BVA Bag valve actuator
Control & instrumentation specifications

Document number SPC2020-BVA-P1-03

Version V7

Project BVA

Authors Dr. Mohammed Bouheraoua
Principal Engineer
Libertine FPE Limited
Mohammed.bouheraoua@libertine.co.uk
+44 (0) 7912626203

Contents

1. Scope 4
2. System Architecture 5
    2.1. BSQ: Bag squeezer assembly 7
    2.2. BCA: Bag carrier assembly 7
    2.3. BVA: Bag valve actuator 9
    2.4. PCU: Power & control Unit 10
3. Software 13
    3.1. Overview 13
4. Control logic 14
5. Alarm system 15
6. Data logging 15
7. Advanced diagnostics 15
8. Hardware interfaces & connectors 16
    8.1. BVA 16
    8.2. PCU 17
    8.3. BCA 18
    8.3.1. BCA display screen and Adruino 19
    8.4. Link cables 19
9. Bill of Material 19

Version history

Version	Issue date	Notes & changes
V1 WIP	21/06/2020	First draft
V2 WIP	08/07/2020	Added interfaces
V3	28/07/2020	Added New BCA CAD
V4	07/08/2020	Updated section 2.1
V5	16/8/2020	SEC: Control section 4 updated in line with 7 August call. Pot controls pressure (force) not volume.
V6	02/09/2020	Update Arduino pins in/out
V7	29/09/2020	Rearrange the PCU sub-d connector to suite the pcb board

1. Scope

The objective of this project is to create a modular bag valve actuator (BVA) suitable for deployment in UK care homes to reduce mortality due to COVID-19 infections during 2020, and to provide an effective early stage intervention to reduce mortality in subsequent annual flu seasons.

The specification documents are summarised as follows:

Document no.	Title	Description
SPC2020-BVA-P1-01	Performance & acceptance test specifications	Requirements specification setting out the design and performance objectives for the ventilator machine and bag valve sub-system. This document also sets out the acceptance testing that the machine will be subjected to.
SPC2020-BVA-P1-02	Interface, installation & operation specifications	This specification describes the mechanical, electrical, cooling and all other interfaces related to the ventilator system. The document also describes the process for installation and commissioning, safe operating parameters and maintenance requirements for the equipment.
SPC2020-BVA-P1-03	Control & instrumentation specifications	This specification describes the control system to be supplied by Libertine. The document also describes the instrumentation interfaces for data logging, and data logging functions performed by Libertine's equipment.

2. System Architecture

The BVA-P1 Bag Valve Actuator is part of the Reference Breathing System architecture as illustrated in Figures 1 & 2 below. The functions of the RBS are described in

