistor, R5, should be introduced between the output of EN1 and R7 to correct the path.
- ➢ Issue: The Ground (GND) on the bottom layer was accidentally connected to the +18V layer.
  - ✓ Resolution: A strategic cut was made to separate the two layers and restore proper functioning, *Figure 21*.

- Assembly:

The assembly of components on the PCBs involves five stages:

1. Application of solder paste using a specific solder mask for each board, *Figure 20*.
2. Manual placement of Surface Mount Device (SMD) components.
3. Placement of the board into a reflow oven. This treatment melts the solder paste, soldering the components onto the board.
4. Insertion and hand-soldering of Through-Hole (TH) components using a soldering iron and solder wire.
5. Final inspection of soldering quality and component arrangement. This review ensures that all components are correctly placed, adequately soldered, and ready for the next stages of testing and integration.

Photos of the final assembly can be found in *Appendix B: PCB Layout, Design Files and Photos of Assembly*

Testing and Validation

- Circuit Validation without applied voltage.

Prior to powering and connecting the circuit's inputs and outputs, a meticulous manual examination was conducted to ensure the electrical continuity of each component and the board's tracks. Once it was ascertained that the results from this verification process were accurate and satisfactory, the board was then powered up, thereby initiating the operational phase.

- Operational Phase Testing

The diode used to avoid reverse polarity in the IRF3710 transistor is not functioning as expected, causing a short circuit when it exceeds a value of 15V. It has been found that without this element, the circuit operates correctly. The only issue arising from removing this element is the potential for the power supply to be connected in reverse, against which the device cannot protect.

As this is a prototype, visual instructions have been provided to guide the technician in correctly connecting this element. In a future revision of this project, a component will be included to block reverse polarity.

- ➢ For DRV8873H:

Both controller outputs are operating as expected, with the multimeter and oscilloscope readings consistently displaying the anticipated 18V. The plot of one of the outputs signals is presented in *Figure 15.*

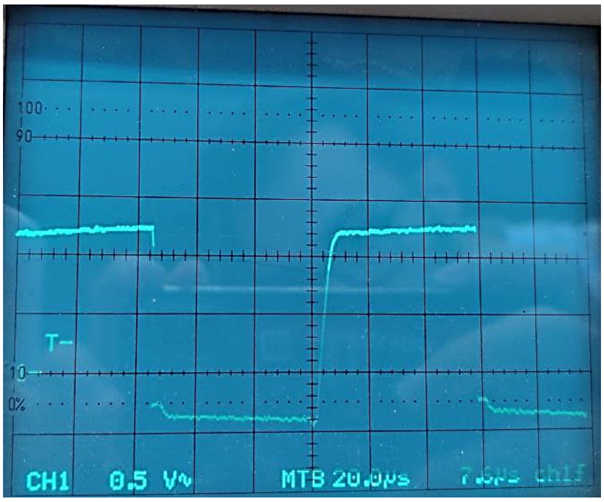


Figure 15 Plot provided by the oscilloscope for half of the DCC output

The controller's output signal for measuring current, using the equation designated inEquation 1 Relation between Current and Voltage measured for the DRV9973H. *Equation 1*, correctly indicates the expected voltage values, as shown in *Figure 17 Measures with a load state*.

The necessary acknowledgement (ACK) signal, crucial for verifying the correct reception of the data packet by the decoder, could not be verified despite several modifications made to the prototype. The circuits used in the simulations, as illustrated in *Figure 18* and *Figure 19*, display the expected functionality that was not achieved.

- For L6206D:

Due to the errors made during the design of this driver, and the lengthy delays in receiving components and printed circuit boards, the functionality of the L6206 driver couldn't be verified within the designated time frame. The corrected design schematics and the files generated for the creation of the PCBs are made available for future modifications and implementation.

Results and Discussion

The DRV8873H controller has been successfully integrated, except for the ACK output signal, the proposed schematic diagrams for this signal in simulation can be seen in *Figure 18* and *Figure 19*.

Figure 16 and Figure 17 clearly illustrate the effective performance of the driver's current measurement output signal, capable of providing a voltage proportional to the current consumed.

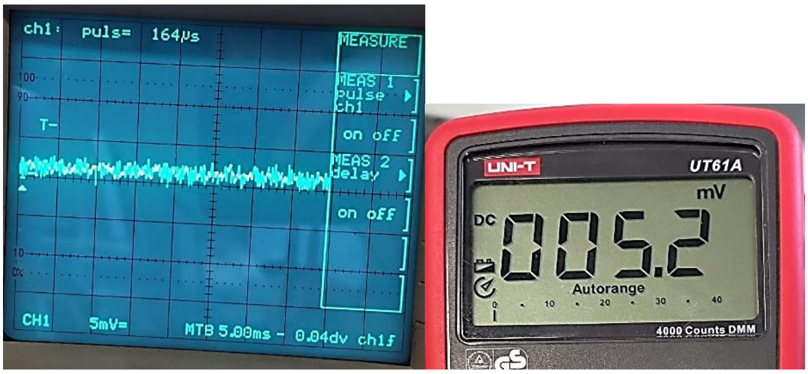


Figure 16 Measures with a no-load state

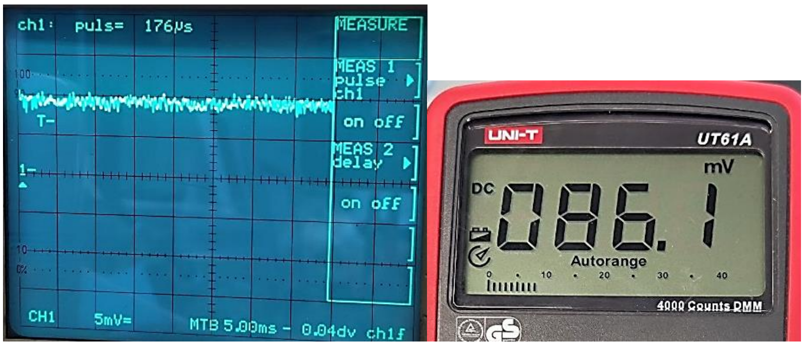


Figure 17 Measures with a load state

As can be seen in *Figure 16*, the output voltage shown for a no-load state is 5mV, while in a load state, *Figure 17*, the multimeter shows 86mV, the same value displayed on the oscilloscope, considering that the probe used is x10, so the value shown on the oscilloscope screen is 10 times less than the original.

This value, using *Equation 1*, would correspond to a current of:

$$I_{measured} = \frac{V_{measured}}{R_{sense}} \cdot 1100 = \frac{86mV}{420\Omega} \cdot 1100 = 0{,}225\,A$$

In terms of overcurrent protection, when the load was short-circuited, the driver was able to cut off the power supply and shut down. This required a restart of the driver, thus demonstrating its protective capability against such failures.

The following schematics from *Figure 18* and *Figure 19* were used to simulate the ACK signal, using the CMES output from the IPROP1 and IPROP2 of the DRV8873 driver, in both cases the output of the comparator work as intended in the simulation. The red boxes drawn in both figures represent the circuit used to simulate the current change read by the driver.

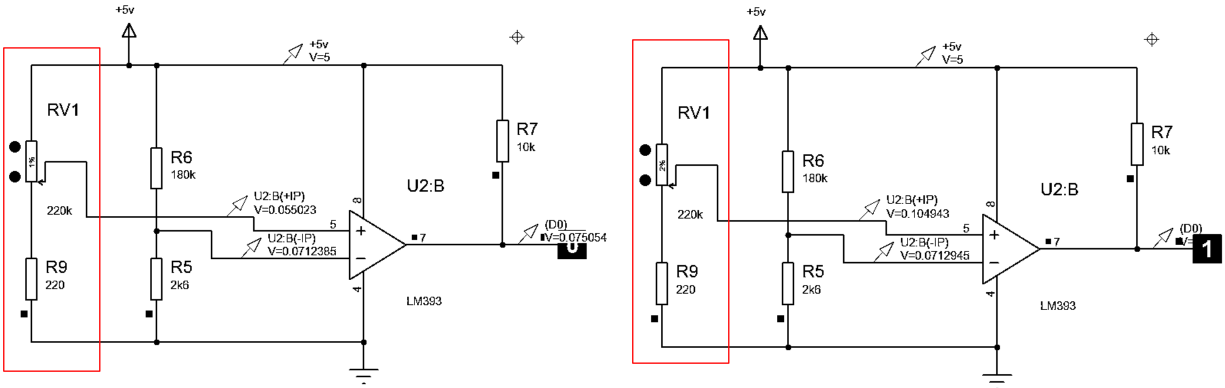


Figure 18 Simulation schematic for the ACK signal proposed.

Figure 18 shows the circuit commonly used by a comparator, where a variable voltage is applied at the non-inverting terminal and a reference voltage, derived from a voltage divider, is supplied to the inverting terminal. The moment the variable voltage surpasses the reference voltage, the comparator switches the state of its output from low to high, providing 5V at the comparator's output and using this terminal as an input to the microcontroller.

