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Peta-pico-Voltron: An open-source high voltage power supply

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ABSTRACT

We present the design (hardware + software) of "Peta-pico-Voltron", a low-current high voltage power supply for electrostatic actuators. Developed primarily for dielectric elastomer actuators, it offers a low-cost solution to generate user controllable voltages up to 5 kV, either continuous, or as square waves with a frequency range between 1 mHz and 1 kHz. The high voltage power supply was developed as an answer to the lack of commercial devices that combine a low cost (<450 USD), portability, and the ability to generate square signals with a high slew rate (>15 V/μs for a 1 pF load). The PCB is designed to be easy to assemble, with a minimum of panel-mounted elements: the unit is controlled from a computer with a user-friendly interface. A Python library of functions is provided, which enables seamless integration of the power supply with other instruments. Alternatively, simple commands can be sent via a serial connection, which makes it possible to control the power supply with any programming language. The PCB footprint with the soldered components is $120 \times 55 \times 25\ \mathrm{mm}^3$ with a weight of 60 g, thus making it a very compact and portable power supply. We also present a battery management circuit to make the system completely standalone when combined with a Raspberry Pi, a touch screen, and a battery.

Specifications table

Hardware name	*Peta-pico-Voltron: a high voltage power supply*
Subject area	*Engineering and Material Science*
Hardware type	*Electrical engineering and computer science*
Open Source License	*GNU General Public License (GNU GPL v3)*
Cost of Hardware	*USD 420*
Source File Repository	*https://osf.io/2ux79/*

1. Hardware in context

The Peta-pico-Voltron (PPV) high voltage power supply has been specifically designed as an affordable and portable versatile power supply for dielectric elastomer actuators (DEAs). DEAs consist of a soft elastomeric membrane sandwiched

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between two compliant electrodes [1]. When a voltage is applied to the electrodes, the generated Maxwell pressure causes the membrane to be compressed and to expand greatly in area (more than 100% strain [1]). This actuation principle and the large actuation strain have been used for many different applications, such as tuneable optics, soft robotics manipulators, microfluidic devices, tactile haptic feedback devices, rotary motors, or soft rubber logic gates to name a few [2,3].

Powering DEAs requires a dedicated electronic circuit, and there are no affordable commercial solutions that are fully adapted to the task. The strain produced by DEAs is proportional to the square of the applied electric field, which is typically of the order of 100 V/μm. As the thickness of the elastomer membrane usually lies between 20 μm and 50 μm, this implies driving voltages in the kilovolt range, albeit at extremely low power. To characterise the response speed of DEAs, it is also necessary to generate step voltages between 0 V and a few kilovolts with a very fast slew rate. In addition, it is often necessary to synchronise the high voltage signal with data acquisition instruments, for example on an automated measurement setup. It is therefore desirable to have the possibility to control the power supply remotely via a computer. Finally, when the actuator under test is used around other instruments (For example in the case of a deformable cell culture system that must be activated inside a portable incubator mounted on a microscope [4]), portability, both in terms of size and weight, is an important factor. The desirable properties of a power supply aimed at controlling DEAs can be summarised as follows:

- High Voltage output (typically up to 5 kV).
- Possibility of generating time-varying signals (square signals, or ideally arbitrary waveforms).
- Possibility of generating high slew rates to create step driving signals.
- Programming interface for combination and synchronisation with other instruments.
- Compact design
- User-friendly

Unfortunately, there are no commercially available power supplies which are both affordable and meet all of the properties above. To this day the authors have tried and used a number of high voltage power supplies (listed in Table 1), however all of these have a number of shortcomings and are less than ideal for controlling DEAs. Laboratory high voltage DC power supplies are heavy, bulky, and only produce DC voltages, albeit extremely stable. High voltage amplifiers have the advantage of being able to generate arbitrary waveforms, but they are heavier, bulkier, and more expensive. Alternatively, DC/DC high voltage converters are cheap and well suited to power electrostatic devices, but they cannot generate rapid square signals, and lack a user-friendly interface. The Biomimetics lab of the Auckland Bioengineering Institute was selling a 4-channel power supply specifically designed for DEAs. However, this model has been discontinued.

