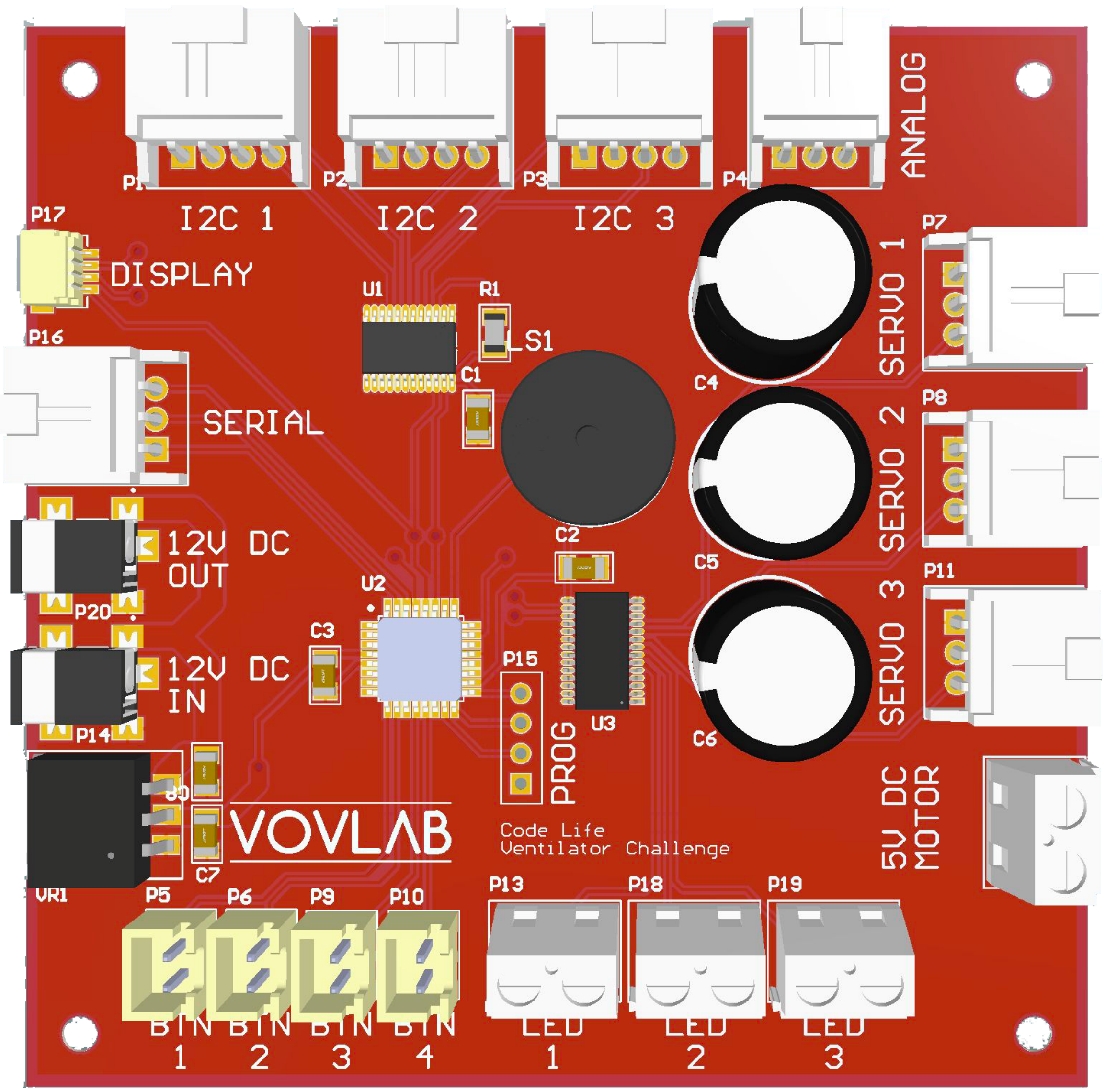
Circuit Design



Designed By

VOVLAB

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Introduction

The prototype allows us to provide proof-of-concept functionality with the required sensors and actuators. To make sure the product survives real-world usage in the medical field, it is necessary to design a PCB that includes all necessary components (microcontroller, capacitors, resistors, connectors, etc.), and that this board meets industry standards as well as mechanical and electrical requirements.

VOVLAB Inc., an award-winning startup that provides custom IoT solutions, has agreed to join the Code Life Ventilator Challenge by designing the PCB and delivering related open-source schematics, bill of materials, layer footprints, 3D renderings and necessary documentation and instructions to facilitate manufacturing and assembly of the PCB. VOVLAB has also taken care of thinking over the overall electrical requirements of the final product.

External Components

A microcontroller board electronically controls the logic of sensors and actuators. It is necessary to place some components directly on the main board, but others need to be positioned further away from the PCB. For prototyping purposes, particular devices were chosen to execute the proof-of-concept, but the following is a list of external components we recommend for the final product design.

Sensors

Temperature, humidity and pressure sensors

To simplify the microcontroller board circuitry, we opted for a BME280-based breakout board that integrates voltage conversion circuitry to allow electrical logic compatibility with the Atmega328P running at 5V:

https://www.digikey.ca/products/en/development-boards-kits-programmers/evaluation-boards-sensors/795?k=adafruit%202652

Oxygen sensor

The SeeedStudio Grove-Gas (O2) electrochemical sensor creates resistance in a circuit, depending on oxygen concentration in the air. A reference voltage is applied and calibration must be done before calculating oxygen concentration based on the voltage that is read on the analog input (voltage being affected by resistance). Even if this particular sensor uses a Grove connector, we chose to integrate a universal header connector on the PCB to allow different types of analog sensors, in case we need to use another oxygen sensor. Grove-to-header cables are widely available as well.

https://www.digikey.ca/product-detail/en/seeed-technology-co-ltd/101020002/1597-1115-ND/5482593

https://www.seeedstudio.com/Grove-4-pin-Female-Jumper-to-Grove-4-pin-Conversion-Cable-5-PCs-per-PAck.html?fbclid=IwAR28QvMxfuXKd4s5sgFO3V6tv3eefkBmzx-AuEn_ZU-ZajhoS5PwOBVMf3E

Motors

Servo motors

MG996R servo motors were chosen as they are widely available and provide plenty of torque to open and close valves. This is why they have a somewhat high current drain (see *Electrical Requirements* section below). They are easily programmable with PWM. Because of the torque involved, it is recommended to purchase a kit that includes metal gears, such as this one:

https://www.amazon.ca/-/fr/Mg996r-Couple-num%C3%A9rique-H%C3%A9licopt%C3%A8re-Voiture/dp/B0716V3WNH/