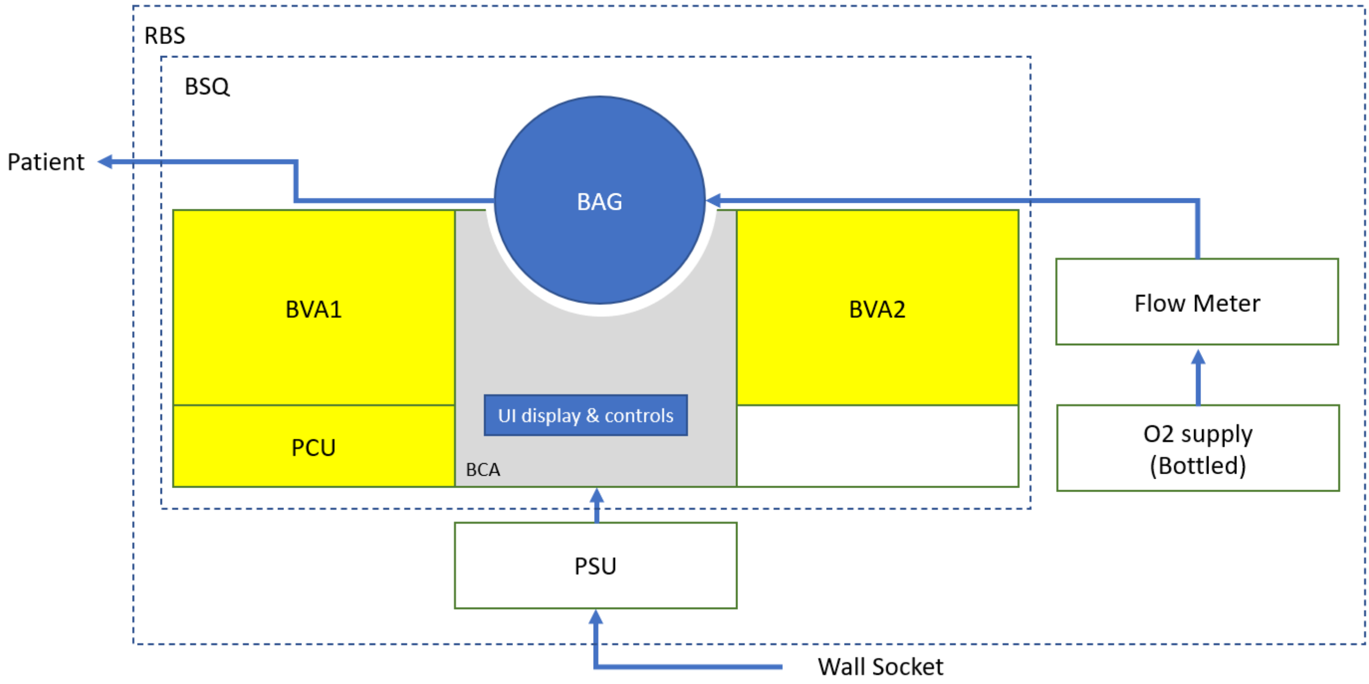


Figure 1 Reference Breathing System Architecture Block Diagram

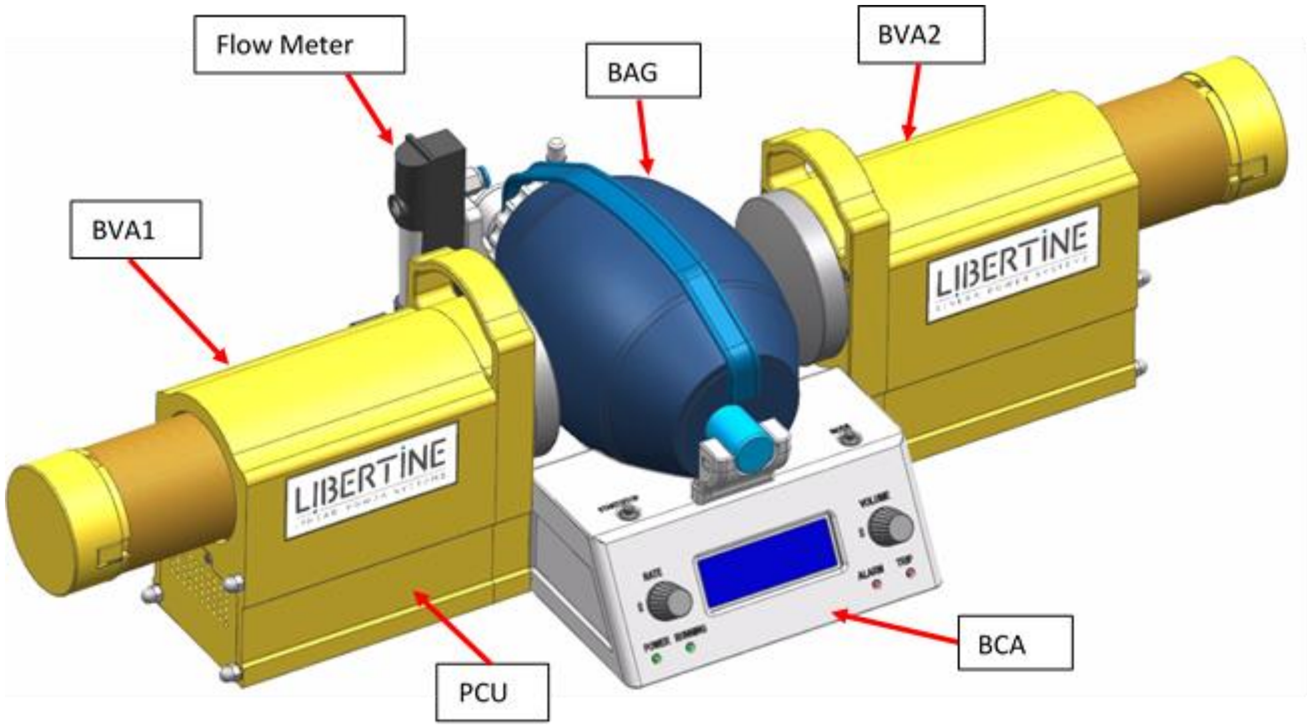


Figure 2 CAD Overview of RBS (O2 Supply and PSU not shown)

Item	RBS function	Performed by	Alternatives	Notes
1	O2 pressure supply regulation	Bottled gas & 10 bar regulator	Hospital O2 Ring Main	
2	Inspiration gas blending	Ambu Bag	UCL CPAP	Compatible with 1?
3	Inspiration pressure regulation	EXTERNAL TO PROJECT	UCL CPAP or Sleep Apnoea Machine	
4	Humidification	N/A (non-invasive)	N/A (non-invasive)	
5	Temperature regulation	N/A (non-invasive)	N/A (non-invasive)	
6	Inspiration elevated pressure regulation	BSQ		
7	Inspiration pressure/volume regulation	BSQ		
8	Inspiration frequency regulation	BSQ		
9	PEEP regulation & filters	EXTERNAL TO PROJECT		Ambu Bag Spur II includes 30mm PEEP Connector
10	Patient sensors (Pressure, flow, breathing rate, temp, humidity, %O2, %CO2, others?)	EXTERNAL TO PROJECT		
11	Power Supply	Benchtop Supply	12V Car Battery	

Table 1 Provision of RBS functions

	Description	Notes
Inputs	External power	Alternatively may be battery powered, 12V
	External O2	Alternatively may use bottled O2 supply
	User interface inputs	
	External trigger for conscious breathing support mode	A signal to resume breathing while the mover is in half way if the patient is detected breathing.
Outputs	Patient mask & gas supply	
	LED display, status LEDs & alarm	

2.1. BSQ: Bag squeezer assembly

The BSQ system incorporates components manufactured by Libertine that forms part of a reference breathing system. There are three assembly components that Libertine will be manufacturing. These components are shown in **Error! Reference source not found.**. BVA, BCA and the PCU. Along ith the Bag and the Power Supply Unit (PSU), these components comprise the Bag Squeezer (BSQ).

	Description	**Notes**
Inputs	External power	Alternatively may be battery powered, 12V
	User interface inputs	
	External trigger for conscious breathing support mode	A signal to resume breathing while the mover is in half way if the patient is detected breathing.
	CPAP gas, at appropriate blend%, humidity, pressure & temperature	
Outputs	Patient mask & gas supply	
	LED display, status LEDs & alarm	

2.2. BCA: Bag carrier assembly

The BCA is the user interface to the RBS it allows the user to turn On/Off change the breathing rate and volume by adjusting the dials in the BCA user interface. The BCA also hosts the Bag Valve Mask (BVM) and power input.

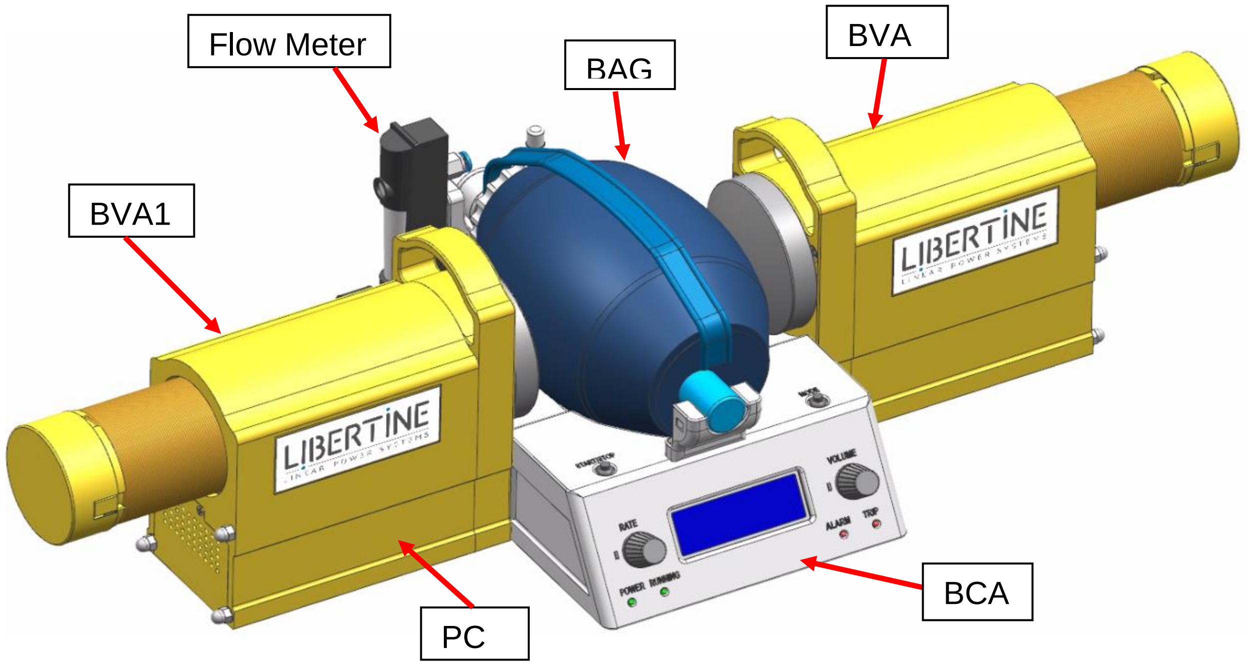


Figure 3 CAD Overview of RBS (O2 Supply and PSU not shown)

Respiratory rate: defines breathing frequency.
Pressure: defines the force profile applied on the bag.