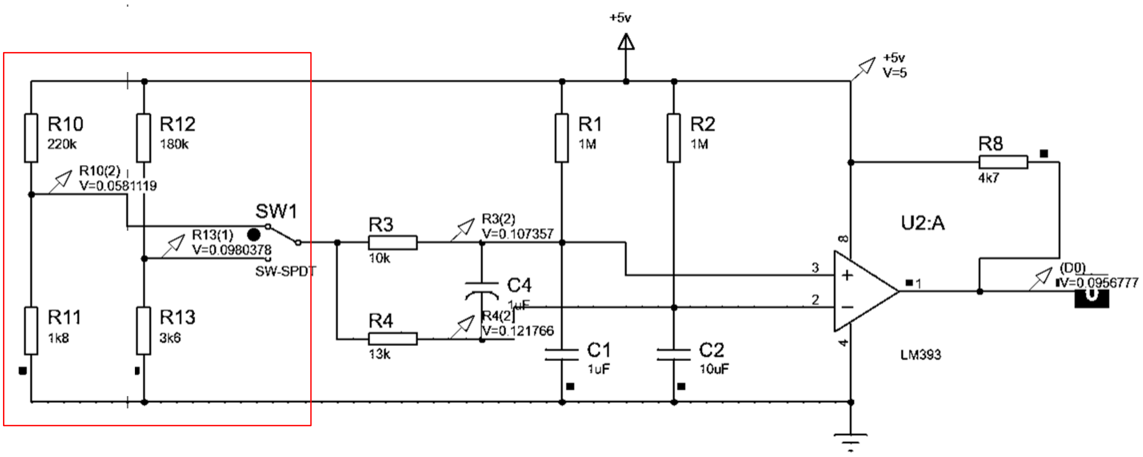


Figure 19 Simulation schematic for the ACK signal used.

Figure 19 shows a circuit used by a timer-based comparator, the operation is similar to the one explained in *Figure 18*, in this case, there is only one input voltage divided into two branches with different time constants, thanks to the resistors and capacitors used, causing one branch to operate slower than the other. This setup results in a brief '1' at the comparator output, long enough for the microcontroller to detect the pulse.

Conclusion

This thesis aimed to develop a power stage for Digital Command Control (DCC) systems by effectively managing and protecting current flow. The research progressed through stages of system architecture analysis, component selection, design specification formulation, and the integration of motor drivers.

The DRV8873H and L6206D motor drivers were chosen for their potential to improve power stage operations. After testing and analysis, the DRV8873H motor driver was successfully implemented, mainly due to its in-built overcurrent protection, thermal shutdown capabilities, and overall robustness in application.

Despite the L6206D motor driver offering interesting features, problems during assembly stage meant it could not be integrated into the final design.

A critical aspect that requires further attention is the acknowledgment signal. Despite the efforts, it was not achievable an effective acknowledgment signal from the decoder, an area that future work could target to improve the system's communication capabilities.

While the implemented design did not completely fulfill all the initial objectives, significant strides were made in developing a more advanced, reliable DCC power stage.

Overall, this thesis contributes valuable insights to the field of DCC system design. It demonstrates the potential of the DRV8873H motor driver in creating more robust power stages and highlights areas requiring further research.

References and Component Datasheet

AVX, KYOCERA. (2023, April 28). *Mouser Electronics*. Retrieved from Capacitors 1: https://www.mouser.de/datasheet/2/40/X7RDielectric-777024.pdf

AVX, KYOCERA. (2023, April 28). *Mouser Electronics*. Retrieved from Capacitors 2: https://www.mouser.de/datasheet/2/40/AutoMLCC-777028.pdf

BOURNS. (2023, April 28). *Mouser Electronics*. Retrieved from 1206 CR Resistors: https://www.mouser.de/datasheet/2/54/cr-1858361.pdf

Diotec Semiconductor. (2023, April 28). *Mouser Electronics*. Retrieved from Diodes: https://www.mouser.de/datasheet/2/849/1n4001-2577232.pdf

Elektronik, Würth. (2023, April 28). *Mouser Electronics*. Retrieved from 3 Pin Connecor: https://www.mouser.de/datasheet/2/445/691101710002-3089413.pdf

Infineon. (2023, April 28). *Mouser Electronics*. Retrieved from IRF3710PbGF MOSFET: https://www.mouser.de/datasheet/2/196/Infineon_IRF3710_DataSheet_v01_01_EN-1732407.pdf

Littelfuse. (2023, April 28). *Mouser Electronics*. Retrieved from 5 x 20 mm Fuses: https://www.mouser.de/datasheet/2/240/Littelfuse_Fuse_477_Datasheet_pdf-555535.pdf

Modular circuits. (2023, April 24). *Modular circuits*. Retrieved from Modular circuits: https://www.modularcircuits.com/blog/articles/h-bridge-secrets/h-bridges-the-basics/

nexperia. (2023, April 28). *Mouser Electronics*. Retrieved from 74HC1G04 Inverter: https://www.mouser.de/datasheet/2/916/74HC_HCT1G04-1541882.pdf

NMRA. (2023). *9.2.3 Bi-Directional Communication.* NMRA STANDARDS.

Rail Community. (2023). *RCN-211.* Verband der Hersteller Digitaler Modellbahnprodukte e.V.

Rail Community. (2023). *RCN-216.* Verband der Hersteller Digitaler Modellbahnprodukte e.V.

Richards, T. (2023, June 28). *dccwiki*. Retrieved from DCC WIKI: https://dccwiki.com/DCC_Power

ST life.augmented. (2023, April 28). *Mouser Electronics*. Retrieved from LM393A Comparator : https://www.mouser.de/datasheet/2/389/lm193-1849624.pdf

ST life.augmented. (2023, April 28). *Mouser Electronics*. Retrieved from L7805CV Voltage Regulator: https://www.mouser.de/datasheet/2/389/l78-1849632.pdf

ST life.augmented. (2023, April 28). *Mouser Electronics*. Retrieved from L6206D Driver Motor: https://www.mouser.de/datasheet/2/389/l6206-1849344.pdf

Texas Instruments. (2023, April 28). *Mouser Electronics*. Retrieved from DRV8873H Motor Driver: https://www.ti.com/lit/ds/symlink/drv8873.pdf?HQS=dis-mous-null-mousermode-dsf-pf-null-wwe&ts=1682686607251&ref_url=https%253A%252F%252Fwww.mouser.de%252F

VISHAY. (2023, April 28). *Mouser Electronics*. Retrieved from 1206 Resistors: https://www.mouser.de/datasheet/2/427/rcve3-1761897.pdf

VISHAY. (2023, April 28). *Mouser Electronics*. Retrieved from 1206 Sulfer Resistors: https://www.mouser.de/datasheet/2/427/rcae3-1761931.pdf

VISHAY. (2023, April 28). *Mouser Electronics*. Retrieved from 6N137 Optocoupler: https://www.mouser.de/datasheet/2/427/6n137-1767489.pdf

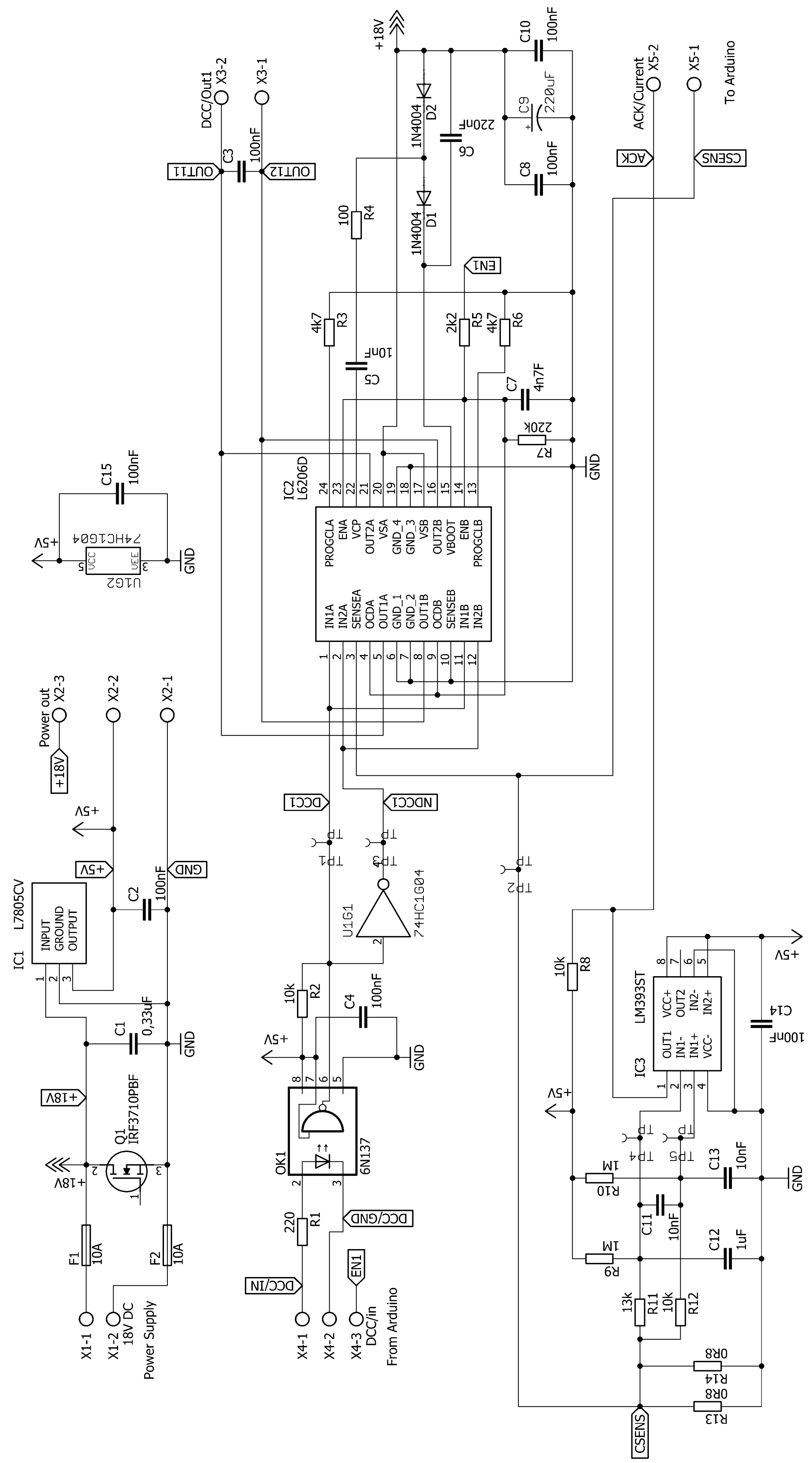
Wúrth Elektronik. (2023, April 28). *Mouser Electronics*. Retrieved from Fuse Holder: https://www.mouser.de/datasheet/2/445/696103201002-3091542.pdf