DC motor

The DC motor serves one purpose: spin blades to create constant airflow. This motor does not need high torque but needs to spin at a very high RPM rate. Our selection was based on this criteria, as well as low current consumption and availability. Because it does not need to change direction or speed, we opted for a 5V DC brush motor without driver for simplicity and low cost. It will be connected directly to a regulated 5V output coming from the microcontroller board. This has also affected our decision to use a high amperage regulator on the PCB. The NMB M1N10FB11G motor is easily available at Digi-Key:

https://www.digikey.ca/product-detail/en/nmb-technologies-corporation/M1N10FB11G/P14354-ND/2417078

Interfaces

OLED display

OLED displays have the advantage of being very readable because each pixel is self-illuminated and does not rely on a backlight. They also consume less energy, but that comes at a higher cost. For this reason, we chose to incorporate a 1.3-inch diagonal display designed by Adafruit. Even with its small dimensions, it remains highly useful, not only because of its readability but also because of the 128x64 resolution that allows it to fit in a lot of information. Small, yet crisp literals are created with the help of widely available libraries. The Adafruit board also incorporates the I2C protocol via a Qwiic connector which simplifies connectivity to the microcontroller board:

https://www.digikey.ca/product-detail/en/adafruit-industries-llc/938/1528-1512-ND/5774238

https://www.digikey.ca/product-detail/en/adafruit-industries-llc/4210/1528-4210-ND/10230021

Buttons

In our final design, it would be appropriate to contain all the electronics in a proper housing to protect the electronics. By doing this, however, we will need to route the electronics to the surface of the enclosure. This requires us to utilize external Buttons that will need to be wired to our circuit board. The standard termination for these buttons is 0.11” quick-connect leads. These can be connected to our PCB using adapters to fit into the JST-XH housing.

https://www.digikey.ca/product-detail/en/e-switch/PV1H240BB/EG5277-ND/5308985

https://www.adafruit.com/product/1152

LEDs

Similar to the buttons, LEDs will have to wire outside of the board. The following LEDs were selected for their low cost, and being compatible with 5V. Three different colours were used to provide an easier understanding of their significance: Green, Red, and Amber. These LEDs have bare 24 AWG wires as terminations, so we have added screw terminals to properly secure them.

https://www.digikey.ca/product-detail/en/visual-communications-company-vcc/5102H1-5V/L10021-ND/59906

https://www.digikey.ca/product-detail/en/visual-communications-company-vcc/5102H5-5V/L10025-ND/59913

https://www.digikey.ca/product-detail/en/visual-communications-company-vcc/5102H3-5V/L10023-ND/59909

Power

UPS

Please refer to the *Electrical Requirements* section below.

Power Supply

Please refer to the *Electrical Requirements* section below.

Electrical Requirements

The power requirements of the Challenge specify that the complete system must operate on mains (110V-240V), as well as on battery for at least 180 minutes (3 hours). Although it was not explicitly specified, it was understood that the system must automatically switch over to battery if ever mains power fails. This is the typical behaviour of a UPS (uninterruptible power supply). To decide which UPS might meet the requirements, overall power consumption was approximated and power rating was chosen to provide an adequate buffer, considering some equipment might be PFC (power factor corrected), and some not. Here is the list of requirements for the UPS:

1. Power rating to run all components simultaneously at any time (W)
2. Battery capacity to run 180 minutes (Ah) without mains power
3. Automatic transfer time fast enough
4. Non-hazardous battery technology

Power Rating and Capacity

To maximize portability, only critical components were chosen to be powered by the UPS. To determine the appropriate power rating, total power consumption of these components was calculated in a worst-case scenario fashion.

These components include :

- Microcontroller board
- Servo motors
- DC motor
- OLED display
- Environmental and oxygen sensors
- Raspberry Pi 3B
- 10.1-inch touch screen

Microcontroller board

The Atmega328P microcontroller consumes, on average, 65mA @ 5V when using its internal 8 Mhz oscillator. Each LED consumes 15mA, and the 5V regulator operates at a maximum of 10mA. The PWM controller has a maximum operating current of 10mA @ 5V, while other discrete components and ICs such as the I2C multiplexer (80uA) consume negligible current.

Power consumption = 130mA @ 5V = 0.65W

Servo motors

Since only one MG996R servo motor may run at a time, we calculate power consumption based on a single motor running without interruption, at its maximum forward current rating.

Power consumption = 900mA @ 6V = 5.4W

DC motor

The DC motor used for air compression has a rated load current of 145mA @ 5V, with a rated load speed of 13850RPM. Because it must operate full-time and does not need speed nor direction control, the motor will source its power directly from the regulated 5V output of the microcontroller board.

Power consumption = 145mA @ 5V = 0.725W

OLED display

The OLED display board consumes an average of 20mA @ 3.3Vm which totals to 0.066W. We'll round this number up.

Power consumption = 40mA @ 3.3V = 0.132W

Sensors

The BME280 sensors consume negligible current (in the order of uA), as well as the ME2-O2 oxygen sensor because of its electrochemical characteristic. The total power consumption contingency buffer will take those into account.

Piezo buzzer

The CPI-137-83T piezo buzzer will only be activated when there is an alarm situation. It consumes 10mA @ 5V. Even if it were running all the time, it would only add 0.05W to the total power consumption, so we won't consider it in our calculations.

Raspberry Pi and 10.1-inch Touch Screen

The 10.1-inch touch screen current consumption is rated at 5W. The specs do not explicitly mention if the power rating includes the Raspberry Pi that attaches to it, so we add the average current consumption of a Raspberry Pi (with HDMI enabled) of 3.75W. The Pi attaches to the screen via its main board USB port.

Power consumption = 5W + 3.75W = 8.75W

Conclusion

The total power needed totals 15.59W, which accounts to 1.3A @ 12 V. It is common practise to add a contingency buffer of 25 % = **19.6W** or **1.6A @ 12V**.

To be able to provide this power for 180 minutes (3 hours), we need a 12V battery that has at least **4.86Ah capacity**.

Automatic Transfer Switch

When using computer equipment with UPS protection, an important factor to evaluate is transfer tolerance when switching from mains to battery power. When using an "off-line" or a "standby" UPS, we must consider the automatic transfer switch time, which may take anywhere between 8 to 40ms, and make sure it is smaller than the system's hold time, ie. the time the system can operate before browning out, due to voltage dropping from lack of power source:

hold time = (operating voltage - brownout voltage) * capacitance / operating current

In our case, because the essential functionality is provided by a microcontroller board (and not the Raspberry Pi), a "reboot" caused by a brownout lasting only a few milliseconds will have practically no effect on logic or mechanical actions, as the software will be loaded almost instantly, resetting all actuators. We will not take into account the transfer time in our UPS selection.

