Prototype of a 12-bit Digital to Analog Converter (DAC) Control System for Glassman High Voltage Supply Powering a 30 kV Electron Gun

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To accelerate electrons up to 30 keV, an electron gun at the basement of Physics Research Building uses a Glassman high voltage power supply which accepts a 0∼+10V control signal. This project aims to generate such control signal with high precision and stability, while being cost-effective, space-saving and remotely controllable, in an Internet-of-Things (IoT) approach that integrates a PC, a Raspberry Pi, integrated circuits and a printed circuit board (PCB). To date, the author has simulated the DAC-based control circuit in LTSpice, designed PCB schematics and footprints in KiCad, hand-soldered all surface-mount and through-hole components onto the PCB manufactured from OSH Park, programmed the Serial Peripheral Interface (SPI) communication between the DAC chip and the Raspberry Pi, and tested the system on an oscilloscope that shows a desired voltage can be generated but with imperfect noise performance. The reduction of noise will be further addressed in the second version of the PCB by implementing low-noise techniques.

I. INTRODUCTION

An electron gun is being installed at the basement of Physics Research Center building at the Univ. of Chicago with premade hardware pieces from Fermilab. In an ultra-high vacuum (UHV) gun pipe, electrons are thermally emitted from a high-temperature cathode, accelerated up to 30keV by a high-voltage plane, and magnetically focused by two downstream solenoids.

A control system for the electron gun was yet to be designed, but should handle the following modules:

- A vacuum and baking system
- A high voltage system
- A cathode
- Two solenoids

This summer, the author focused on controlling the high voltage system, though it could be generalized to other modules. The other modules will be briefly introduced before the high voltage system is elaborated.

To minimize beam loss, we plan to achieve a UHV in two stages: a roughing pump (1 atm to 10^{-7} torr), and an ion pump (10^{-5} to 10^{-9} torr). Since their operational ranges do not fully overlap, a control system needs to gauge the chamber pressure and regulate the pumps accordingly. Furthermore, a heater will be installed and controlled to bake off any residual gas embedded in the chamber walls.

A high-temperature cathode inside the gun pipe is used to thermally knock electrons off of a metal. A control system for its power supply needs to regulate the cathode temperature via an analog signal with a proportional—integral—derivative (PID) algorithm.

Two solenoids generate magnetic fields that focus the electron beam. A control system for their power supplies needs to regulate a high current but not necessarily a high voltage.

FIG. 1. A Glassman MK50N1.5 high voltage power supply

We use a Glassman model MK50N1.5 (Fig. 1) for supplying a high voltage up to 30 kV that accelerates electrons kicked off from the cathode. This model is negatively polarized, drives 0∼50 kV and 0∼1.5 mA, and may operate on remote voltage control via a 0∼+10 V signal. The output voltage accuracy is 1% of a setting plus 0.5% of rated voltage; the ripple is better than 0.03% RMS of rated voltage plus 0.5 V at full load. So at a 30 kV operation, the precision of the power supply itself is 0.1%. We should aim for a control signal with noise performance at least better than 0.1%. [1]

While an option remains to simply purchase a system-ready data-acquisition (DAQ) box that outputs a precise analog voltage with remote connectivity, the author decided to design a printed circuit board (PCB) hosting a DAC chip that would be remotely controlled by a Raspberry Pi, as it has the potential of being more cost- and space-efficient, beyond being a fun engineering challenge itself.