Appendices

Appendix A: Circuit Schematics

1. **L6206D Schematic**
    - **L6206D Schematic Part 1, Page 1**
    - **L6206D Schematic Part 2, Page 2**

2. **DRV8873H Schematic**
    - **DRV8873H Schematic Part 1, Page 3**
    - **DRV8873H Schematic Part 2, Page 4**



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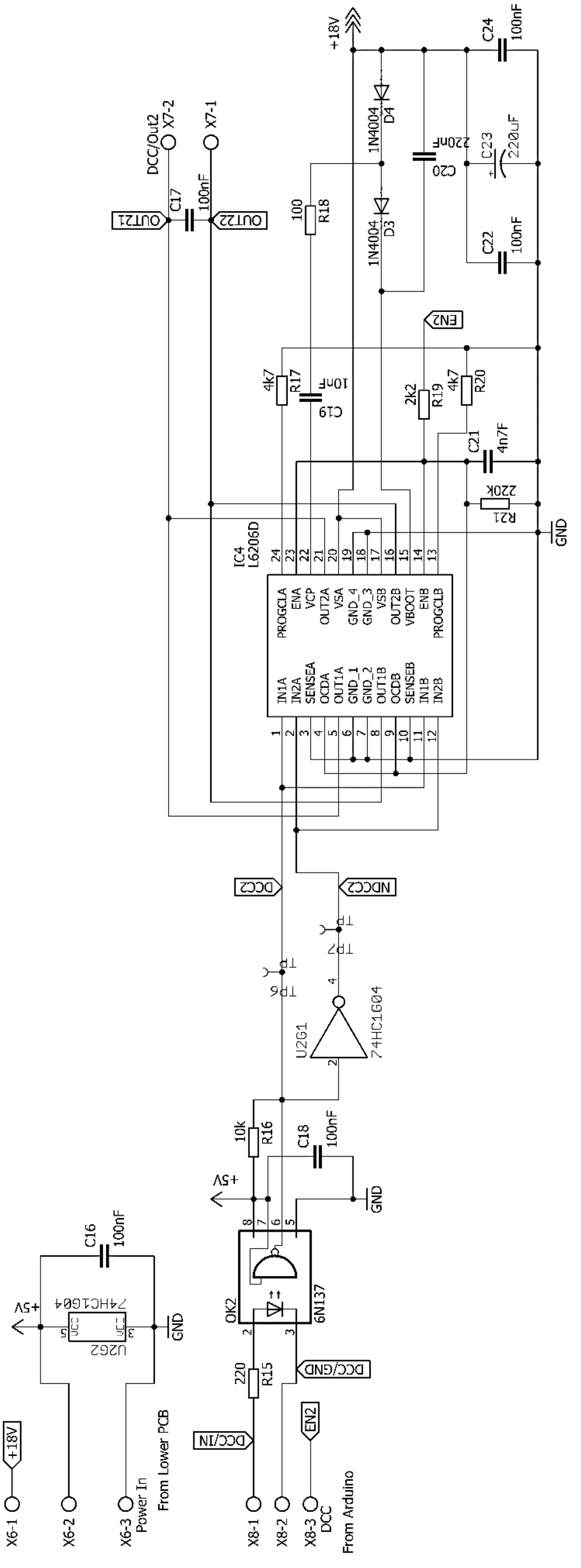
Drawn	28/04/2023	S. Sanchez	Samuel Sanchez	
Revised	11/07/2023	S. Sanchez		

Scale	Title	Page	1 of 4
1:1	L6206D SCHEMATIC PART 1	Date	28/04/2023



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Revised	11/07/2023	S. Sanchez		

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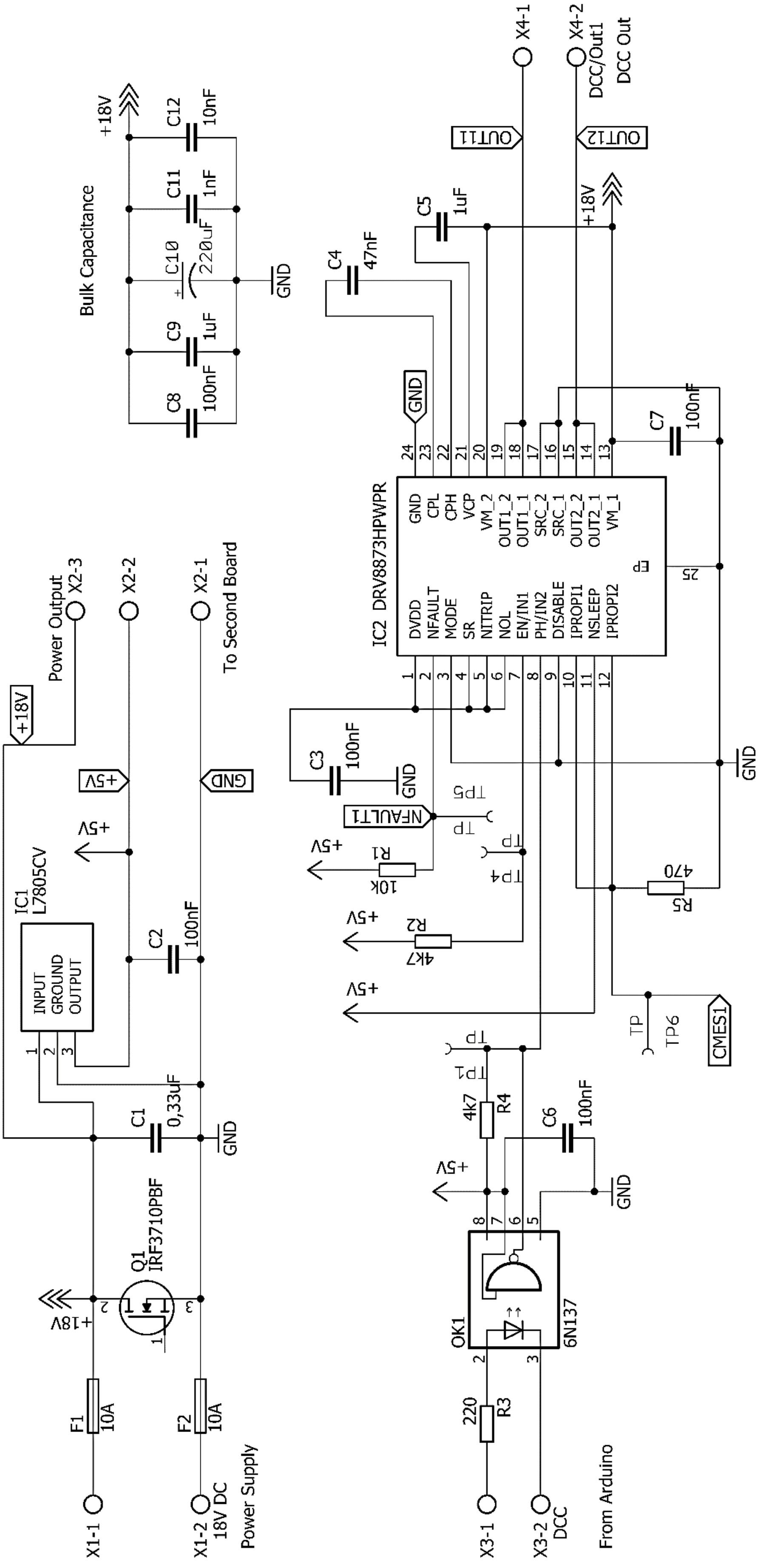

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Revised	11/07/2023	S. Sanchez		