Battery Technology

It is imperative that the UPS battery must be safe, especially in a medical environment. We must exclude traditional lead-acid based batteries and opt for AGM or gel batteries instead. Ideally, lithium-ion batteries would be better, provided it has BMS protection against over-discharge, over-charge, etc. The cost of lithium batteries is higher than lead-acid AGM or gel, but they weigh at least half as much.

UPS

There exists a plethora of UPS devices, and most of them deliver high power ratings to accommodate PCs, servers, etc. but short runtimes on battery (5-10 minutes typical), as they are designed to shut down the attached equipment safely during power outages. Our need is particular. We do not require a high power rating (approximately 20W) for all our electrical equipment, but we need a relatively long runtime (180 minutes). Usually, to get long runtimes, one must purchase a UPS that has a high power rating. We have finally found a UPS designed specifically for low power devices that need to run for long periods of time during power outages, such as routers, modems, etc.

This UPS is the APC Back-UPS Connect Network UPS (CP12142LI):

- Input/output voltage: 12V
- Input current: 3.5A
- Output current: 3.2A
- Output power capacity: 38W
- Battery technology: Lithium-ion
- BMS protection: yes
- Battery capacity: 19500mAh
- Runtime @ 20W: 6.6 hours
- Net weight: 1.65lbs
- Connectors: DC barrel 2.5mm (Vin and Vout)
- Cable: 8-inch DC barrel cable included

With its 19.5Ah battery capacity, 38W power capacity, Lithium-ion battery technology and ultra-low weight, size and cost, this UPS fits our needs perfectly.

Power Supply

A 110-240VAC to 12VDC 5A power supply is needed to provide power from mains to the UPS, and the microcontroller board will be connected to the UPS via the cable included with the UPS. For this reason, the microcontroller board is designed with a 12V regulator and provides another DC barrel connector to power the 12VDC 10.1-inch touch screen and Raspberry Pi.

https://www.amazon.ca/-/fr/adaptateur-dalimentation-Commutation-Transformateur-vid%C3%A9osurveillance/dp/B07J5HTBF1/

PCB Design

Advantages

While breadboard or hand-soldered designs offer a quick and easy way to prototype a design, it is not acceptable for mass-production. One of the reasons is that the assembly processes involve following a very cryptic wiring diagram and manually performing all the connexions.

Printed circuit

A Printer Circuit Board, however, removes that headache entirely. By containing all the complicated wiring, you remove any possibility of introducing human error to your circuit. This has the added benefit of being able to mass-produce the circuit for quick and easy distribution. Time-To-Market is reduced dramatically as the number of devices to be produced increases. The only wiring required is to the peripherals, which are connected to clearly defined terminals on the PCB using standard connectors.

Increased reliability

The wiring from circuit boards are also vastly more reliable. A criteria that's absolutely essential for medical devices. They are safe from any mechanical failures, such as a damaged wire or weak contact. This is especially important when using high-frequency protocols such as i^2C. This protocol is very sensitive to interference or resistance. As such, it is highly recommended to minimize any failure points along its path.

Power efficiency

Custom circuit board designs also have the added benefit of being more power-efficient compared to using a mixture of protyping solutions. Contrary to development boards such as an Arduino Uno, a custom PCB only includes the components that are necessary to the design, thus minimizing power consumption.

Reduced Costs

Furthermore, by providing our own circuit board design, rather than relying on other vendors, we greatly reduce the manufacturing costs. This is especially true for large scale orders, as the cost per board drops significantly.

The following are the manufacturing and assembly costs for this PCB by MacroFab:

Amount	Cost per unit (CAD $)	Total cost (CAD $)
10	160.4	1604
50	81.46	4073
100	64.34	6434
500	49.80	24898
3000	33.54	100618.95

Smaller size

Lastly, PCBs allow miniaturization with the use of much smaller components. This results in a much more compact and elegant solution and also reduces the size of the enclosure required to protect the circuit.

Design Decisions

Power

A lot of thought went into the powering of the circuit. With the three servo motors, along with one DC motor, we had to anticipate the possibility of a high current spike across our circuit. We also have a couple of different voltage requirements for the circuit to function, needing 12V for the touch screen and Raspberry Pi contraption, and 5 volts for the servos with 5 volts logic.

Power Source

To simplify the circuit, we decided to start with a 12V power source because it allows us to share a common power source between the Raspberry Pi and its accompanying touch screen, and the rest of our components. We thus offer direct access to the 12V for the touch screen monitor, which itself is capable of powering the Pi. With the rest of the 12V, we bring it down to 5V through a voltage regulator to obtain the 5V necessary to power the rest of our components. The selected voltage regulator is also capable of delivering up to 5A, which meets the maximum current draw requirement of the circuit, including the DC and stepper motors.

Voltage Spikes

The most noticeable current spike comes from the servo motors. For this reason, 470uF decoupling capacitors have been placed in front of each servo motor to assist in delivering the necessary current. The same principle has been repeated for each integrated circuit to ensure everything works as intended.

Connectors

The connectors were selected to match its intended purposes and to support the necessary cable gauges to match the current passing through. This resulted in five different types of wire-to-board terminals on the PCB that best fit their target peripheral.

Connector	Usage
DC Barrel	12V DC Input, 12V DC Output
JST-SH	OLED display
JST-XH	Buttons connector
Shrouded 2.54mm	Environment Sensor(3), O2 sensor, Servo(3)
Screw terminal	5V DC Motor, LEDs

The DC barrel was chosen based on two reasons. The first is that there are many 110V/220V to 12V adapters that provide a DC barrel connector. The second is that our recommended UPS also happens to provide a 12V DC barrel connector. This would simplify the need to source cables, as these are widely available. On top of this, the connector is a single plug, meaning there is no risk of damaging the electronics by inverting the polarities. This connector is also compatible with the Raspberry Pi's touch screen.

For our sensors and servos, we have chosen a simple shrouded 2.54mm pitch terminal. This connector was found to be the ideal solution as it is directly compatible with the 2.54mm pitch cables of the servo motors. The sensors also provide easy connection using these cables, which are widely available, as 2.54mm cables are the prototype standard thanks to Arduino and breadboards. The shrouds provide tightness and protection against pin bending.