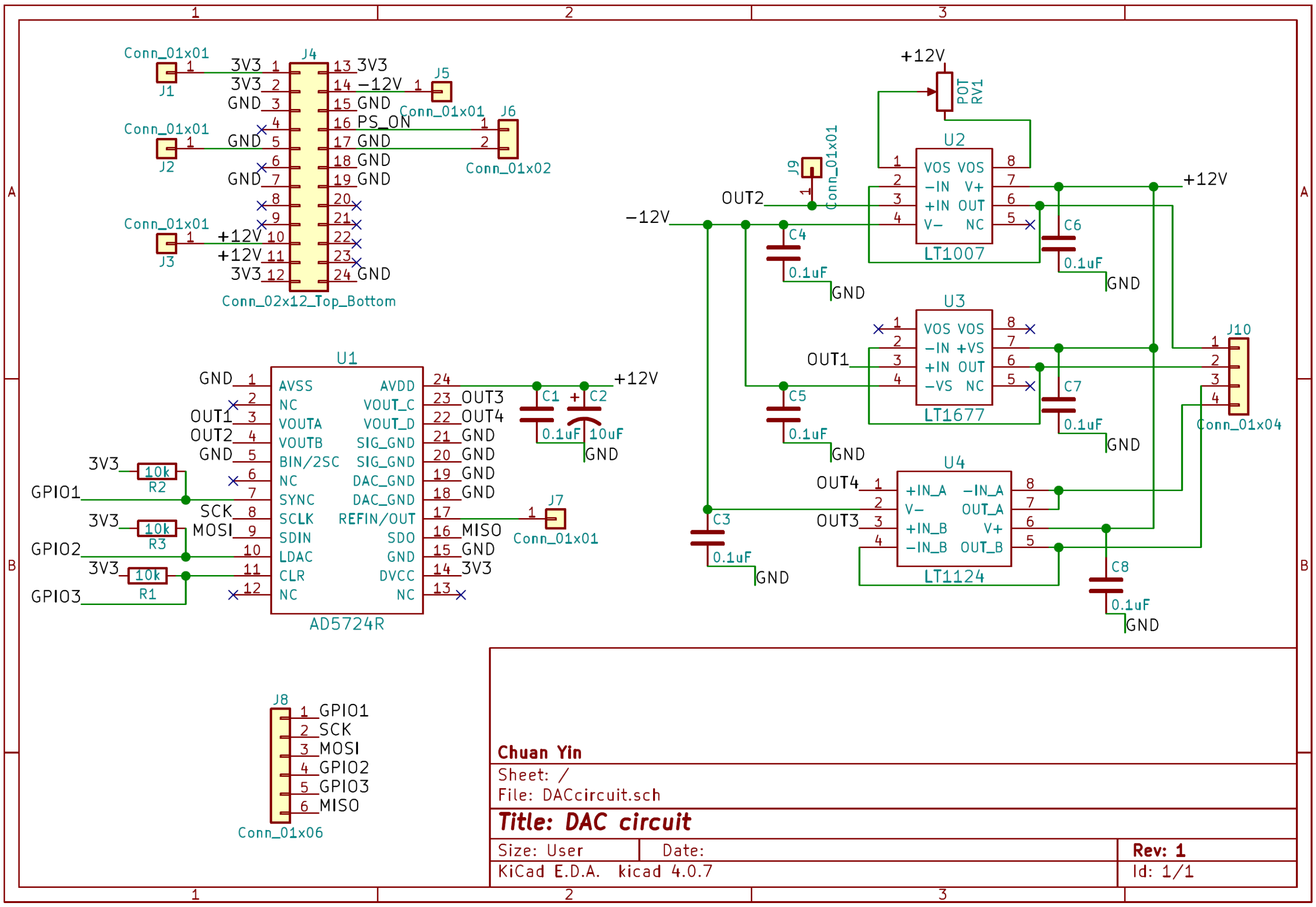


FIG. 2. Schematics for PCB v1: maroon denotes components; green denotes electrical connections; black denotes net names. Pins with the same net name are connected.

II. EXPERIMENTAL SET-UP

For a circuit to generate a 0∼10 V analog control signal for the Glassman high voltage power supply, essential building blocks include a power, a digital input, a DAC chip, and op-amps. For schematics see Fig. 2.

A 24-pin ATX (Advanced Technology eXtended) power supply is chosen because of its diverse output values: 3.3 V can power a digital circuit of the DAC (i.e. DVCC) and pulls-up active low input pins (i.e. SYNC, LDAC, CLR), +12 V can power an analog circuit of the DAC (i.e. AVDD) and positive circuits of the op-amps (i.e. V+), and -12 V can power negative circuits of the op-amps (i.e. V-). [5]

Digital inputs (J8 in the schematics) include a code to be converted into analog voltage and settings for the DAC, both of which come from a Raspberry Pi.