	Description	**Notes**
Inputs	External power	Alternatively may be battery powered, 12V
	User interface inputs	Adjust breathing frequency and pressure.
	External trigger for conscious breathing support mode	A signal to resume breathing while the mover is in half way if the patient is detected breathing.
Outputs	Power and signals distribution	
	LED display, status LEDs & alarm	

2.3. BVA: Bag valve actuator

The BVA module draws on Libertine's control systems IP created for other linear actuator applications, and utilises established voice coil e-machine prior art used in other medical and industrial devices.

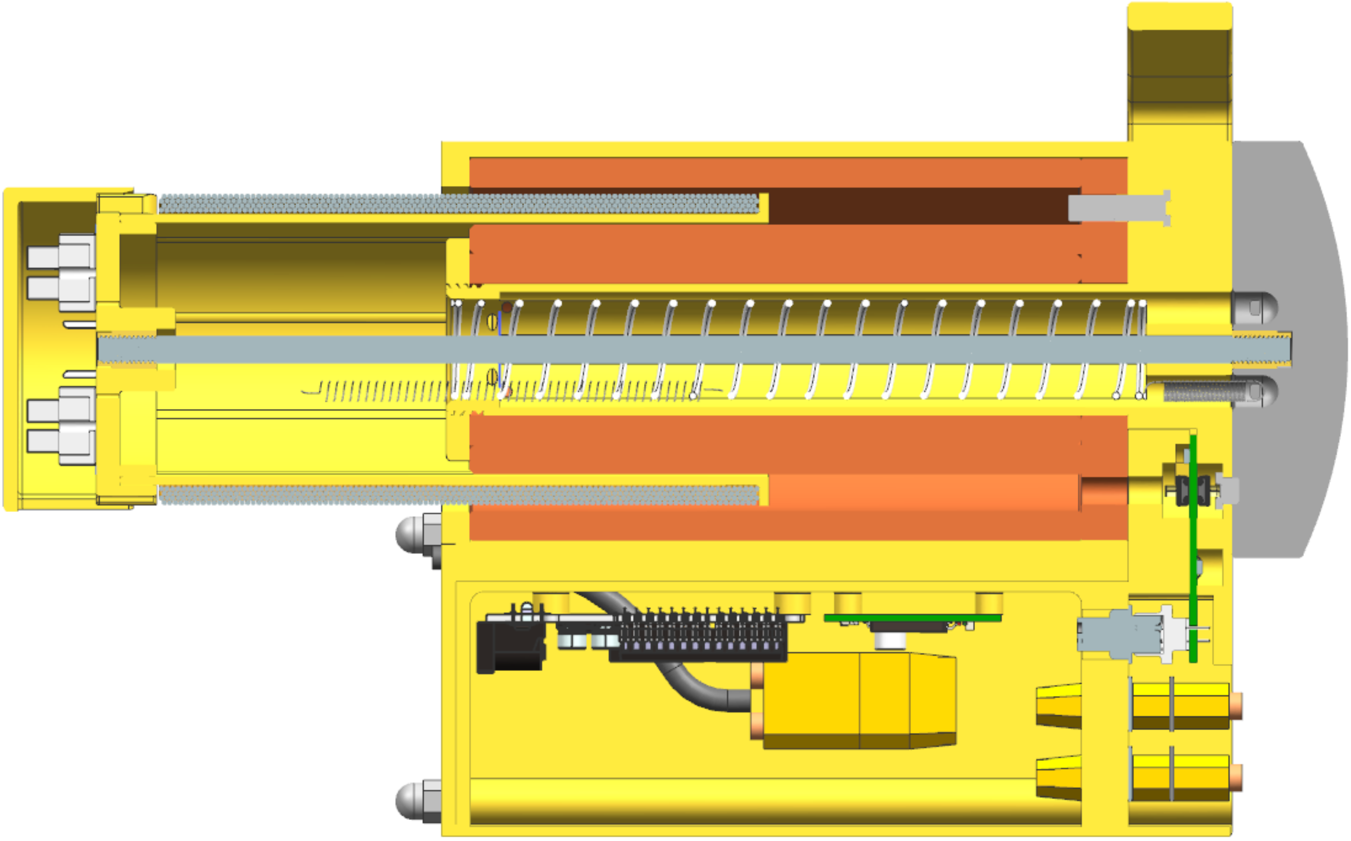


Figure 4 BVA & PCU

	Description	Notes
Inputs	Controlled power	From the PCU power board
Outputs	Force/displacement cycles	
	Position switch & temperature signals	

2.4. PCU: Power & control Unit

The voice coil machines will be driven by Arduino Uno board supplying PWM switching signal to **VNH5019** Motor Driver board to dive the coils. Each board drive one machine, the Arduino drives two boards, current feedback fed from the boards to the Arduino for force control. A 12V DC power supply to drive the two machines.

The control system is designed based on off the shelf components that are widely available in the market and affordable prices for the wider community.