Mechanical

Every electronic design has to incorporate a housing of some sort to hide and protect the circuit. This was kept in mind during the PCB design process and is ultimately why the buttons, LEDs, and OLED are mounted separately from the board itself. The dimensions of the PCB were also kept under consideration to minimize its overall size. This is in case people would prefer to 3D print their case themselves, in which case the size is important to keep under consideration to fit on printer platforms and reduce overall print time.

PCB dimensions:

- Size: 3.5”x3.5”x1”
- Hole diameter: 3mm

Parts

Microprocessor (U2)

The microprocessor selected is ATmega328PB-AU. It was selected for being Arduino compatible, which provides an easy and well-documented method of setting up the device. It also allows us to reuse the same tested sketch for our prototype, with minimal modifications. This would speed up the transition from our working prototype to a more refined solution.

The ATmega328PB-AU is also compatible with 5V logic, allowing us to stay with 5V. Otherwise, a 3.3V microprocessor would require additional logic level converters to scale the data signal back up to 5V for the servo motors.

PWM Controller (U3)

Our circuit makes a lot of use of the Pulse Width Modulation (PWM) to obtain analog outputs. This is done by creating a square wave at a precise frequency to reach our desired output voltage. In order for this to work well and in a reliable manner, precise timing is required. While the microcontroller does have an internal clock, it is unreliable at accurately creating such signals. This is because the clock is a shared resource, and small delays can be introduced if the microprocessor is busy or hangs, affecting the resulting signal.

For this reason, we decided to introduce an external PWM controller. By containing its own independent crystal, this controller is capable of generating more consistent PWM signals as a result. This allows us to more accurately control our servo motors, reducing the risk of any glitches caused by the MCU. This is especially important to consider as they are used to regulate medical treatment.

I^2C Multiplexer (U1)

Inter-Integrated Circuit (I^2C) works by assigning a peripheral or sensor to a specific address from 0x00 to 0x127. Each peripheral is pre-assigned an address. In the event where two addresses overlap, peripherals typically have a choice of alternate addresses to pick from. In our design, we make use of three BME280 sensors as temperature and pressure sensors. The caveat of this sensor, however, is that it only works under the address 0x76 or 0x77, leaving one sensor to be left undetectable.

To resolve this problem, we introduced the PCA9685PW i^2C multiplexer. This integrated circuit creates multiple separate i^2C channels which allow us to interface with multiple peripherals of the same address. We can thus keep the BME280 at the default address of 0x77.

Piezo Buzzer

The CPI-137-83T piezo buzzer is placed directly on the PCB and serves as an audible alarm. It puts out 85dB at 10cm and should be a good complement to the red LED. Its frequency is in the 3800-4800Hz range.

Programming

The microprocessor used is the ATmega328PB-AU. This chip is Arduino compatible, allowing for easy programming through the exposed serial bus. However, before we can upload a sketch onto the board, the bootloader must first be burnt onto the ATmega. For this reason, the SPI interface pins are exposed at P15 as through-holes on the board. These can be connected by using spring-loaded POGO pins if available, or by simply holding the wires over the through-hole.

Conclusion

All-in-all, this design is robust and is ready for market. From the moment the PCBs are ordered, we can expect to receive them within a month, which offers enough time to gather the rest of the materials. Once the parts are received, the programming and assembly processes are quite fast thanks to the simplified circuit and standard connector design, avoiding the need for exhaustive tests for each produced circuit before using it out in the field.