A DAC chip (U1 in the schematics) converts a digital code to an analog voltage. The AD5724R chip in particular has a 12-bit resolution and DNL error of ± 1 LSB maximum, so its precision is $2^{-12} = 0.02\%$ which is better than the 0.1% of the Glassman supply. Its output voltage range is software programmable and can be set to +10 V or +10.8 V, which is compatible with the required 0∼10V control signal, given rail-to-rail. Having 4-channel outputs would be useful should the chip be used in future to control four power supplies. The chip communicates with the Raspberry Pi via the Serial Peripheral Interface (SPI), a full duplex mode protocol using a master-slave architecture. Serial Clock (SCLK), Master Output Slave Input (MOSI) and Master Input Slave Output (MISO) pins on the DAC are all connected to the designated pins on the Raspberry Pi for standard SPI communication, whereas Load DAC (LDAC) pin on the DAC is connected to a General Purpose Input Output (GPIO) pin on the Raspberry Pi and acts like Slave Select (SS). Additionally, the chip has an excellent output noise spectral density of 320 nV/Hz measured at 10 kHz, and contains an integrated reference so that board design can be simplified without a voltage reference. [5]

Two single-channel (LT1007, LT1677) and one double-channel (LT1124) op-amp are connected to the four DAC outputs in a voltage follower configuration, sourcing enough current to drive the Glassman power supply at the DAC output voltage. The op-amps are all low-noise, but differ in channel-counts and whether one has input offset voltage adjustment (pin 1 and 8 on U2). [6] [7] [8]

Other components in the design include debugging holes, 0.1 μF and 10 μF bypass capacitors in front of all power supplies to block high-frequency noise especially those above 1 MHz, and 10 kΩ pull-up resistors for tying active low input pins to HIGH until a GPIO goes LOW, as the pins should not be left floating.

Here is a table of components used in PCB v1:

Surface-Mount Components	**DigiKey Part Number**
ATX PWR CONN 1 BDLK 24 POS	A127799-ND
CAP ALUM 10UF 20% 16V SMD	493-2099-1-ND
CAP ALUM 10UF 20% 35V SMD	PCE3948CT-ND
RES SMD 10K OHM 0.5% 1/10W 0805	RR12P10.0KDCT-ND
IC OPAMP GP 12.5MHZ 8SO	LT1124IS8#PBF-ND
IC DAC 12BIT DSP/SRL 24TSSOP	AD5724RBREZ-REEL7CT-ND
IC OPAMP GP 8MHZ 8SO	LT1007CS8#PBF-ND
IC OPAMP GP 7.2MHZ RRO 8SO	LT1677IS8#PBF-ND
TRIMMER 10K OHM 0.1W J	TC33X-103ECT-ND

Through-Hole Components	**DigiKey Part Number**
CONN IC DIP SOCKET 8POS TIN	AE9986-ND
IC OPAMP GP 7.2MHZ RRO 8DIP	LT1677CN8#PBF-ND
CAP ALUM 10UF 20% 25V RADIAL	P19522CT-ND
IC OPAMP GP 12.5MHZ 8DIP	LT1124CN8#PBF-ND
IC OPAMP GP 8MHZ 8DIP	LT1007ACN8#PBF-ND

As for laying out the PCB footprint (Fig. 3-5), we decided on a double-layer board—top layer as signal plane and bottom layer as ground plane—a more economical yet wiring-wise difficult choice than a four-layer board. In consideration that a ground plane should have very low resistance and inductance to serve as a return path of signals, the design minimizes crossovers that puncture the ground plane (i.e. ground vias). In a mixed-signal PCB design, a digital circuitry is noisy due to switching current spikes, yet more immune to noise, whereas an analog circuitry is very vulnerable to noise on both power supplies and grounds. To prevent digital noise from deteriorating analog performance, digital return currents should not pass through analog circuitries. Thus the ATX power supply (unfiltered, noisy) is placed at the bottom, the Raspberry Pi connector (digital) and DAC inputs (digital) on the middle, and DAC outputs (analog) and op-amps (analog) at the top. Traces for power are thicker to reduce resistance and therefore voltage drop. Bypass capacitors are placed as close to power pins as possible to minimize inductive noise. [2]

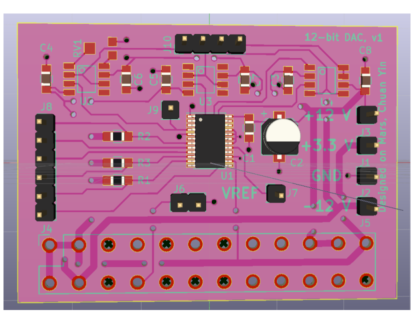


FIG. 3. Computer graphics of the PCB with mounted components, generated by KiCad 3D viewer.