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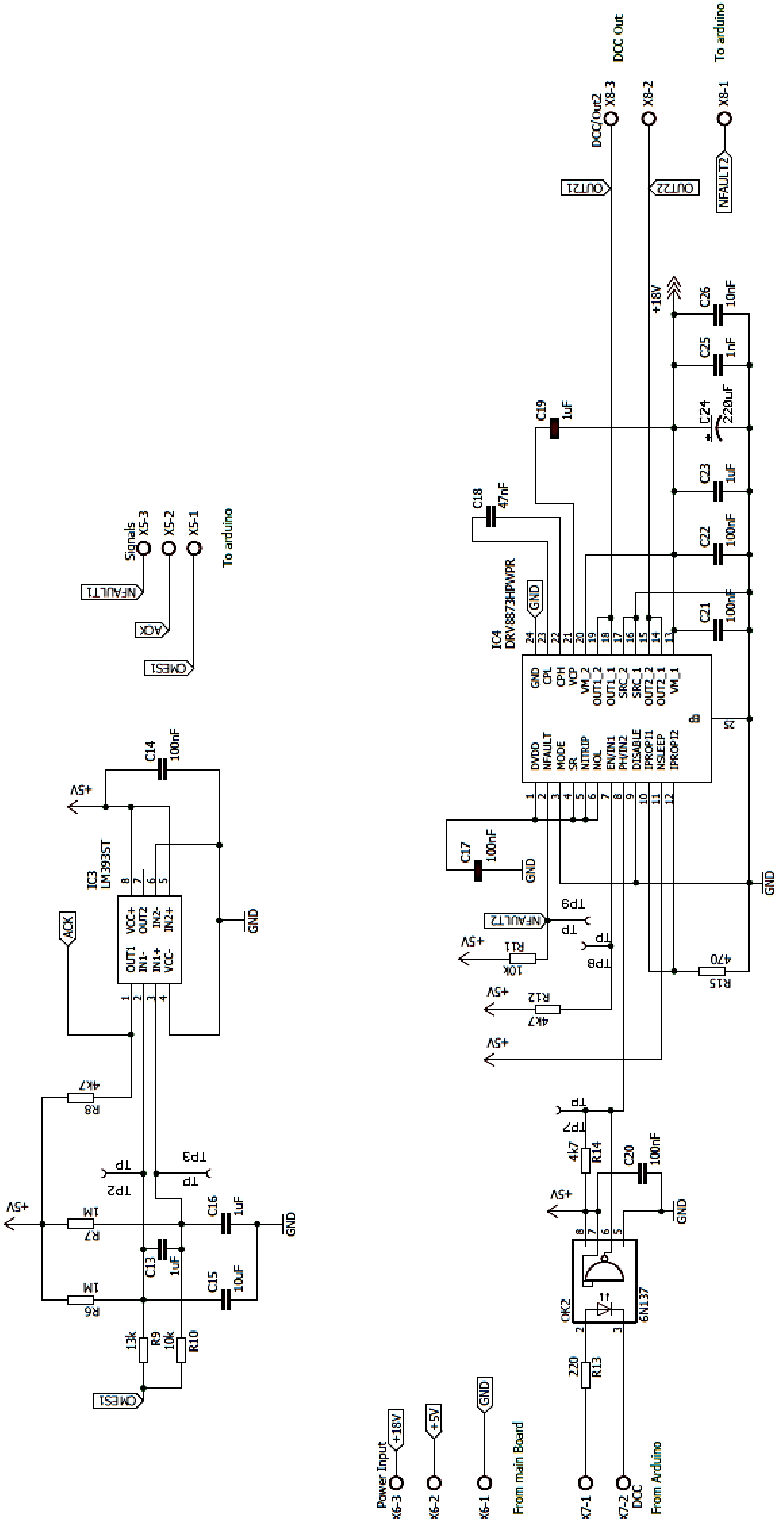

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Revised	11/07/2023	S. Sanchez		

Scale	Title	Page	4 of 4
1:1	DRV8873H SCHEMATIC PART 2	Date	28/04/2023

Appendix B: PCB Layout, Design Files and Photos of Assembly

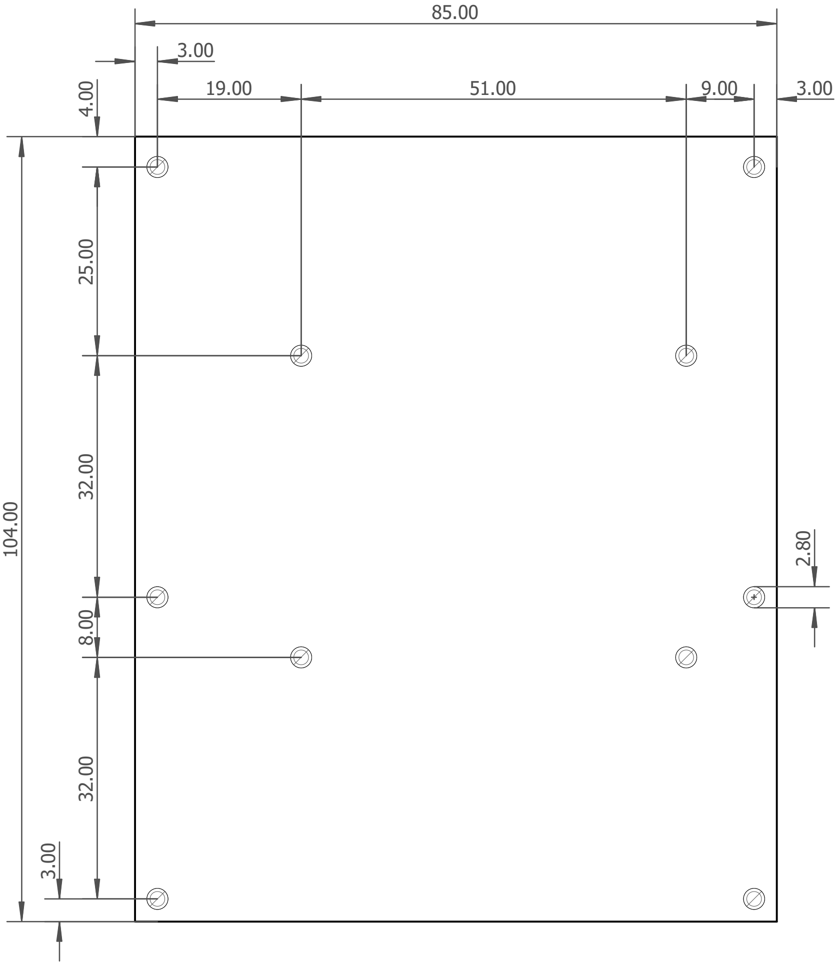
1. **L6206D PCB Layout and Design Files**
    - **L6206D PCB And Holes Measurements, Page 1**
    - **L6206D Serigraphy, Page 2**
    - **L6206D Top Net, Page 3**
    - **L6206D Bot Net, Page 4**
    - **L6206D Drills, Page 5**

2. **DRV8873H PCB Layout and Design Files**
    - **DRV8873H PCB And Holes Measurements, Page 1**
    - **DRV8873H Serigraphy, Page 2**
    - **DRV8873H Top Net, Page 3**
    - **DRV8873H Bot Net, Page 4**
    - **DRV8873H Drills, Page 5**

3. **Photos of the final assembly**

NOTES

All measurements are in mm.
All holes are 2.8 mm



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Drawn	26/04/2023	S. Sanchez	Samuel Sanchez	
Revised				

Scale	Title	Page	1 of 5
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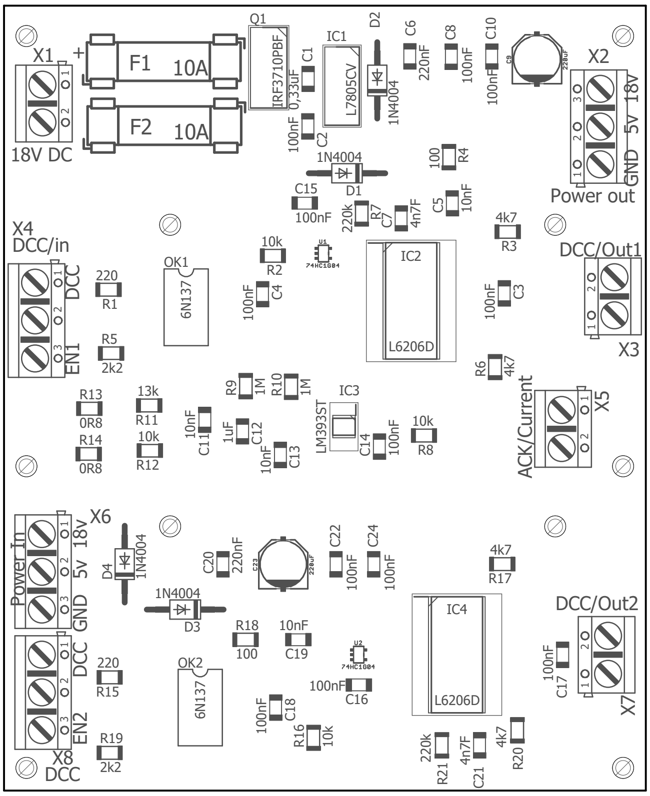

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Scale	Title	Page	2 of 5
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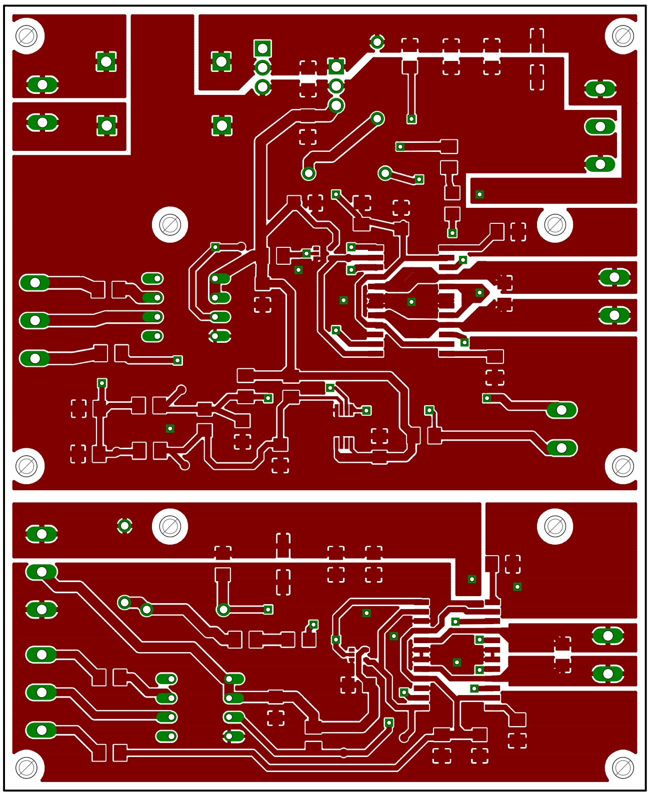