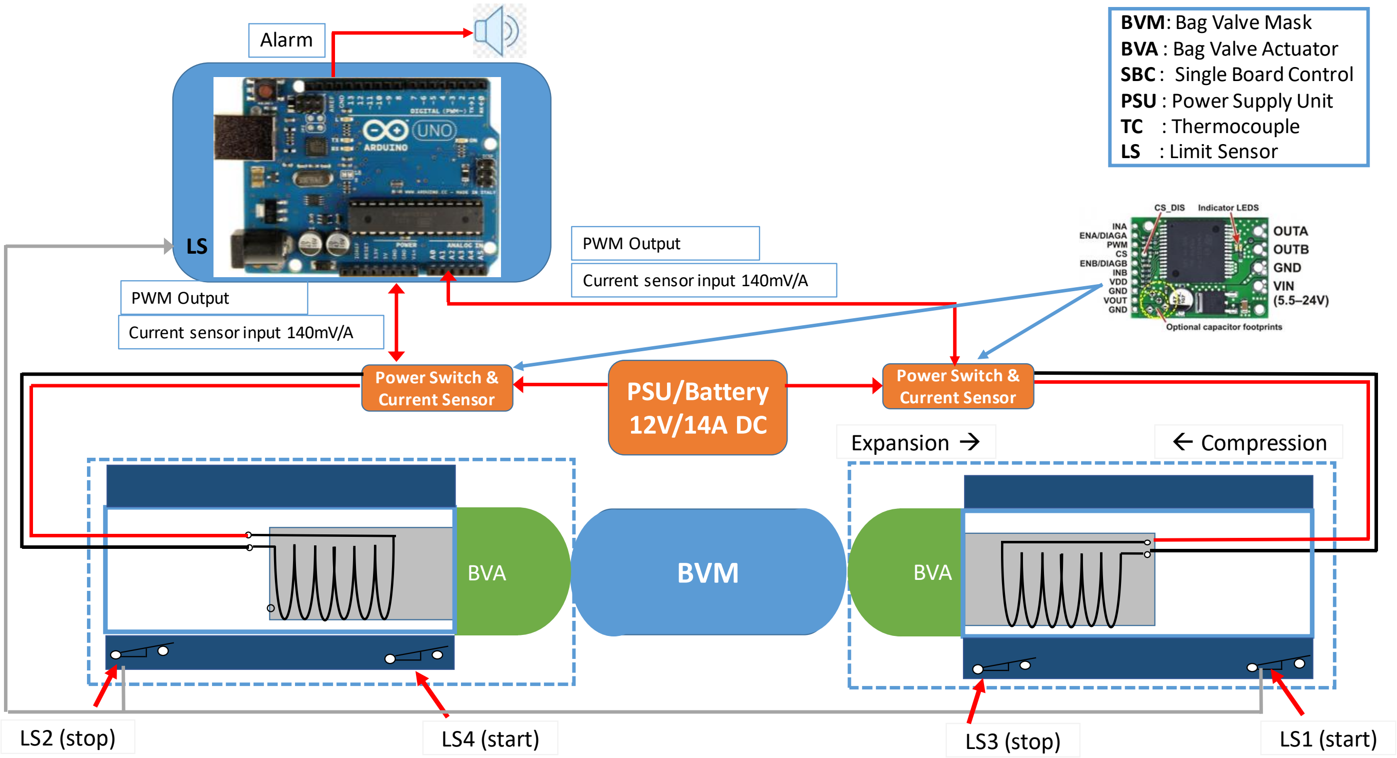


Figure 5 Arduino Based Control Schematic for BVA

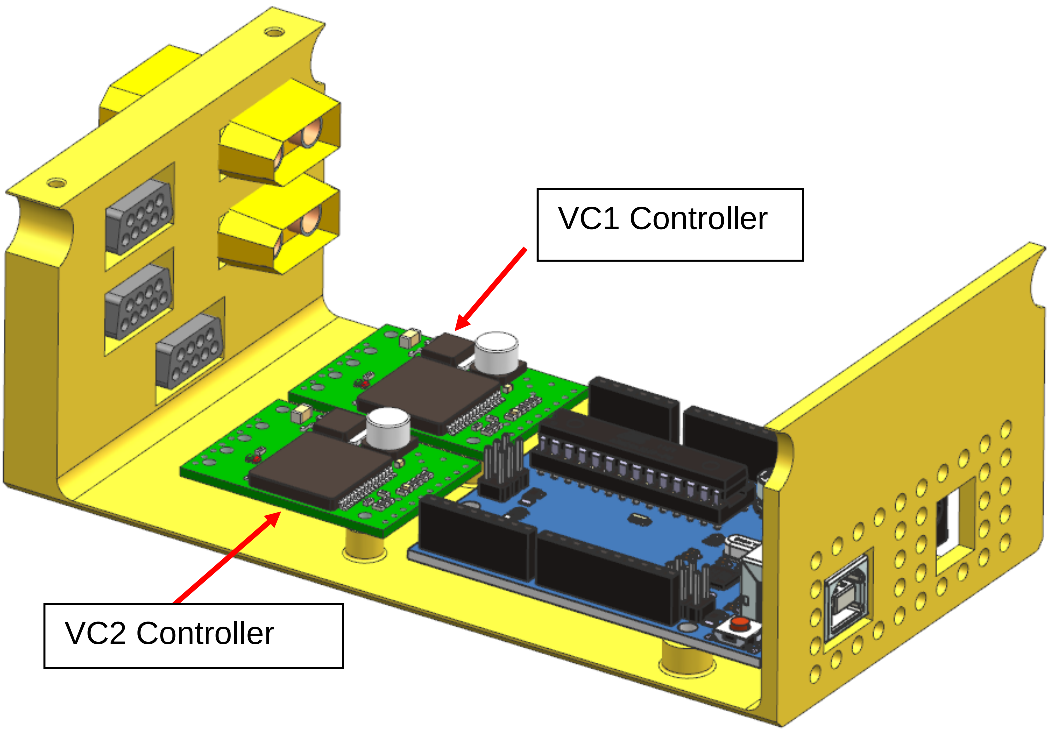


Figure 6 First prototype of the PCU

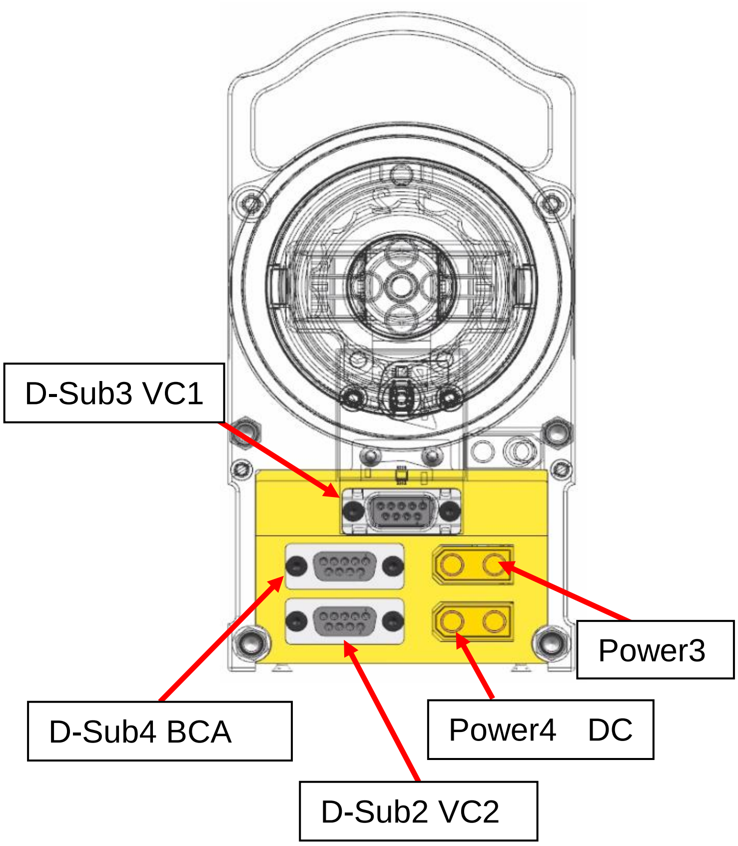


Figure 7 Front View PCU Electrical Connections

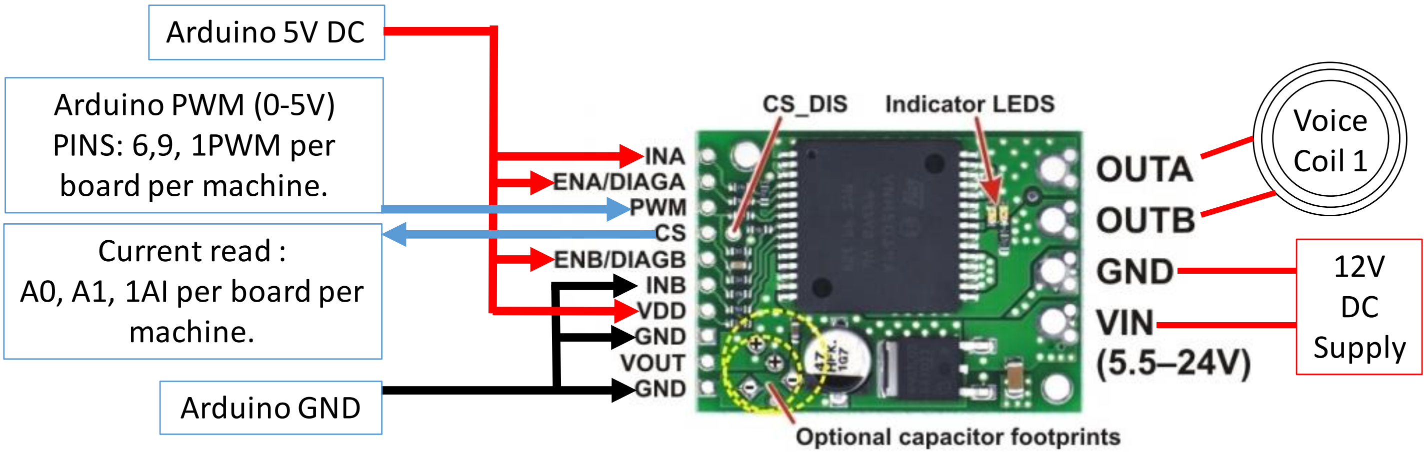


Figure 8 Wiring diagram for VNH5019 Motor Driver Carrier 12A

IN_A	IN_B	$DIAG_A/EN_A$	$DIAG_B/EN_B$	OUT_A	OUT_B	CS (V_{CSD} = 0 V)	Operating mode
1	1	1	1	H	H	High imp.	Brake to V_{CC}
1	0	1	1	H	L	$I_{SENSE} = I_{OUT}/K$	Clockwise (CW)
0	1	1	1	L	H	$I_{SENSE} = I_{OUT}/K$	Counterclockwise (CCW)
0	0	1	1	L	L	High imp.	Brake to GND

Table 2 Truth table in normal operating conditions

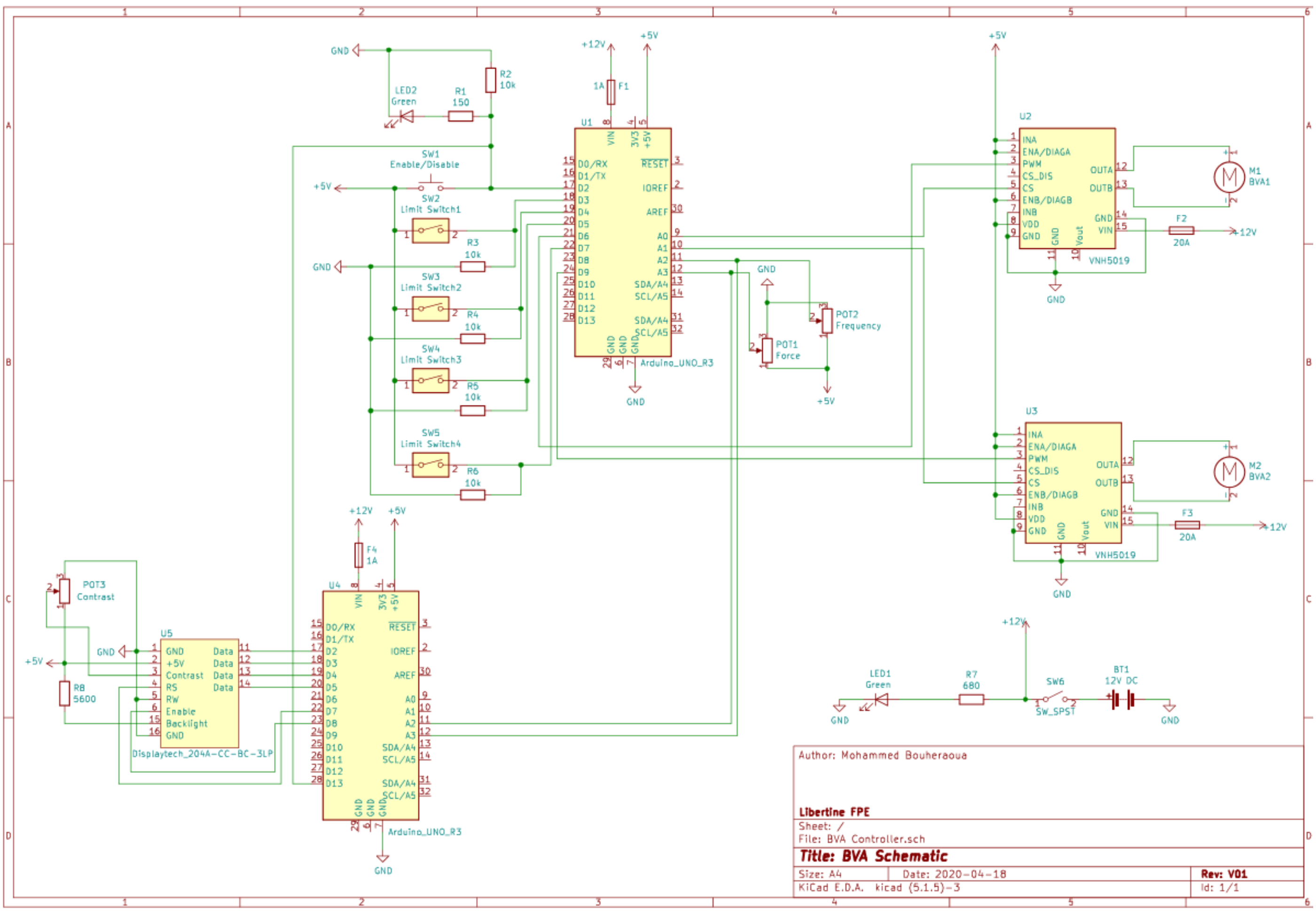


Figure 9 BVA Control Schematic

Sensor list	Type	Direction	Number	Scaling
Current sensor	Analogue	input	2	140mV/A
Limit switch	Digital	input	4	
Temperature	Analogue	input	4	

Power	Type	Amplitude	Number
DC Supply	DC	Input 12V	1

Control output	Type	Amplitude	Number
Force demand	Digital PWM	Output 5V	2
Alarm	DC	Output 5V to Buzzer	1

3. Software

3.1. Overview

The software design is implemented with state machine described in Table 3.

State	Input	Output	Alarm/Stop conditions
1. Start	Power on	Status LED	Thermal limit
2. Compression Compress the Bag (May include an 'Adapt' state where force is scaled to achieve a target stroke time)	• Compression profile Force V Time With adapt term to adjust Force up or down to meet the time. • Current feedback • Limit switch	Current demand as PWM signal.	Thermal limit Stroke time (position limits) outside of defined values Other?
3. Expansion The mover returns to starring position with breaking profile and spring expansion.	• Expansion profile Force V Time To ensure the mover isn't slammed back by the expansion of the bag. • Current feedback • Limit switch	Current demand as PWM signal.	Thermal limit Stroke time (position limits) outside of defined values
4. Stop	Stop	Status LED	Thermal limit
5. Off	Power off	Status LED	