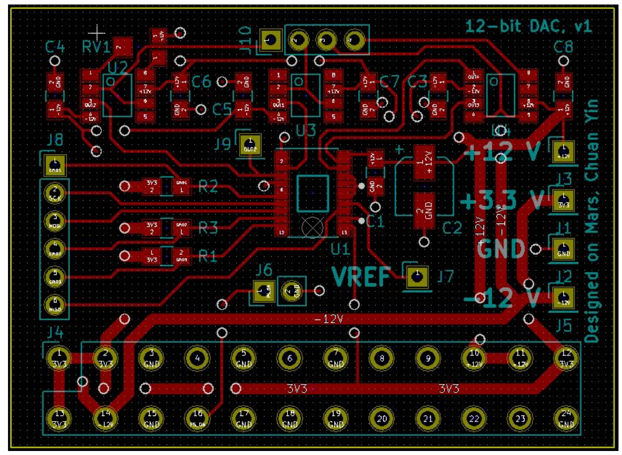


FIG. 4. KiCad footprint of the front side of the PCB: red indicates copper traces for electrical connection and copper pads for surface-mount technology (SMT) components; yellow indicates copper pads for through-hole components thus exist on both sides; blue indicates front silkscreen which does not play any electrical importance; the white circles are vias that electrically connect the two layers. Front soldermask is not shown in this picture.

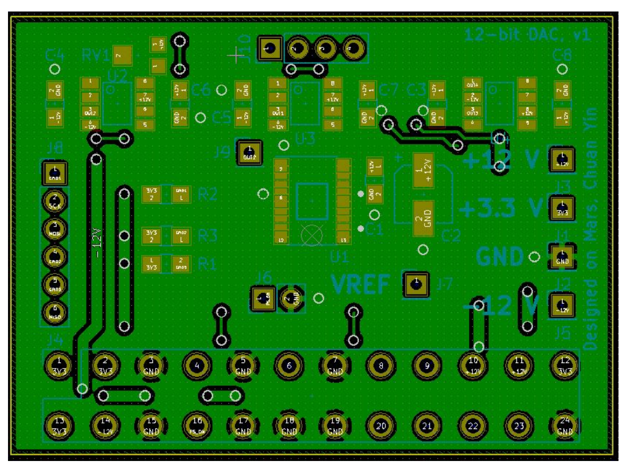


FIG. 5. KiCad footprint of the back side of the PCB. Only copper pads for through-hole components are exposed. One can see that all paired vias on the front side are connected on the back side, and isolated with a clearance from the rest of the back (ground) plane.

III. RESULTS

After receiving the bare PCB manufactured from OSH Park (Fig. 6), the author hand-soldered all SMT and through-hole components onto the board using a Hakko FX-888D soldering station, a normal-sized soldering tip, flux, and a thin solder wire, then visually examined all soldering connections under a microscope at home (for example Fig. 7).

However, to the author's surprise, upon power-on testing (Fig. 8), in less than a second, the board was fried and smoking. By checking electrical connections on the bare board using a multimeter, which should have been done in the first place, we found that the +12 V power is shorted to the ground plane, causing the trace and the laminated layer to heat up immensely until broken and smoking! (Fig. 9(a))

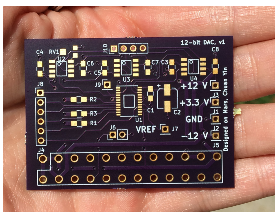


FIG. 6. Manufactured bare board: dimension as small as 55 mm by 40 mm. The author's hand shown as size reference.

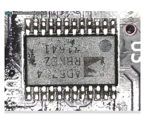


FIG. 7. A microscope picture viewing the DAC chip (7.8 mm by 4.4 mm) soldered onto the board, as an example of checking good electrical connection.