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Revised				

Scale	Title	Page	3 of 5
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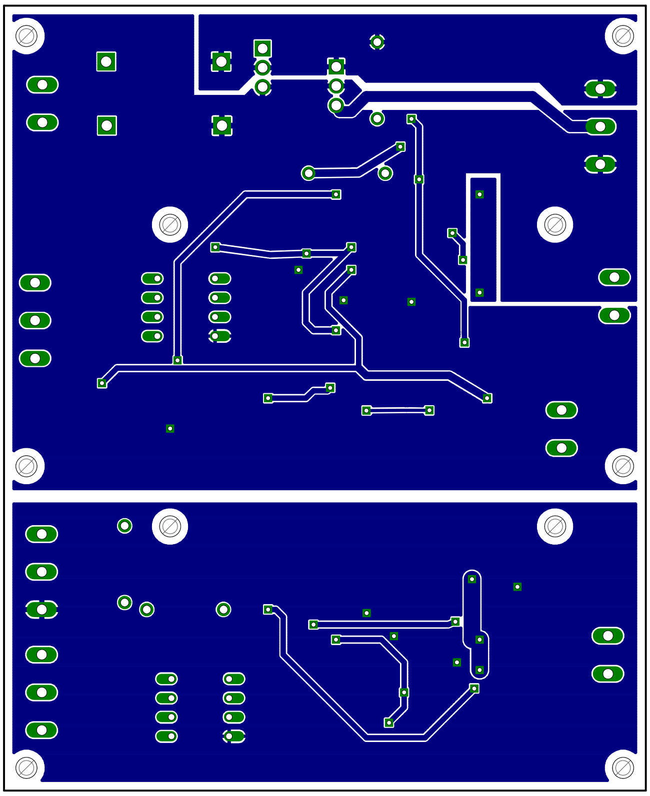

	Date	Name	Signature
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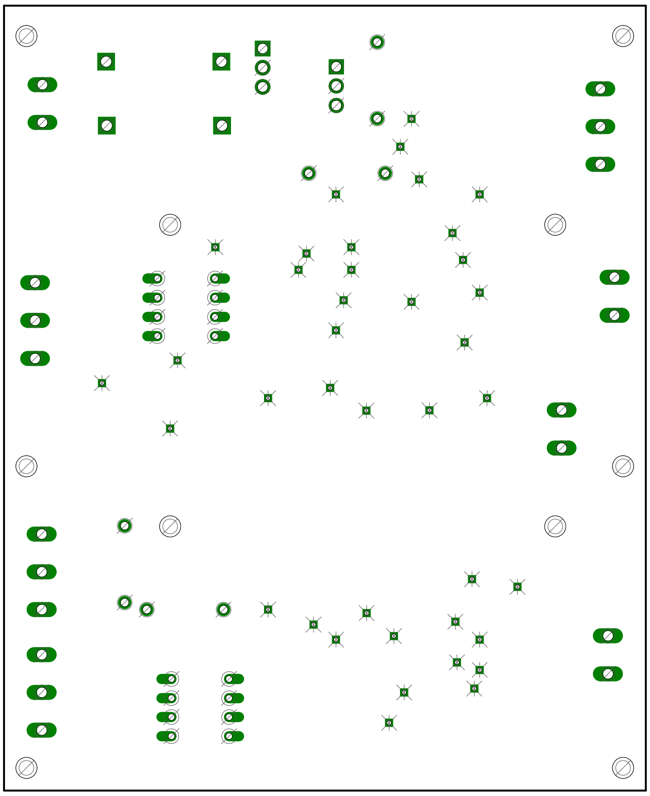
Revised			

DESIGN AND IMPLEMENTATION OF A POWER STAGE FOR DIGITAL COMMAND CONTROL (DCC) SYSTEMS WITH ENHANCED CURRENT MANAGEMENT AND PROTECTION FEATURES

Scale	Title	Page	4 of 5
1:1	L6206D BOT NET	Date	26/04/2023



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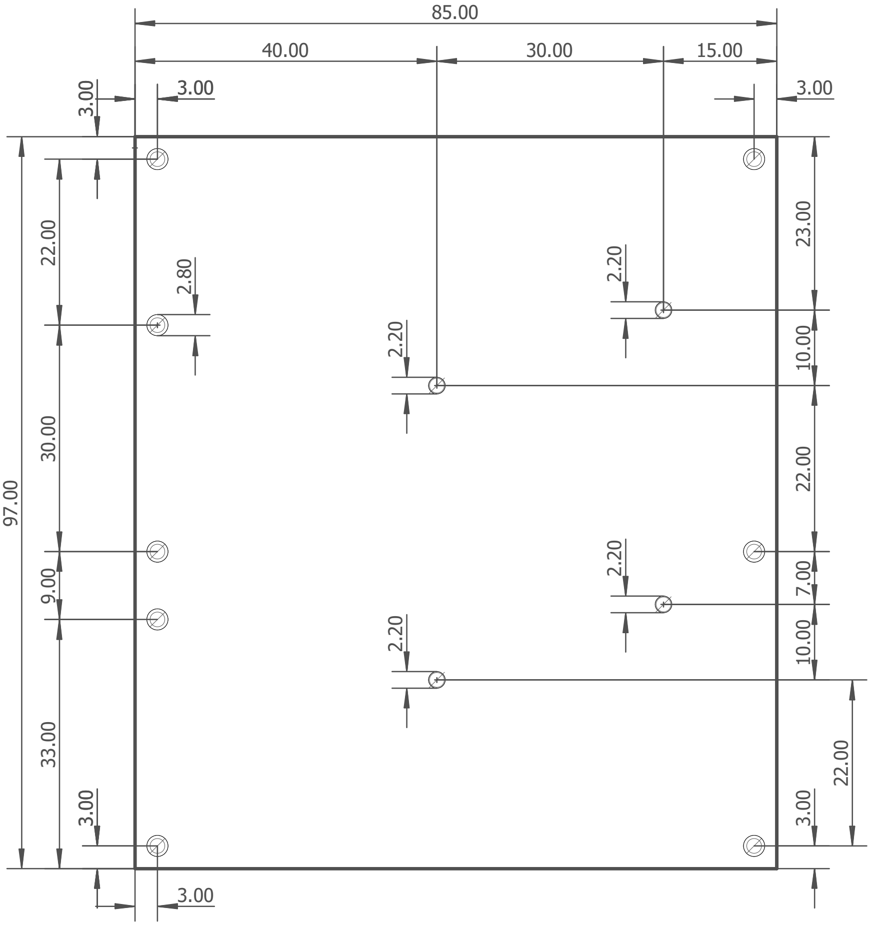
Drawn	26/04/2023	S. Sanchez	Samuel Sanchez
Revised			

DESIGN AND IMPLEMENTATION OF A POWER STAGE FOR DIGITAL COMMAND CONTROL (DCC) SYSTEMS WITH ENHANCED CURRENT MANAGEMENT AND PROTECTION FEATURES

Scale	Title
1:1	L6206D DRILLS

Page	5 of 5
Date	26/04/2023

NOTES
All measurements are in mm.
All holes near the edge are 2.8 mm
All inner holes are 2.2 mm



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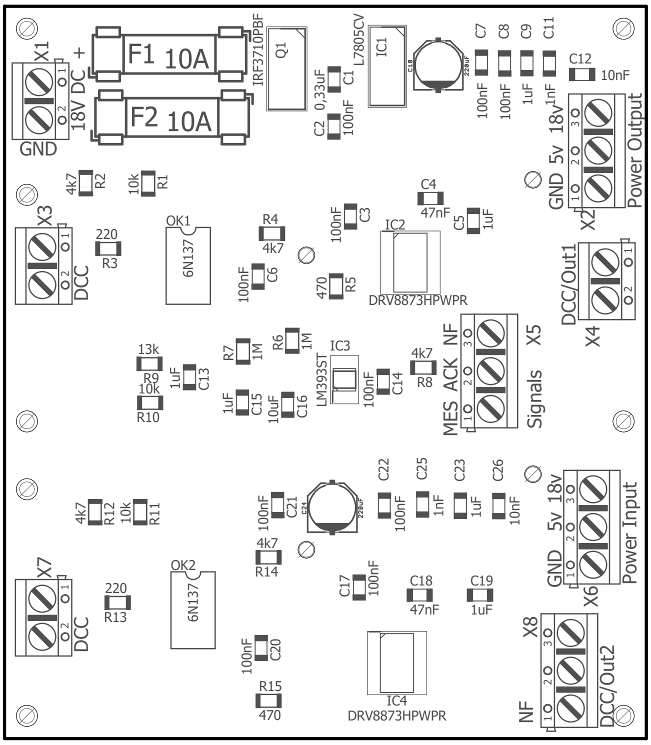
Scale	Title	Page	1 of 5
1:1	DRV8873H PCB AND HOLES MEASUREMENTS	Date	26/04/2023



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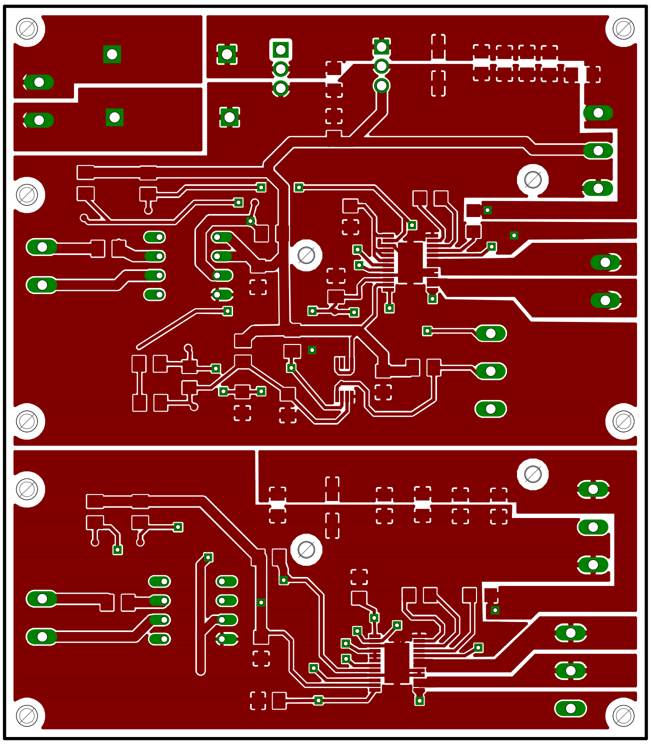
Drawn	26/04/2023	S. Sanchez	Samuel Sanchez
Revised			