Table 3 States description of the controller

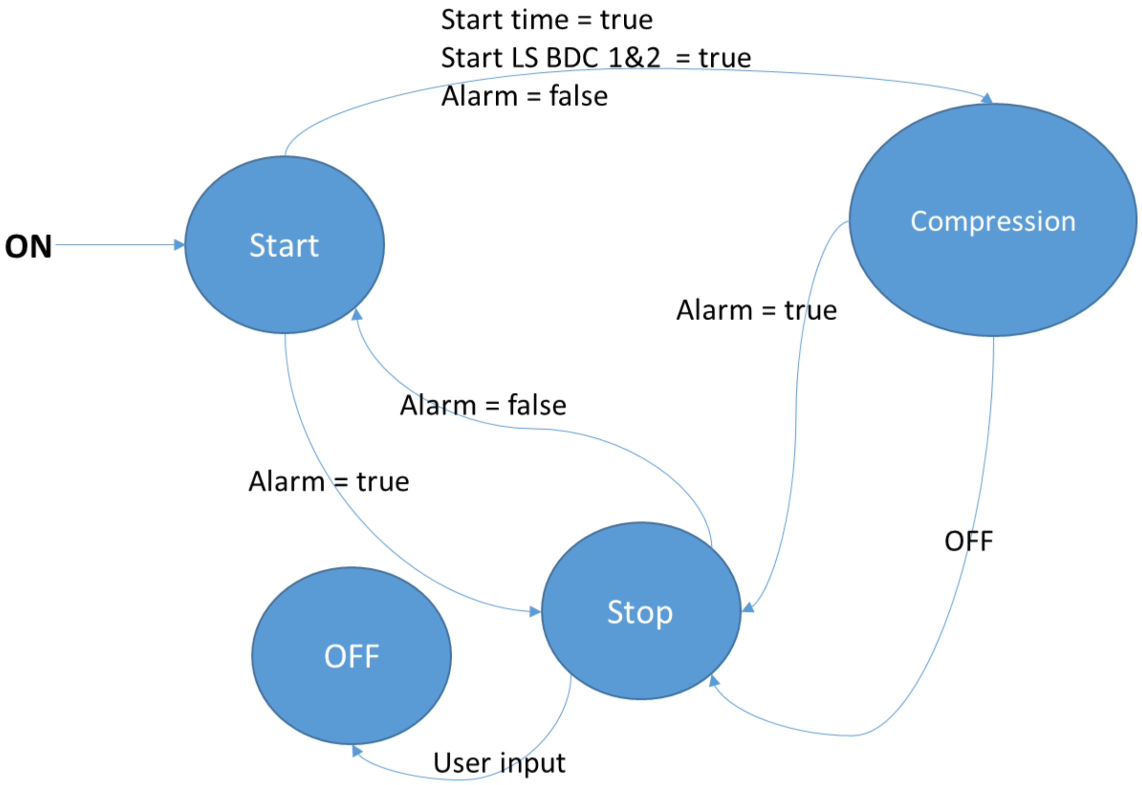
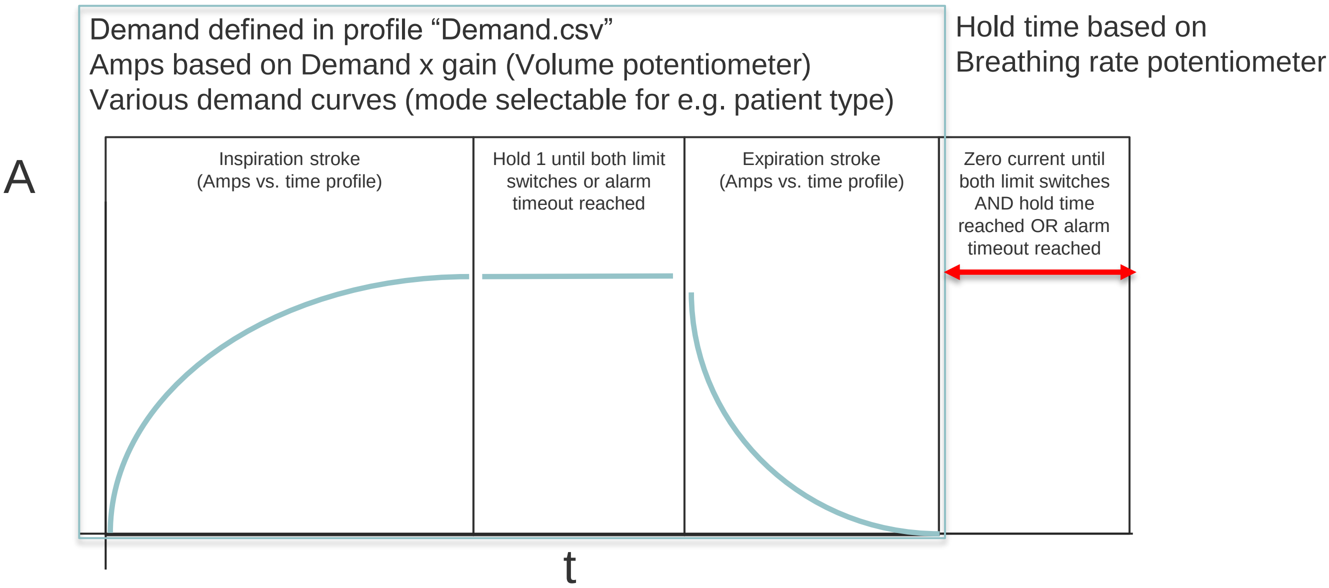


Figure 10 State diagram of the control system

4. Control logic

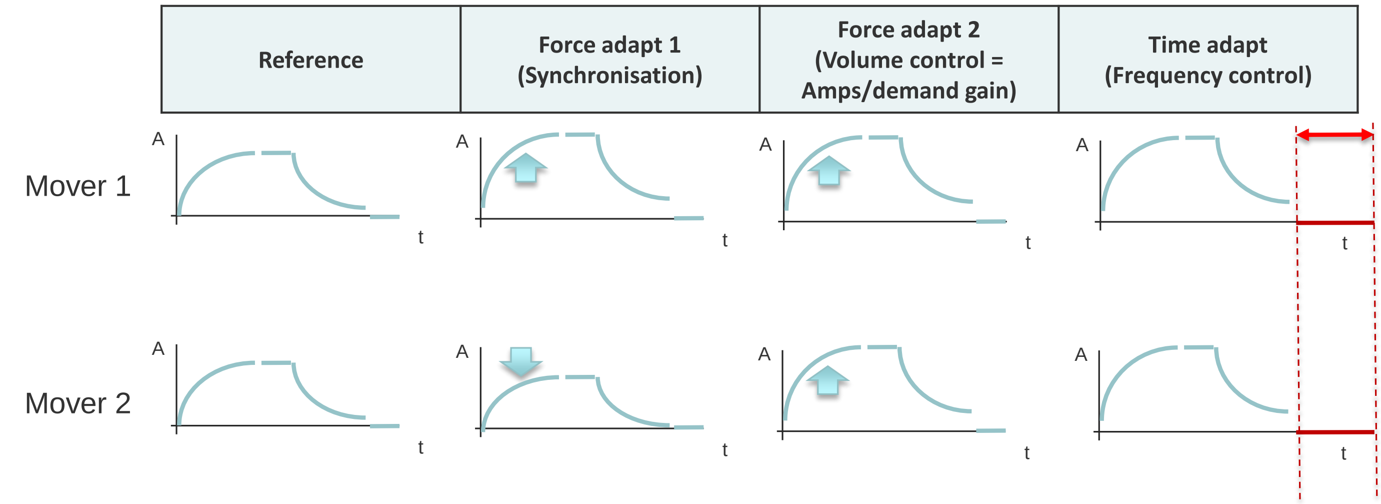


The 'bottom of stroke' limit switch is used to detect the end of the cycle
The 'top of stroke' limit switch should be treated as a position warning.