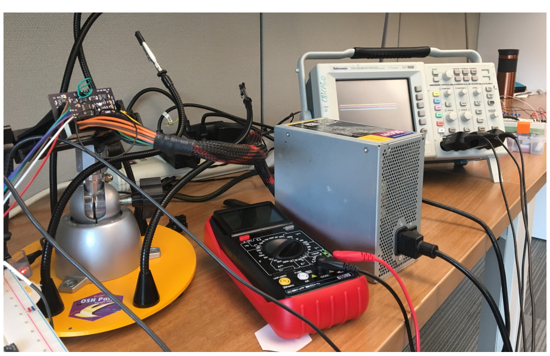
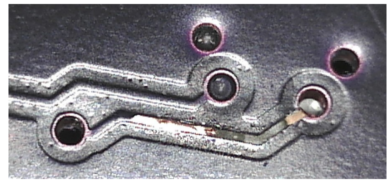
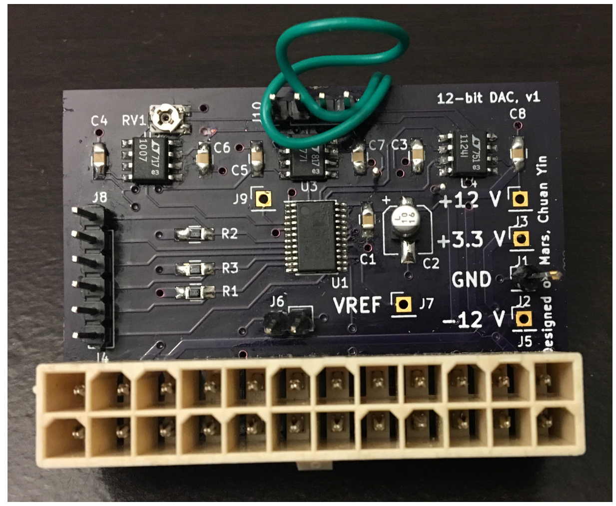


FIG. 8. Testing setup of the first control system contains a PCB with components soldered on, a Raspberry Pi connected to WiFi, an ATX power supply, a multimeter, an oscilloscope, and a panavise.



(a)Microscope picture showing broken copper trace and disappeared solder mask after the PCB was fried.

(b)Back: a jumper wire connecting two broken vias.



(c)Front: a trace slightly above C6 causing the short was cut.

FIG. 9. A close look at the fried board and how we fixed it.

The mistake was in fact caused by not sending the latest version of KiCad footprint to the manufacturer, where the ground plane zone has been refilled. In the old version, however, a +12 V via was drilled and electrically connected to the ground plane directly without any clearance. To fix the PCB, we cut a trace causing the short to disconnect the two planes (Fig. 9(c)), and used a jumper wire to bridge the two disconnected vias (Fig. 9(b)).

On the software level, the DAC chip needs to communicate with the Raspberry Pi via SPI. This can be done in C++ programming by using wiringPi libraries and referencing closely the datasheet of AD5724R.

```
#include <iostream>
#include <errno.h>
#include <wiringPi.h>
#include <wiringPiSPI.h>
#include <unistd.h>
#include <stdio.h>

using namespace std;
static const int CHANNEL = 0;
// wiringPiSPISetup write to buffer and read
// It outputs the length of buffer in bytes
// g++ -Wall -o dac_spi dac_spi.cpp -lwiringPi
```

```
int main()
{
    wiringPiSetup ();
    pinMode (2, OUTPUT);
    pinMode (3, OUTPUT);
    digitalWrite (2, HIGH); // LDAC
    digitalWrite (3, LOW);  // CLR

    wiringPiSPISetup(CHANNEL, 5000); // kHz
    cout << "Initialized" << endl;

    // Write to the power control register:
    // Power-up all DACs and internal reference
    unsigned char refout[3]={0x10, 0x00, 0x1F};
    wiringPiSPIDataRW(CHANNEL, refout, 3);

    // Write to the output range select register:
    // Set DACs range to +10V
    unsigned char setRange[3]={0x0C, 0x00, 0x01};
    wiringPiSPIDataRW (CHANNEL, setRange, 3);

    // Write to the DAC register:
    // Set DACB output to 1V
    unsigned char setOut[3]={0x01, 0x10, 0x00};
    wiringPiSPIDataRW(CHANNEL, setOut, 3);

    // Write to the control register:
    // Updates the DAC register and DAC output
    unsigned char updateDac[3]={0x1D, 0x00, 0x00};
    wiringPiSPIDataRW(CHANNEL, updateDac, 3);
}
```