DESIGN AND IMPLEMENTATION OF A POWER STAGE FOR DIGITAL COMMAND CONTROL (DCC) SYSTEMS WITH ENHANCED CURRENT MANAGEMENT AND PROTECTION FEATURES

Scale	Title	Page	2 of 5
1:1	DRV8873H SERIGRAPHY	Date	26/04/2023



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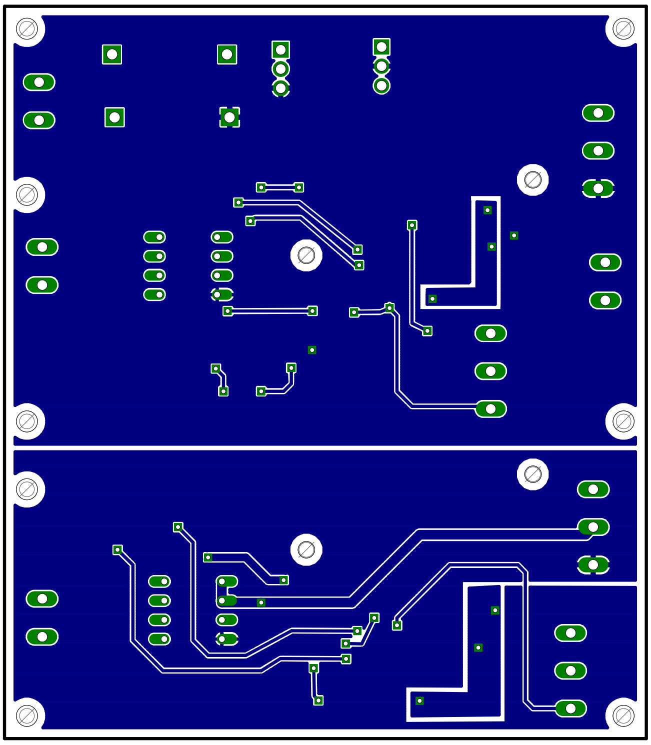
DESIGN AND IMPLEMENTATION OF A POWER STAGE FOR DIGITAL COMMAND CONTROL (DCC) SYSTEMS WITH ENHANCED CURRENT MANAGEMENT AND PROTECTION FEATURES

Scale	Title	Page	3 of 5
1:1	DRV8873H TOP NET	Date	26/04/2023



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Drawn	26/04/2023	S. Sanchez	Samuel Sanchez	
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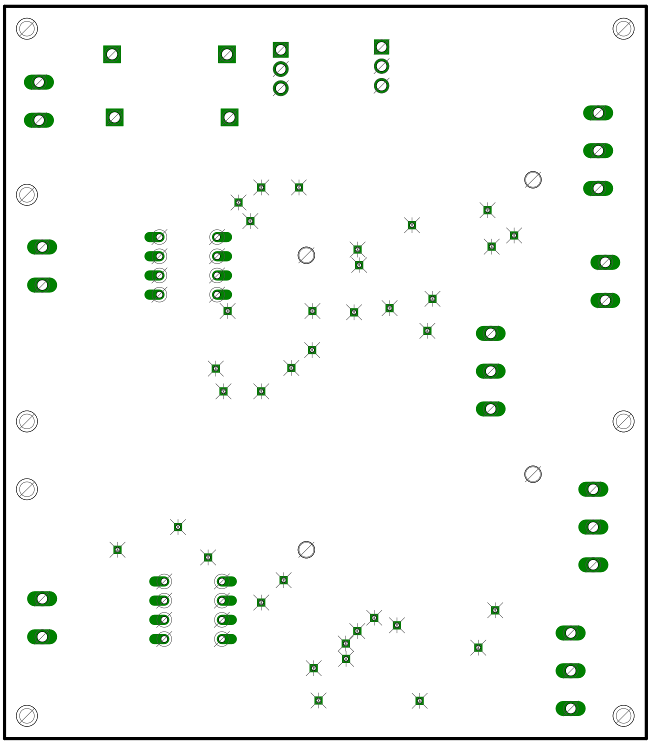
Scale	Title	Page	4 of 5
1:1	DRV8873H BOT NET	Date	26/04/2023



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Drawn	26/04/2023	S. Sanchez	Samuel Sanchez	
Revised				

Scale	Title	Page	5 of 5
1:1	DRV8873H DRILLS	Date	26/04/2023

3. Photos of the final assembly

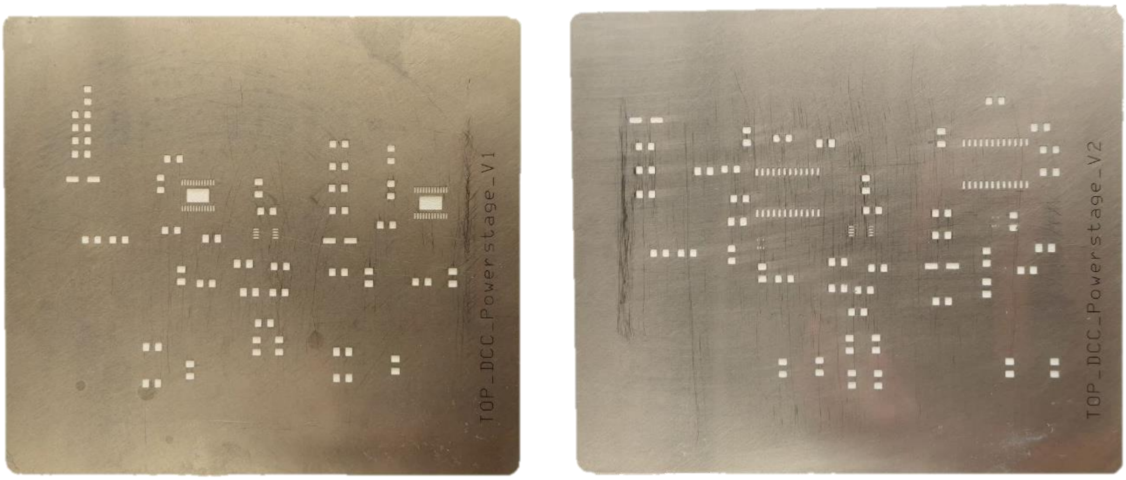


Figure 20 Solder Masks for each PCB (DRV8873H left and L6206D right)

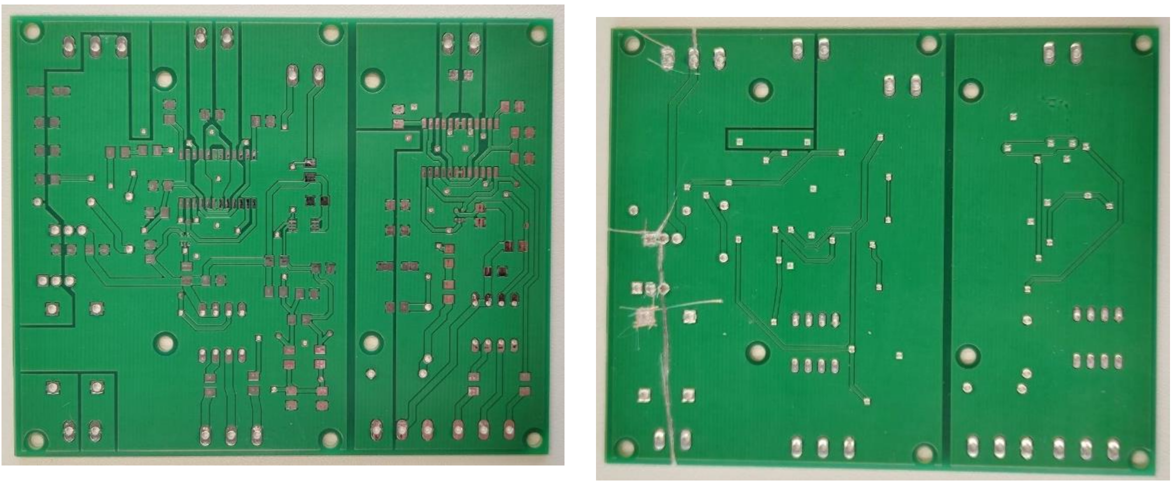


Figure 21 L6206D PCB (Top Layer left and Bot Layer right)