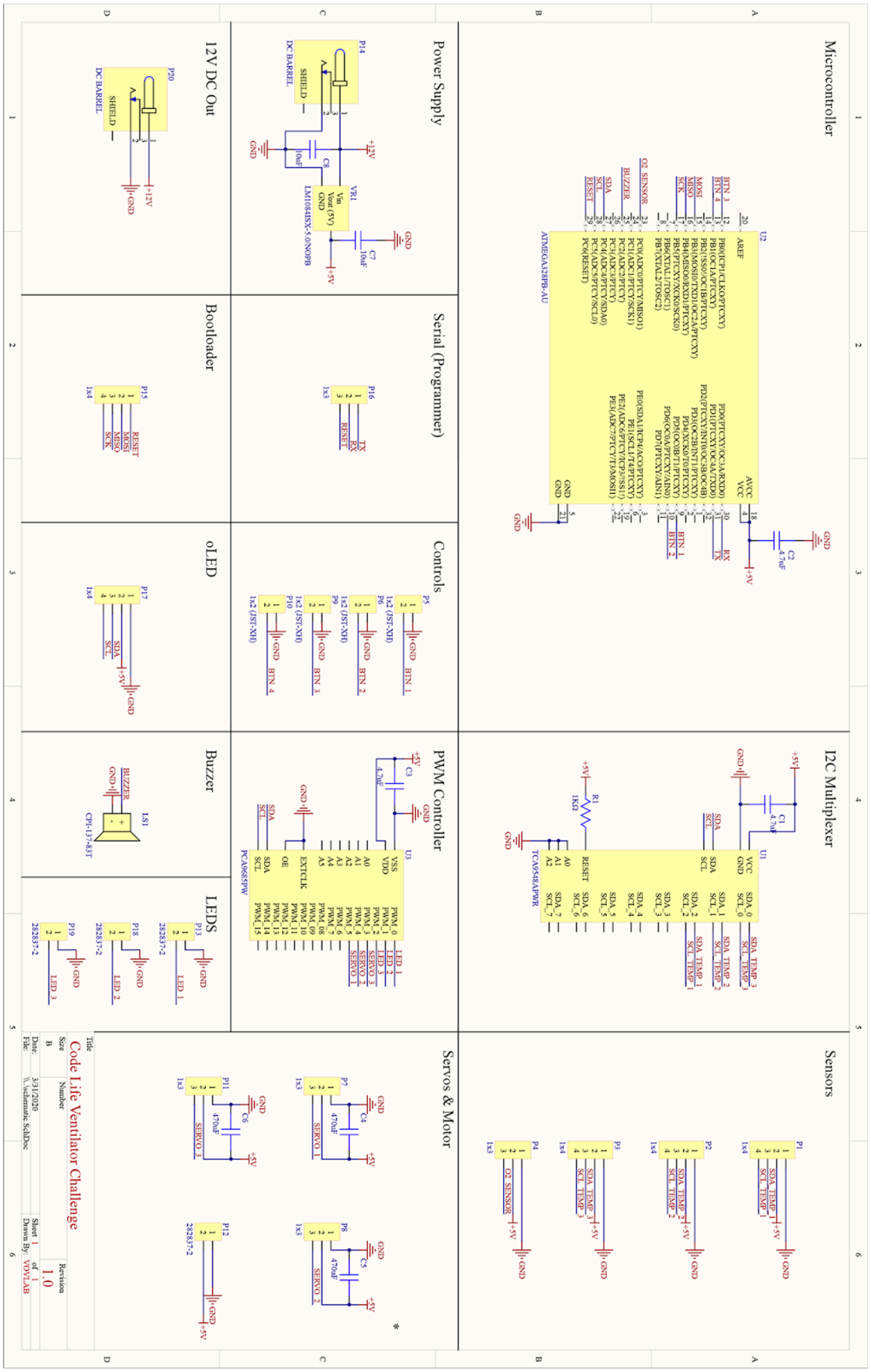
Annexe

Bill of Materials

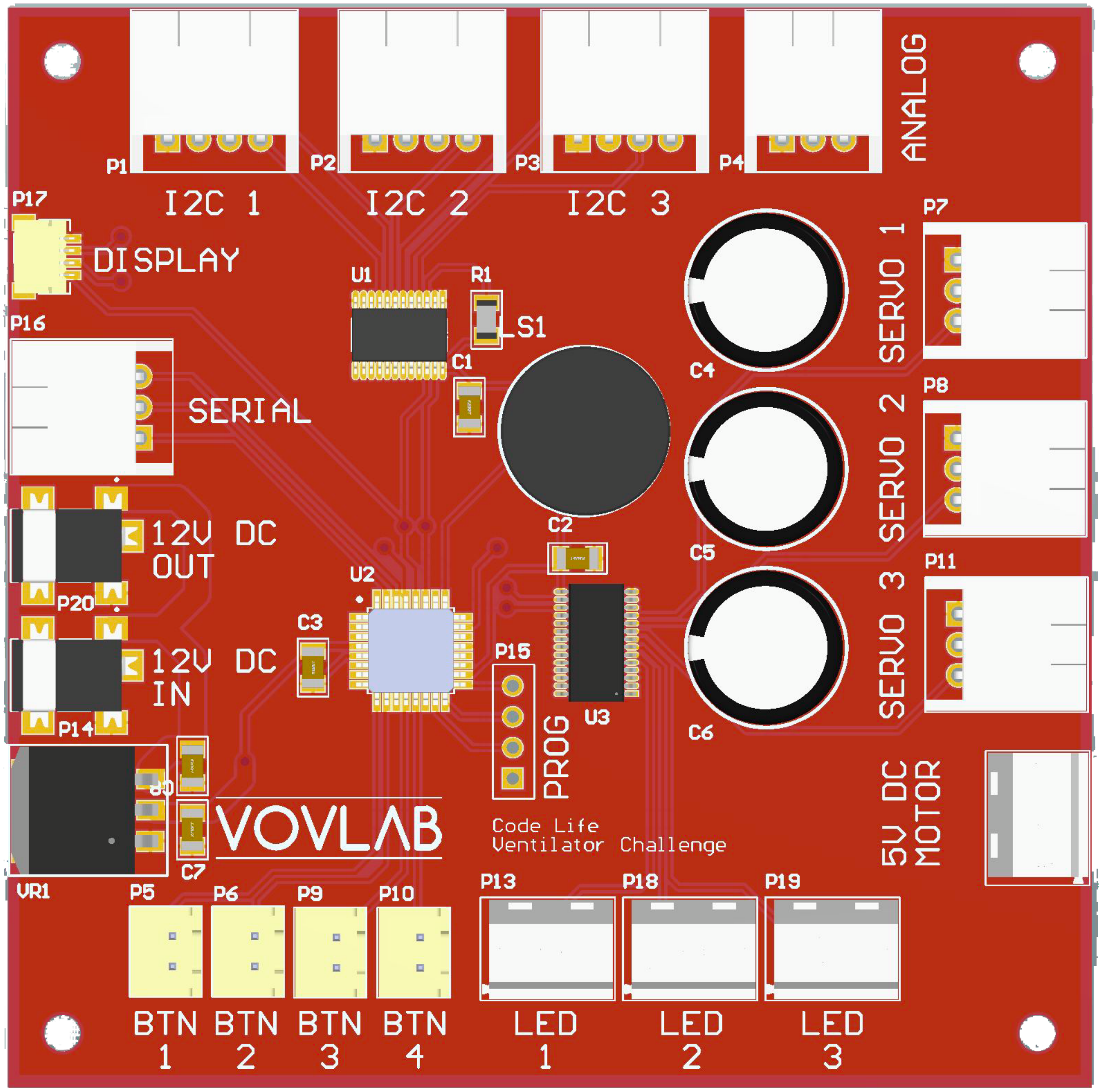
Bill of Materials

Line #	Designator	Quantity	Name	Description	Manufacturer 1	Manufacturer Part Number 1	Supplier 1	Supplier Part Number 1	Instructions
1	C1, C2, C3	3	4.7uF	4.7µF 25V Ceramic Capacitor X7R 1206 (3216 Metric) 0.126 L x 0.063" W (3.20mm x 1.60mm)"	Wurth Electronics	885012208068	Digi-Key	732-7573-6-ND	
2	C4, C5, C6	3	470uF	PANASONIC - EEUFM1H471 - Aluminium Electrolytic Capacitor, FM Series, 470 - F, - 20%, 50 V, 12.5 mm, Radial Leaded RoHS Compliant: Yes	Panasonic	EEUFM1H471	Digi-Key	P12400-ND	
3	C7, C8	2	10uF	WURTH ELEKTRONIK - 885012108021 - SMD Vícevrstvý Keramický Kondenzátor, 10 µF, 25 V, 1206 [3216 Metrické], ± 20%, X5R	Wurth Electronics	885012108021	Digi-Key	732-7645-6-ND	
4	P1, P2, P3	3	1x4	PCB header 1x4P, 90136-2204, Molex	Molex	90136-2204	Digi-Key	WM8205-ND	
5	P4, P7, P8, P11, P16	5	1x3	Conn Shrouded Header HDR 3 POS 2.54mm Solder RA Thru-Hole C-Grid III™ Tray	Molex	90136-2203	Digi-Key	WM8204-ND	
6	P5, P6, P9, P10	4	1x2 (JST-XH)	CONN HEADER XH TOP 2POS 2.5MM	JST	B2B-XH-A-GU	Digi-Key	455-2946-ND	
7	P12, P13, P18, P19	4	282837-2	Conn Terminal Blocks F 2 POS 5.08mm Solder ST Thru-Hole 13.5A/Contact	TE Connectivity	282837-2	Digi-Key	A113320-ND	
8	P14, P20	1	DC BARREL	CONN PWR JACK 1X3.4MM SOLDER	CUI	PJ-075CH-SMT-TR	Digi-Key	CP-075CHPJDKR-ND	
9	P15	1	1x4						DNP
10	P17	1	1x4	Conn Shrouded Header HDR 4 POS 1mm Solder RA SMD T/R	JST	SM04B-SRSS-TB(LF)(SN)	Digi-Key	455-1804-6-ND	
11	R1	1	1KO	RES SMD 1K OHM 5% 1/4W 1206	Yageo	RC1206JR-071KL	Digi-Key	311-1.0KERDKR-ND	
12	U1	1	TCA9548APWR	TEXAS INSTRUMENTS - TCA9548APWR - I2C SWITCH W/ RESET, 8-CH, TSSOP-24	Texas Instruments	TCA9548APWR	Digi-Key	296-34905-6-ND	
13	U2	1	ATMEGA328PB-AU	IC MCU 8BIT 32KB FLASH 32TQFP	Microchip / Atmel	ATMEGA328PB-AU	Digi-Key	ATMEGA328PB-AU-ND	
14	U3	1	PCA9685PW	LED DRVR 3.3V/5V Automotive 28-Pin TSSOP T/R	NXP Semiconductors	PCA9685PW/Q900,118	Digi-Key	568-5931-6-ND	
15	VR1	1	LM1084ISX-5.0/NOPB	IC REG LIN 5V 5A DDPAK/TO263-3	TI National Semiconductor	LM1084ISX-5.0/NOPB	Digi-Key	LM1084ISX-5.0/NOPBDKR-ND	
16	LS1	1	CPI-137-83T	BUZZER, 13.9 MM, 7.5 MM DEEP, P,	CUI Devices	CPI-137-83T	Digi-Key	2223-CPI-137-83T-ND	