The frequency of the stroke can be adjusted by

(i) modifying hold time
(ii) scaling the time axis of the force demand profile to meet the desired frequency.

The maximum pressure to be applied can be adjusted by scaling the force/current axis of the force demand profile.



The two movers are synchronized at the bottom of the stroke (end of cycle), the leading mover waits until the lagging mover's limit switch is operated.

The time error between the two limit switches at BDC is used to adjust the scaling the force/current axis of the force demand profiles of the two movers (Leading mover force is reduced, lagging mover force is increased)

5. Alarm system

An important part of this application is the alarm that indicates different patient parameters such as exhaled volume or airway pressure. The ventilation system must be able to detect whether a breath has been taken.

For this application we infer to a complete breath by achieving a complete compression stroke, if a stroke is not completed within 8 seconds the buzzer must sound an alarm.

6. Data logging

Logging data to laptop/SD card with PicoScope 2000 series capable of 1kHz.

Time (s)	Current Demand1 (A)	Current Feedback 1 (A)	Start switch1	Stop switch1	Current Demand2 (A)	Current Feedback2 (A)	Start switch2	Stop switch2

Table 4 Log file format

7. Advanced diagnostics

The limit switches act as a position datum, against which we can 'learn' the characteristic of inductance vs. position for each machine through the stroke over not very many cycles.

Given that we want the machine design to be as versatile as possible (easily adapted for local iron tube sizes etc) this avoids the risk of getting estimated position wrong with certain designs for reasons we don't yet know about.

It also means the machines could be downgraded to run with a much simpler controller in some situations, if required.

Estimated position gives us force vs. position gives us a rough pressure/volume diagram, the diagnostic value of which is going to be huge:

1) In each stroke we can detect choking, blocked airway or detached mask
2) Over multiple strokes we can log and flag trends via simple statistical process control algorithms that could help inform clinical decisions

Given that these devices are likely going to be used pre/outside of ICU, we could log data corresponding to subtle changes in patient condition that might point to a deterioration and allow an earlier but ***shorter*** or ***more successful*** ICU intervention = less pressure on ICU ventilators, better outcomes.

In terms of the coding roadmap, here's what I'd like to achieve:

8. Hardware interfaces & connectors

8.1. BVA

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name
Power1	Power Plug 180-5382	Input	1	OUT A	Power from PCU **Power2/ Power3 for BVA2** 180-5378	OUT A
			2	OUT B		OUT B

Table 5 BVA power connector

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name
D-Sub1	BVA-P1-PCB 795-2210	Input	5	VDD	PCU **D-Sub3** 446-737	VDD
		Output	4	SW1 (TDC)		SW1
		Output	3	SW2 (BDC)		SW2
		Output	2	Temp1		Temp1
		Output	1	Temp2		Temp2
		Input	6	GND		GND

Table 6 BVA limit switch and temp connector

8.2. PCU

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name	Arduino
Power2	Power Socket 180-5378	Output	1	OUT A	BVA1 **Power1** 180-5382	OUT A	
			2	OUT B		OUT B	
Power3	Power Socket 180-5378	Output	1	OUT A	BVA2 **Power3a**180-5382	OUT A	
			2	OUT B		OUT B	
Power3a link cable	Power Plug 180-5382 **Power3**	Output	1	12V DC	Power Plug 180-5382 **Power1**	12V DC	
			2	GND		GND	
Power4	Power Socket 180-5378	Input	1	12V DC	BCA **Power5**180-5382	12V DC	12V DC
			2	GND		GND	GND

Table 7 PCU power connectors

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name	Arduino
D-Sub3	PCU 446-737	Output	5	VDD	BVA-P1-PCB **D-Sub1** 795-2210 BVA1	VDD	5V (5)
		Input	4	LSW1 (TDC)		LSW1	D2 (17)
		Input	3	LSW2 (BDC)		LSW2	D3 (18)
		Input	2	Temp1		Temp1	AI0 (9)
		Input	1	Temp2		Temp2	AI1 (10)
		Output	6	GND		GND	GND (7)
D-Sub2	PCU 446-737	Output	5	VDD	BVA-P1-PCB **D-Sub1** 795-2210 BVA2 with **L1**	VDD	5V (5)
		Input	4	LSW1 (TDC)		LSW1	D5 (20)
		Input	3	LSW2 (BDC)		LSW2	D7 (21)
		Input	2	Temp1		Temp1	AI2 (11)
		Input	1	Temp2		Temp2	AI3 (12)
		Output	6	GND		GND	GND (7)
D-Sub4	PCU 446-737	Output	1	Enable/Disable	BCA **D-Sub5** 446-692	Enable/Disable	D4 (19)
		Input	2	POT1		POT1	A4 (13)
		Input	3	POT2		POT2	A5 (14)

Table 8 PCU signal connectors

Interface With	Power Board	Arduino
	INA (1)	5V (5)
	ENA/DIAGA (2)	5V (5)
	PWM (3)	D6 (21) VC1 D9 (24)VC2
	ENB/DIAGB (5)	5V (5)
	INB (6)	GND (7)
	VDD (7)	5V (5)
	GND (8)	GND (7)
	GND (10)	GND (7)
VC+	OUTA	
VC-	OUTB	
GND	GND	
12V DC	VIN	

Table 9 Power interface with Arduino

8.3. BCA

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name
Power5	Power Plug 180-5382	Output	1	12V	BVA1 **Power4** 180-5378	12V
			2	GND		GND
Power6	Power Socket 180-5378	Input	1	12V	Power Plug 180-5382 from Battery/PSU	12V
			2	GND		GND

Table 10 BCA power connectors

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name
D-Sub5	BCA 446-692	Input	1	Enable/Disable	PCU **D-Sub4** 446-737	Enable/Disable
		Output	2	POT1		POT1
		Output	3	POT2		POT2

Table 11 BCA signal connectors

8.3.1. BCA display screen and Adruino

System	Display screen	Arduino
	GND (1)	GND (7)
5V	5V (2)	5V (5)
POT3	Contrast (3)	
	RS (4)	D7 (22)
	RW (5)	GND (7)
	Enable (6)	D8 (23)
R5600 to 5V	Backlight (15)	
	Data (11)	D2 (17)
	Data (12)	D3 (18)
	Data (13)	D4 (19)
	Data (14)	D5 (20)
POT1		A2 (11)
POT2		A3 (12)
Enable SW		D13 (28)

Table 12 Display screen to Arduino

8.4. Link cables

ID	Part #	Direction	Pins	Signal Name	Interface With	Signal Name
L1	186-4043	Output	5	VDD	Links **Sub3 to D-Sub1**	VDD
		Input	4	SW1 (TDC)		SW1
		Input	3	SW2 (BDC)		SW2
		Input	2	Temp1		Temp1
		Input	1	Temp2		Temp2
		Output	6	GND		GND