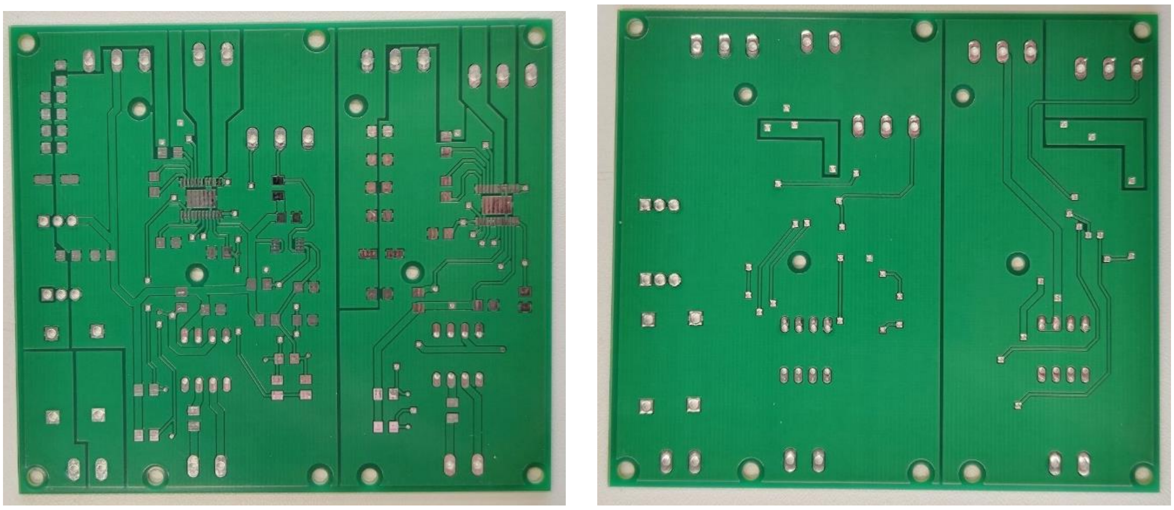


Figure 22 DRV8873H PCB (Top Layer left and Bot Layer right)

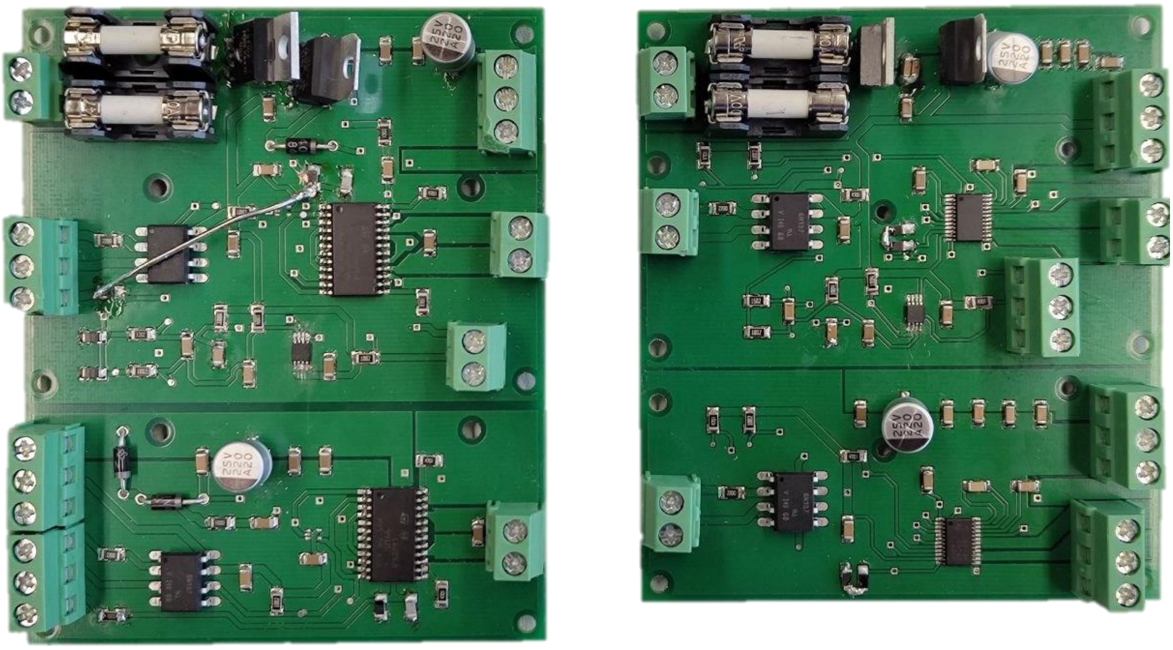
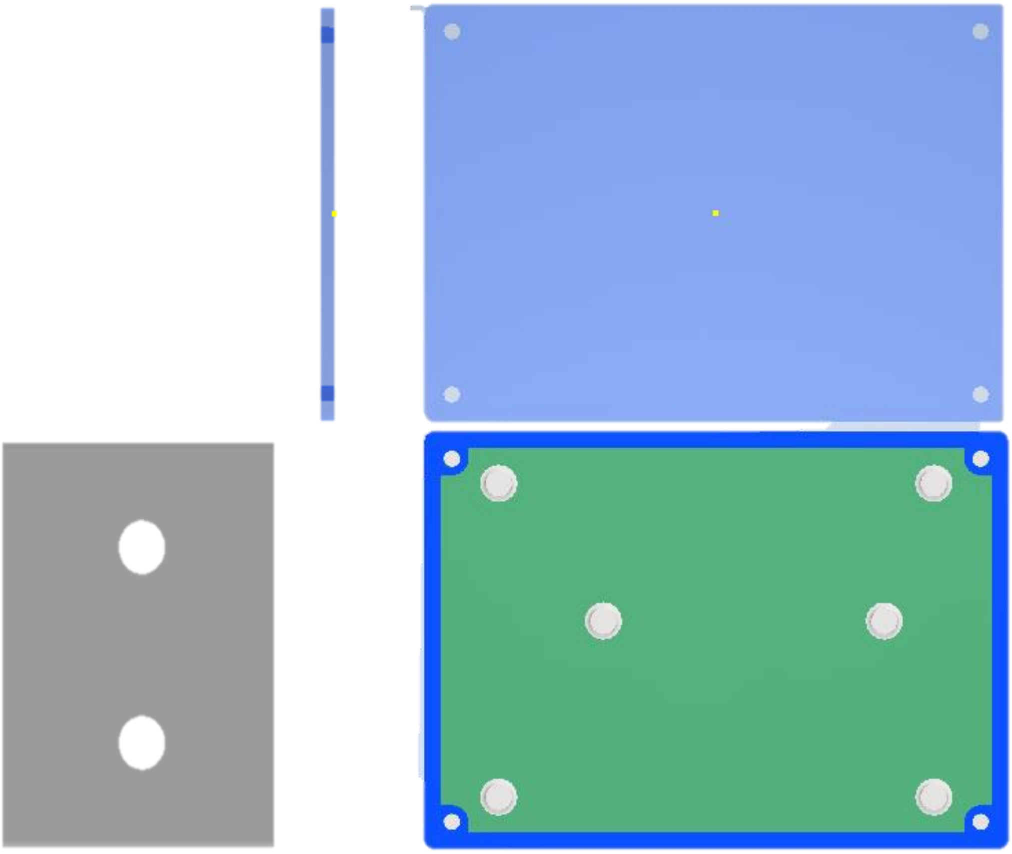
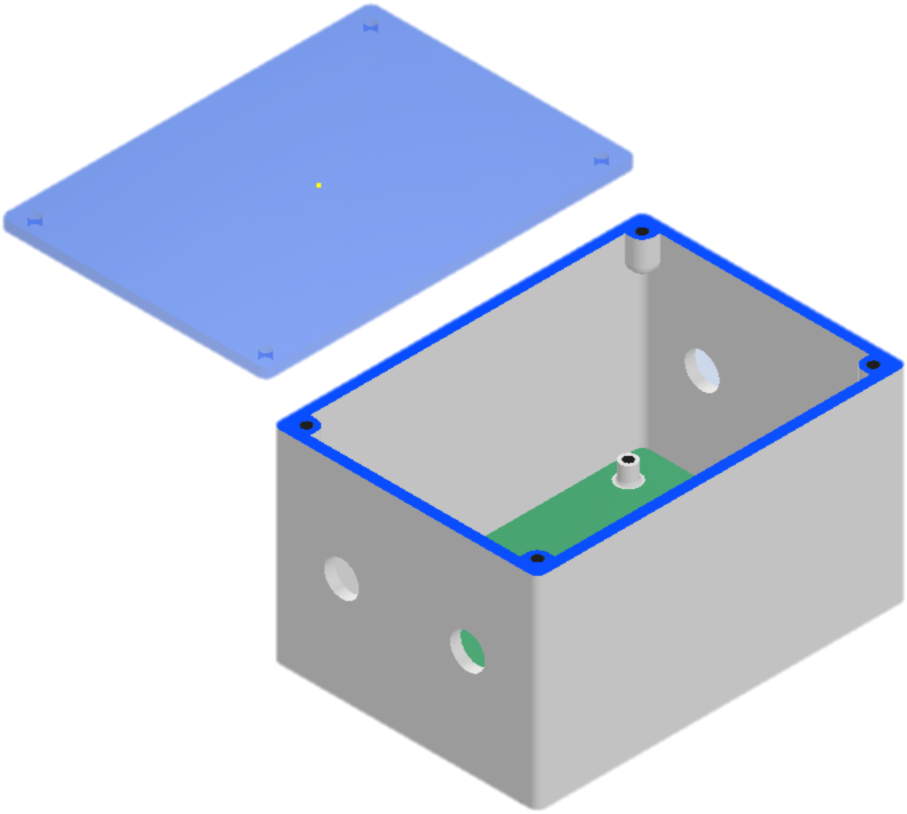


Figure 23 Assembled PCBs (L6206D left and DRV8873H right)