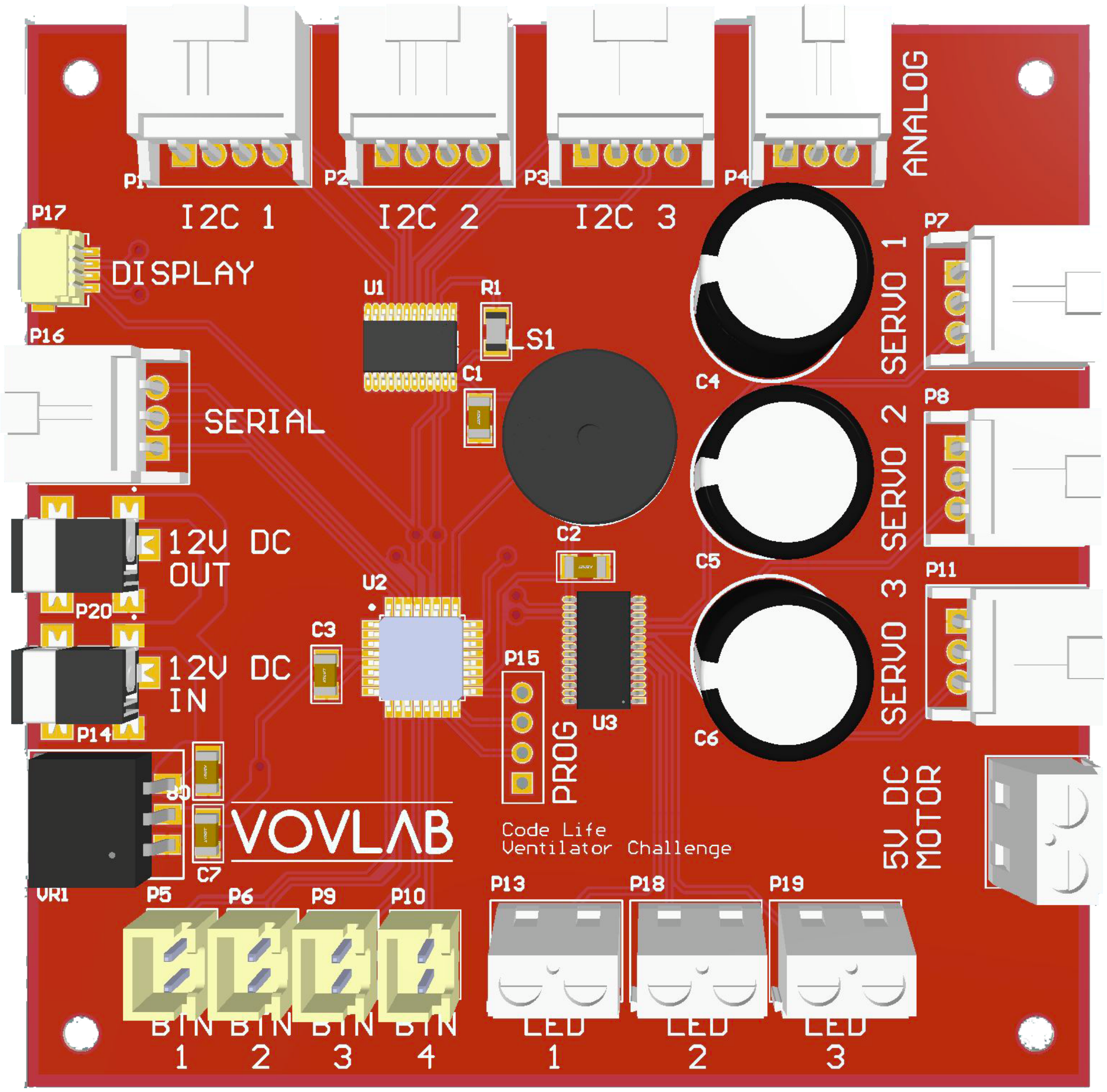
Schematic


Microcontroller
Power Supply
12V DC Out
Serial (Programmer)
Bootloader
Controls
oLED
I2C Multiplexer
PWM Controller
Buzzer
LEDS
Sensors
Servos & Motor
Code Life Ventilator Challenge