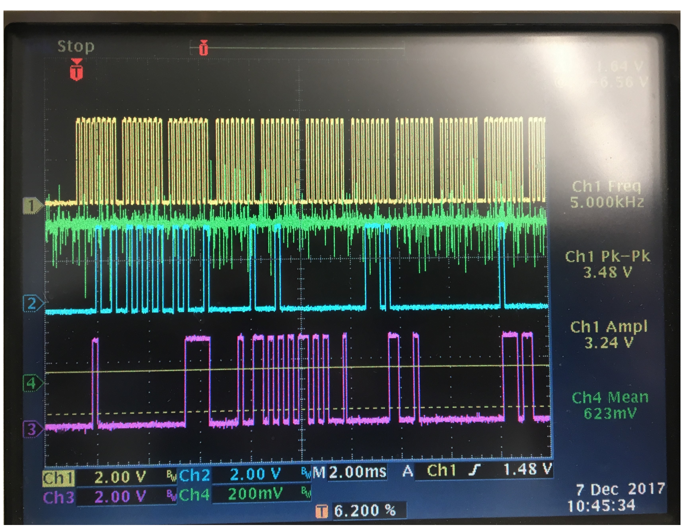


FIG. 10. An oscilloscope capture showing successful SPI connection: Ch1 SCLK, Ch2 MOSI, Ch3 MISO, Ch4 DAC output. LOW 0 V HIGH 3.3 V. Both MOSI and MISO update at each clock cycle of the SCLK on different edges. Data—hexadecimals in the code—is written to AD5724R chip in a 24-bit word format (i.e. three bytes). MISO follows MOSI after three sets of clocks, as it should. Ch4 output is noisy.

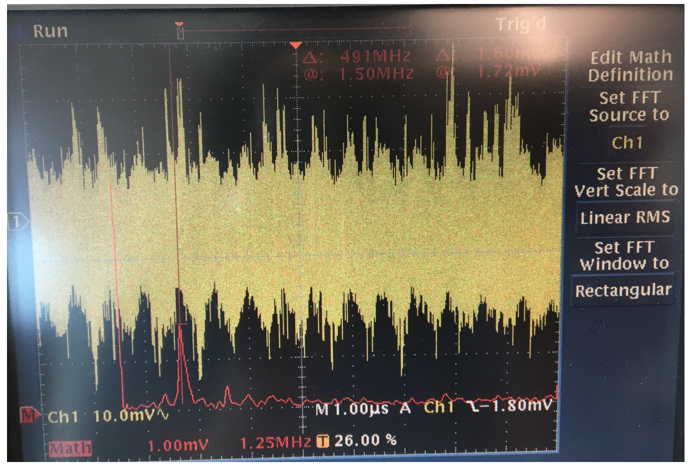


FIG. 11. An oscilloscope of FFT of the ATX power supply itself (AC-coupled), showing a fundamental component of the switching noise is 1.25 MHz.

As seen in Fig. 10, the DAC output is very noisy. To diagnose the reason, we used an oscilloscope to perform a fast Fourier transform (FFT) on the ATX 3.3 V output shown in Fig. 11. The noise has a fundamental frequency of 1.25 MHz, which is likely due to the switching noise of the ATX power supply.

IV. DISCUSSION

The goal for the second design is to reduce noise. An immediate fix is to place two bypass capacitors, 0.1μF and 10μF ceramic, in front of the digital power of the DAC (DVCC) to block high-frequency noise from entering the DAC or the ground plane. Additionally, we plan to use a precision linear power supply with voltage range of 30 V instead of a switched-mode power supply (SMPS) that an ATX is, to eliminate switching noise. The author intends to set the supply voltage at 15V, and use two low-dropout (LDO) linear regulators (NCV8674 and MCP1754) to obtain fixed outputs 12 V and 3.3 V. There is no need of -12 V for unipolar operation. [10] [9]

The author plans to design a four-layer board as it reduces the number of track crossing thus achieves a better ground plane, while also simplifies designing process. The four layers from top to bottom will be: signal, power, ground, signal, as the signal layers needs components to be soldered onto. For a multi-layer PCB that has both analog and digital circuitry, whether to have a shared ground plane or to have separate ground planes is a debated topic. [3] [2] [4]