Table 13 Link cables

9. Bill of Material

Update the BOM

	ID	Component	RS part number	Mfr Part No	Manufacturer	Quantity	rice per unit exc (£	Min quantity	RoHS Compliant	Note
	U4	Arduino Uno Rev3 MCU Development Board A000066	715-4081	A000066	Arduino	1	16.44	1	Yes	
	POT1,POT2,POT3	CTS Linear Potentiometer with an 6.35 mm Dia. Shaft - 1kΩ, ±20%, 5W Power Rating, Linear, SMD	179-0664	026TB32R102B1A1	CTS	3	2.58	1	Yes	
	U5	Displaytech 204A-CC-BC-3LP Alphanumeric LCD Display, White on Blue, 4 Rows by 20 Characters, Transflective	532-6818	204A-CC-BC-3LP	Displaytech	1	11.35	1	Yes	
	R8	RS PRO 5.6kΩ 0.25W Carbon Film Resistor ±5%	707-7723	RS PRO	RS PRO	1	0.12	10	Yes	
BCA	LED1,LED2	2.2 V Green LED 3mm Through Hole, Kingbright L-934GD	228-5944	L-934GD	Kingbright	3	0.4	5	Yes	
		2 V Red LED 3mm Through Hole, Kingbright L-934ID	228-5916	L-934ID	Kingbright	2	0.4	5	Yes	
	SW6	Marquardt Single Pole Single Throw (SPST), On-None-Off Rocker Switch Panel Mount	741-0902	1831.3313	Marquardt	1	2.33	1	Yes	
	F4	Littelfuse 1A Black Car Fuse, 32V dc	787-4110	0287001.PXCN	Littelfuse	1	0.17	10	Yes	
	F4	Littelfuse 20A Inline Fuse Holder for ATO Blade Fuse, 32V ac/dc	787-4356	FHAC0001ZXJG	Littelfuse	1	3.25	1	Yes	
		RS PRO Compact Power Connector Socket, 2P, 40A, 500 V dc	180-5378	RS PRO	RS	6	1.422	10	Yes	
	U1	Arduino Uno Rev3 MCU Development Board A000066	715-4081	A000066	Arduino	1	16.44	1	Yes	
	F1	Littelfuse 1A Black Car Fuse, 32V dc	787-4110	0287001.PXCN	Littelfuse	1	0.17	10	Yes	
		RS PRO 20A Yellow Car Fuse, 32V dc	563-762	RS PRO	RS PRO	2	0.14	10	Yes	
	F1,F2,F3	Littelfuse 20A Inline Fuse Holder for ATO Blade Fuse, 32V ac/dc	787-4356	FHAC0001ZXJG	Littelfuse	3	3.25	1	Yes	
		RS PRO Battery Terminal, Screw	509-7633	RS PRO	RS PRO	1	6.97	1	Yes	
		MIKROE-512, 10 piece Breadboard Jumper Wire Kit	791-6454	MIKROE-512	MikroElektronika	1	2.41	1	Yes	
		MIKROE-511, 10 piece Breadboard Jumper Wire Kit	791-6450	MIKROE-511	MikroElektronika	1	2.41	1	Yes	
		Alpha Wire Black, 3.3 mm^2 Hook Up Wire EcoWire Series , 30m	687-7639	6718 BK005	Alpha Wire	1	42.84	1	Yes	
		Alpha Wire Red, 3.3 mm^2 Hook Up Wire EcoWire Series , 30m	687-7648	6718 RD005	Alpha Wire	1	42.84	1	Yes	
	R1	RS PRO 150Ω 0.25W Carbon Film Resistor ±5%	707-7603	RS PRO	RS PRO	1	0.12	10	Yes	
	R9	RS PRO 820Ω 0.25W Carbon Film Resistor ±5%	707-7669	RS PRO	RS PRO	1	0.12	10	Yes	
	R7	RS PRO 680Ω 0.25W Carbon Film Resistor ±5%	707-7656	RS PRO	RS PRO	1	0.12	10	Yes	
PCU	R2,R3,R4,R5,R6	RS PRO 10kΩ 0.25W Carbon Film Resistor ±5%	707-7745	RS PRO	RS PRO	2	0.108	10	Yes	
	U2,U3	VNH5019 Motor Driver Carrier 12A		Pololu	VNH5019	2	19.2	1	Yes	Alternative 393-9377, or solid state relay with similar characteristics, 5V control, 20V@20A, with minimum of 500ms switch time
		RS PRO Compact Power Connector Plug, 2P, 40A, 500 V dc	180-5382	RS PRO	RS	5	1.422	10	Yes	
		TE Connectivity, AMPLIMITE HDP-20 Straight Military Crimp D-Sub Connector, Socket, 9 Pin	446-737	205203-3	TE Connectivity	3	0.74	1	Yes	
		TE Connectivity, AMPLIMITE HDP-20 Straight Crimp D-sub Connector, Plug, 9 Pin	446-692	205204-4	TE Connectivity	1	0.76	1	Yes	
		Startech 500mm, DB-9 (9 Pin, D-Sub) Male to DB-9 (9 Pin, D-Sub) Female, Serial Cable Assembly	186-4043	MXT10050CMBK	Startech	1	2.99	1	Yes	
		TE Connectivity AMPLIMITE 109 Series size 20 Male Crimp D-sub Connector Contact, Gold over Nickel Plated Signal, 24	680-9210	205089-1	TE Connectivity	3	0.422	5	Yes	male
		TE Connectivity AMPLIMITE 109 Series size 20 Female Crimp D-sub Connector Contact, Gold Plated Signal, 24 → 20	680-9222	205090-1	TE Connectivity	15	0.7	5	Yes	female
	S1,S2	Natural, White Round Tactile Switch, Single Pole Single Throw (SPST) 50 mA 2.5 (Dia.)mm PCB	909-7993	1571634-2	TE Connectivity	2	0.13	10	Yes	
	U$1,U$2	Maxim Integrated DS600U+T&R, Analog Temperature Sensor -40 → +125 °C ±0.75°C, 8-Pin µSOP	190-5202	DS600U+T&R	Maxim Integrated	2	3.27	2	Yes	
PCB Board	X1	TE Connectivity Amplimite HD-20 Series, 9 Way PCB D-sub Connector Plug, 2.743mm Pitch, with 4-40 UNC, Female Screw Lock	795-2210	1-5747871-6	TE Connectivity	1	4.56	1	Yes	
	R3,R4	Panasonic 10kΩ, 0805 (2012M) Thin Film SMD Resistor ±0.1% 0.125W - ERA6AEB103V	565-948	ERA6AEB103V	Panasonic	2	0.47	5	Yes	
	R5,R6	Vishay 1kΩ, 0805 (2012M) Thick Film SMD Resistor ±1% 0.125W - CRCW08051K00FKEA	679-0982	CRCW08051K00FKEA	Vishay	2	0.03	50	Yes	
	C3,C4	AVX 0805 (2012M) 100nF Multilayer Ceramic Capacitor MLCC 50V dc ±10% SMD 08055C104KAT2A	464-6688	08055C104KAT2A	AVX	2	0.012	50	Yes	

Table 14 BVM BOM