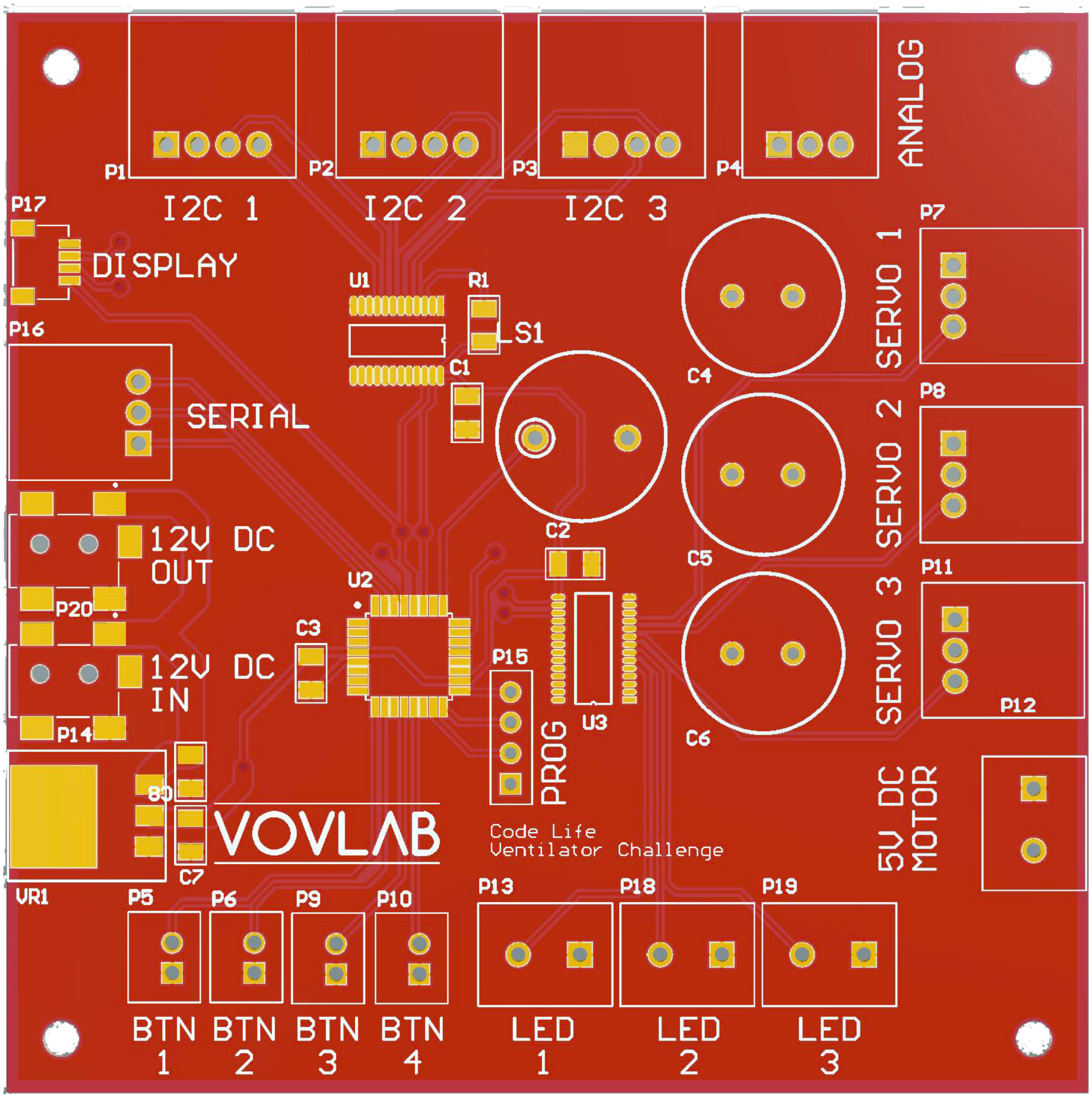
Top view - Orthographic



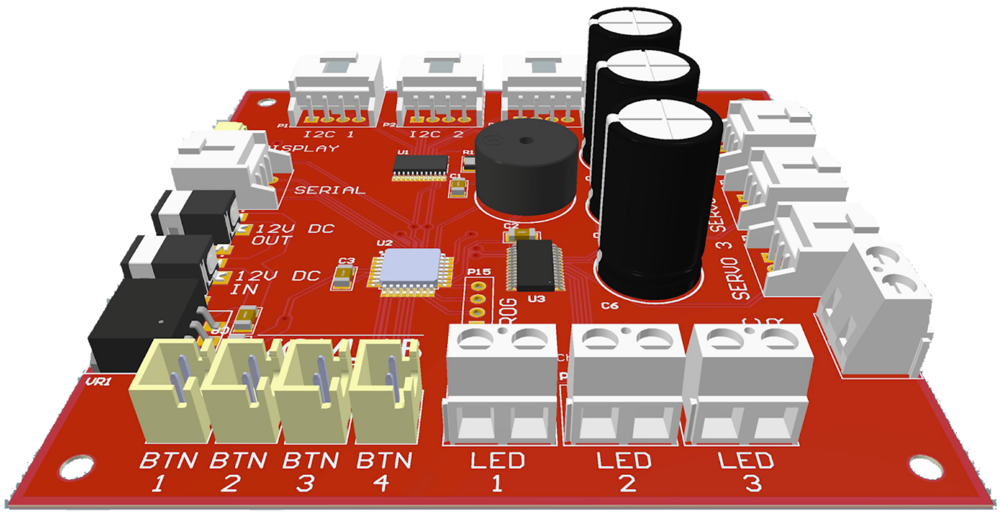
Top view - 3D


P1
P2
P3
P4
ANALOG
I2C 1
I2C 2
I2C 3
P17
DISPLAY
U1
R1
LS1
P7
SERVO 1
P16
C1
C4
SERIAL
P8
SERVO 2
12V DC
OUT
C2
C5
P20
U2
P11
SERVO 3
C3
P15
12V DC
IN
P14
U3
C6
PROG
VOVLAB
Code Life
Ventilator Challenge
5V DC
MOTOR
C7
VR1
P5
P6
P9
P10
P13
P18
P19
BIN 1
BIN 2
BIN 3
BIN 4
LED 1
LED 2
LED 3