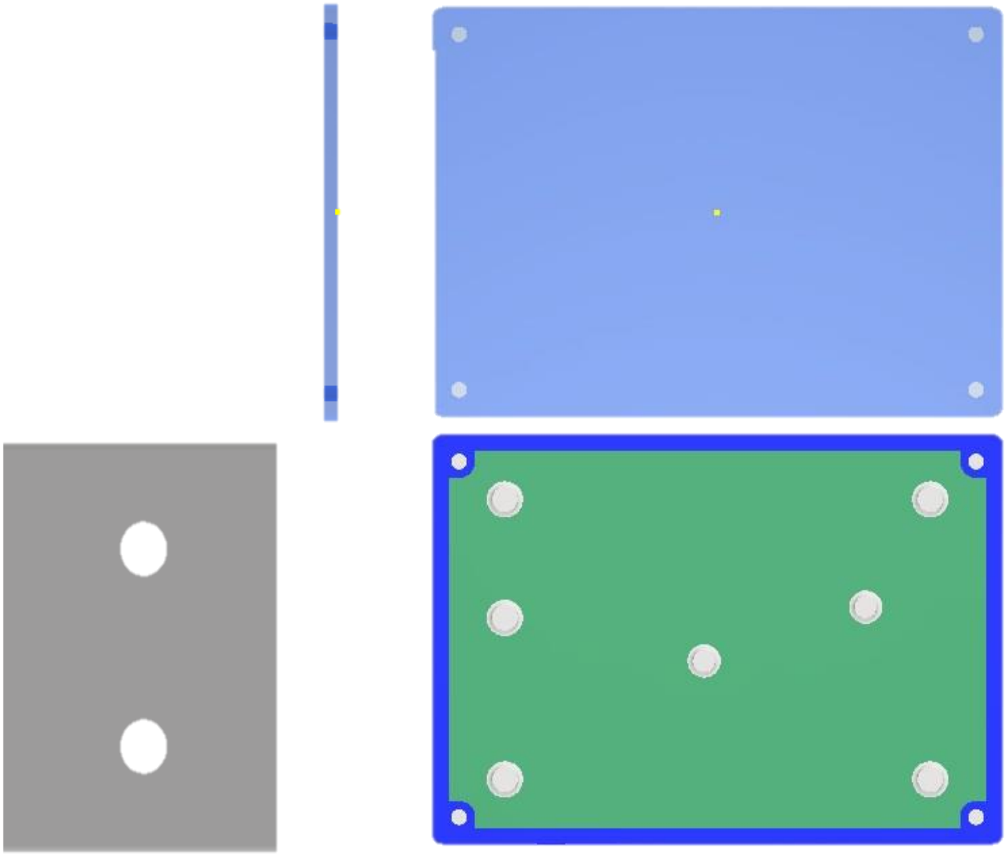
Appendix C: Cases for the PCBs

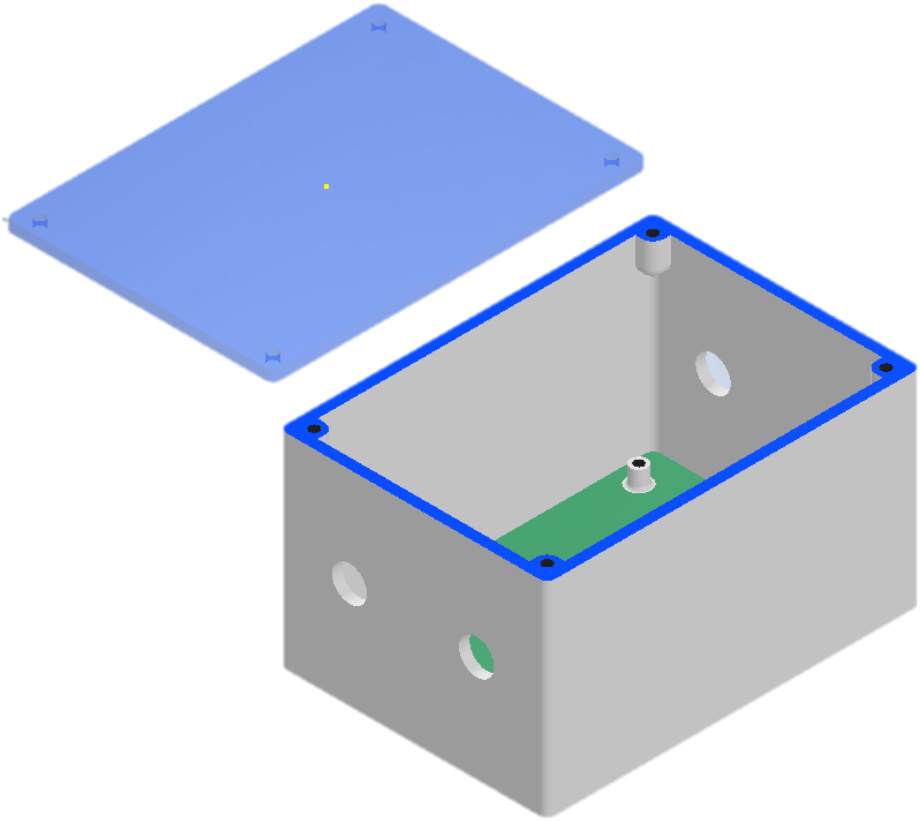
- **L6206D Case**





- **DRV8873H Case**





Appendix D: Bill of Materials

- **L6206 Bill of Materials**

Qty	Value	Device	Package	Description
1	0,33uF	C-EUC1206	C1206	CAPACITOR, European symbol
12	100nF	C-EUC1206	C1206	CAPACITOR, European symbol
2	220uF	C-POLAR-1206	1206-POLAR	100µF polarized capacitors
1	1uF	C-EUC1206	C1206	CAPACITOR, European symbol
4	10nF	C-EUC1206	C1206	CAPACITOR, European symbol
2	220nF	C-EUC1206	C1206	CAPACITOR, European symbol
2	4n7F	C-EUC1206	C1206	CAPACITOR, European symbol
2	10A	SHK20L	SHK20L	FUSE HOLDER 5 x 20 mm, SH contact, SHH1 Schukat, E1073 Buerklin
2	10A	Fuse	5 x 20 mm	FUSE 5 x 20 mm
4	10k	R-EU_M1206	M1206	RESISTOR, European symbol
2	0,8	R-EU_M1206	M1206	RESISTOR, European symbol
2	100	R-EU_M1206	M1206	RESISTOR, European symbol
1	13k	R-EU_M1206	M1206	RESISTOR, European symbol
2	1M	R-EU_M1206	M1206	RESISTOR, European symbol
2	220	R-EU_M1206	M1206	RESISTOR, European symbol
2	220k	R-EU_M1206	M1206	RESISTOR, European symbol
2	2k2	R-EU_M1206	M1206	RESISTOR, European symbol
4	4k7	R-EU_M1206	M1206	RESISTOR, European symbol
4	1N4004	1N4004	DO41-10	DIODE
2	6N137	6N137	DIL08	MOTOROLA OPTO COUPLER
2	74HC1G04	74HC1G04	SOT353	Single Inverter
1	IRF3710PBF	IRF3710PBF	TO220AB	N-channel MOSFET Transistor, 57 A, 100 V, 3-Pin TO-220AB
4	2 pin Connector	AK500/2	AK500/2	CONNECTOR
4	3 pin Connector	AK500/3	AK500/3	CONNECTOR
2	L6206D	L6206D	SOIC-24N	Full Bridge Motor Driver, 8 to 52V, 24-Pin SOIC
1	L7805CV	L7805CV	TO220AB	Single Linear Voltage Regulator, 1.5A 5 V, 3-Pin TO-220
1	LM393ST	LM393ST	8-Pin MSOP	Dual Comparator, CMOS/TTL O/P, 1.3us 2 36 V 8-Pin MSOP

- **DRV8873H Bill of Materials**

Qty	Value	Device	Package	Description
1	0,33uF	C-EUC1206	C1206	CAPACITOR, European symbol
10	100nF	C-EUC1206	C1206	CAPACITOR, European symbol
5	10nF	C-EUC1206	C1206	CAPACITOR, European symbol
2	1nF	C-EUC1206	C1206	CAPACITOR, European symbol
4	1uF	C-EUC1206	C1206	CAPACITOR, European symbol
2	47nF	C-EUC1206	C1206	CAPACITOR, European symbol
2	220uF	POLAR-1206	POLAR-1206	POL CAPACITOR, European symbol
3	10k	R-EU_M1206	M1206	RESISTOR, European symbol
1	13k	R-EU_M1206	M1206	RESISTOR, European symbol
2	1M	R-EU_M1206	M1206	RESISTOR, European symbol
2	220	R-EU_M1206	M1206	RESISTOR, European symbol
2	470	R-EU_M1206	M1206	RESISTOR, European symbol
5	4k7	R-EU_M1206	M1206	RESISTOR, European symbol
2	10A	SHK20L	SHK20L	FUSE HOLDER 5 x 20 mm, SH contact, SHH1 Schukat, E1073 Buerklin
2	10A	Fuse	5 x 20 mm	FUSE 5 x 20 mm
2	6N137	6N137	DIL08	MOTOROLA OPTO COUPLER
2	DRV8873HPWPR	DRV8873HPWPR	SOP65	Motor Controllers & Drivers 10A H-Bridge Motor Driver
1	IRF3710PBF	IRF3710PBF	TO220AB	N-channel MOSFET Transistor, 57 A, 100 V, 3-Pin TO-220AB
1	L7805CV	L7805CV	TO220AB	Single Linear Voltage Regulator, 1.5A 5 V, 3-Pin TO-220
1	LM393ST	LM393ST	8-Pin MSOP	Dual Comparator, CMOS/TTL O/P, 1.3us 2 36 V 8-Pin MSOP
4	2 pin Connector	AK500/2	AK500/2	CONNECTOR
4	3 pin Connector	AK500/3	AK500/3	CONNECTOR