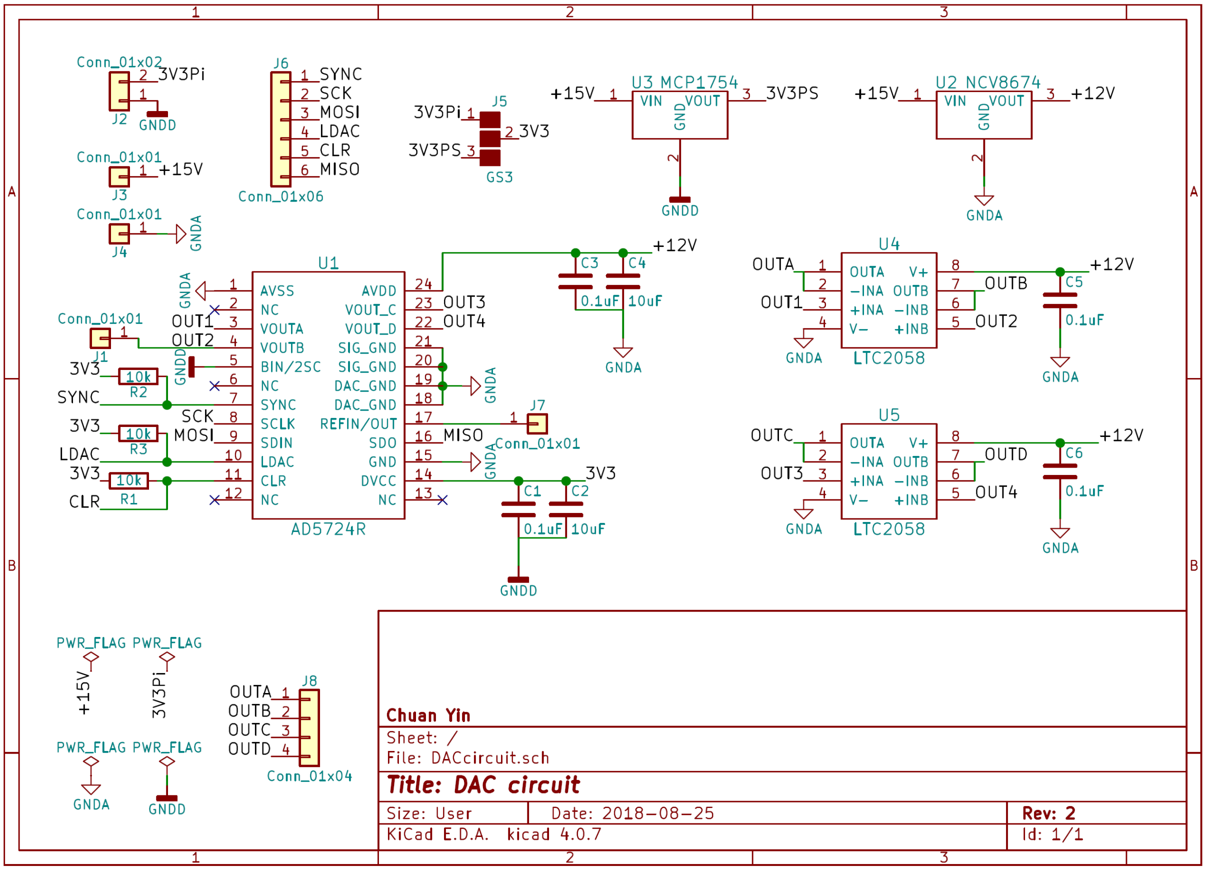


FIG. 12. Schematics for PCB v2.

V. CONCLUSIONS

This project concerns building an electronic system to generate a precise 0∼10 V control signal for Glassman high voltage power supply. The architecture of the system is that a computer remotely accesses a Raspberry Pi, the Raspberry Pi sends a digital code to a DAC chip hosted on a PCB via the SPI protocol, and the DAC with an op-amp circuit produces the precise output voltage that can drive Glassman. So far, the author has designed, mounted, and tested version 1 of the PCB, and written software for the SPI communication. Better data needs to be taken and analyzed for the DAC output. The noise performance of the DAC output will be addressed in version 2 design.

VI. ACKNOWLEDGEMENTS

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