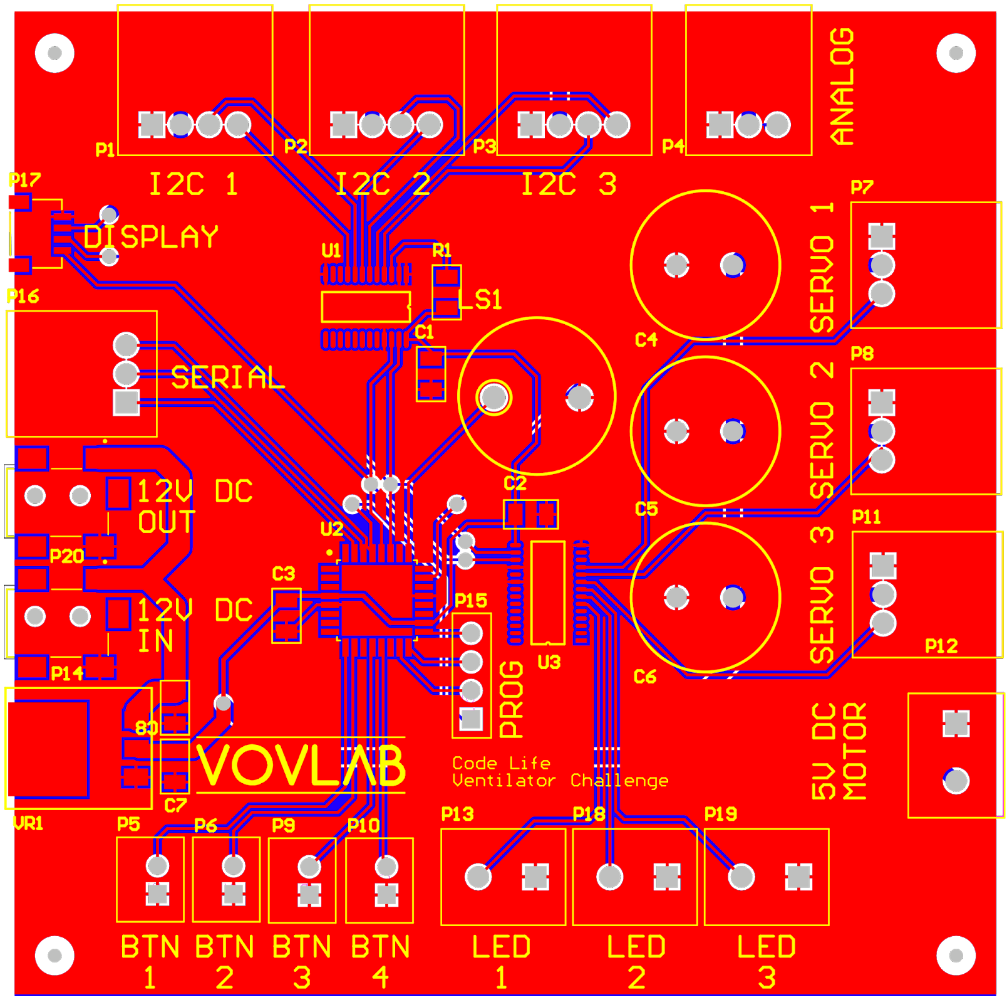
Top view – Footprints



Angled view - 3D

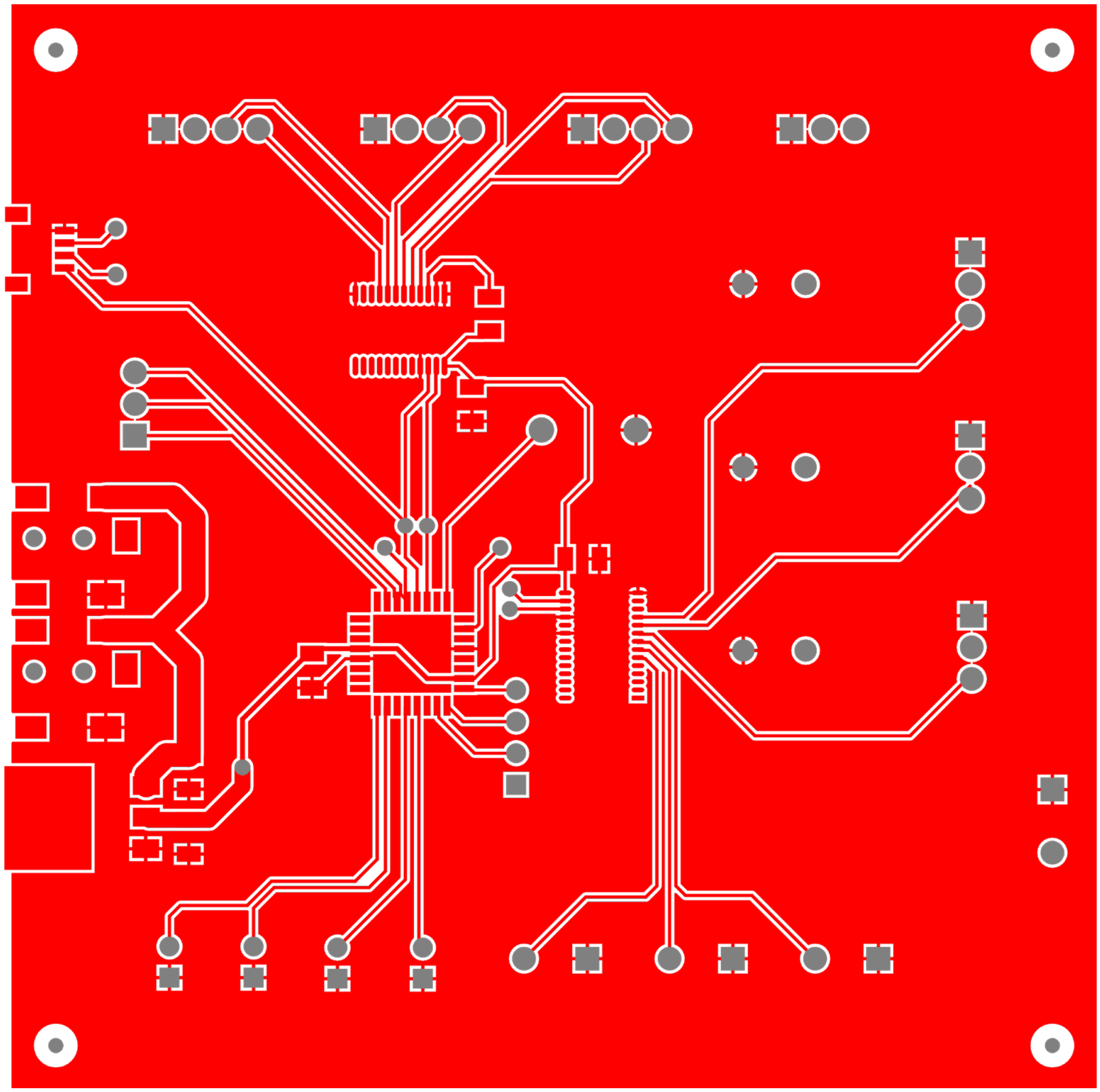


All layers



I2C 1
I2C 2
I2C 3
ANALOG
DISPLAY
SERIAL
LS1
12V DC OUT
12V DC IN
SERVO 1
SERVO 2
SERVO 3
PROG
VOVLAB
Code Life Ventilator Challenge
5V DC MOTOR
BTN 1
BTN 2
BTN 3
BTN 4
LED 1
LED 2
LED 3

Top layer



Bottom layer