We have therefore designed PPV to address the shortcomings of commercial power supplies when used to drive DEAs. PPV combines a PID-regulated high voltage DC/DC converter with a fast high voltage switch based on photodiodes. The regulated converter generates a stable voltage that can then be rapidly switched on and off to produce a square signal. Simple commands can be sent to PPV via a serial connection to control the power supply, making it easy to integrate it with other instruments in an automated setup, for example to synchronise the high voltage actuation signal with data acquisition. We have demonstrated the utility of our power supply in an automated measurement setup to evaluate the degradation of DEA electrodes, in which a PPV, a digital multi-meter, and a camera were controlled by a LabVIEW programme [5]. A user-friendly Python GUI is also provided for controlling PPV.

The cost of the power supply is around USD 420. The expensive components are the DC/DC converter (USD 170, i.e. 40% of the price), and the two photodiodes (USD 130, i.e. 30% of the price). We have chosen to use a commercial high-voltage DC/DC converter to reduce the number of components and make the power supply easy to assemble, although this component represents a substantial portion of the total cost. Seelecke's group has recently published a design for a high-voltage DC/DC converter for a total price of less than 10 euros [6]. It would be possible to further decrease the cost of PPV by integrating Seelecke's approach in lieu of the XP Power DC/DC converter that we have used. The second component that impacts on price are the two photodiodes that are used to rapidly switch the high voltage on and off. They are necessary to obtain square signals with a high slew rate.

Table 1
Summary of the pros and cons of the 4 main types of commercial power supplies we have used to power dielectric elastomer actuators.

Type	Example	Pros	Cons	Price (USD)
DC power supply	Stanford Research Systems PS350/500 V-25 W [7]	• Precise and stable output	• Only DC • Bulky	2300 with GPIB programming interface
HV amplifier	Trek 609E-6 [8]	• Large bandwidth (13 kHz) • Can generate arbitrary signals	• Requires a function generator • Bulky	7700
DC/DC converter	XP Power A50-P [9]	• Light and compact	• Only DC • Requires additional components	170
Other	Auckland Bioengineering Institute EAP controller	• Designed for DEAs • 4 channels	• Discontinued • Low slew rate • Limited to 20 Hz	10,000

Additional information on PPV, including illustrated step-by-step instructions for the soldering and testing of the power supply, as well as future updates to the project are available at http://petapicovoltron.com.

2. Hardware description

The PPV project is articulated around the PCB of the high voltage power supply (Fig. 1), whose assembly, testing and usage is described in detail in this article. In its most simple usage configuration, the PPV PCB is connected to an AC/DC adapter and to a computer or tablet running the user interface. Optionally, it can be combined with a Raspberry Pi [10], an LCD touch-screen, and a battery with management circuit to form a standalone unit. Information regarding the battery management circuit and the assembly of the standalone version is given at the end of the article. This is an optional configuration which is not required to use PPV.

The PPV is an accurate HV power supply with high frequency switching capability in a compact form factor. The PPV offers:

- PID regulated DC power supply with an absolute error of less than 5 V (5 kV PPV).
- High voltage switch enabling square signals from 1 mHz up to 1 kHz with a slew rate >15 V/μs, or continuous DC output.
- Simple communication protocol to aid project integration.
- User-friendly cross-platform graphic user interface.

The benefits of the PPV are explained in more detail below along with specific references to the hardware. The schematic diagram of the circuit is shown in Fig. 2.

2.1. DC high voltage power supply

The high-voltage is produced by a *XP power (formerly EMCO) series A* proportional DC/DC converter (EMCO1). PPV can accommodate different voltage ratings of the converter. Although any series A model with a 5 V input rating can be used, we provide component values for the following output voltage ratings: 5 kV, 3 kV, 2 kV, 1.2 kV, and 500 V. The *Arduino micro* (uC1) [11] provides a 10 bits PWM signal, so the voltage setting resolution depends on the voltage rating of the DC/DC HV converter (i.e. about 5 V for a 5 kV model, and about 2 V for a 2 kV model). The 5 V input power generated by the regulator reg1 feeds the converter EMCO1 through a mechanical switch (S2), which acts as a safety switch to ensure that no high voltage is produced when it is disabled. The PWM signal from uC1 pin 18 is used to control a buck converter formed by transistor Q2, inductor L1, and capacitance C3, in order to control the driving voltage of the proportional DC/DC converter EMCO1. A resistive divider formed by resistors R6 and R9 is connected to the high voltage generated by the converter EMCO1 on pin 3,

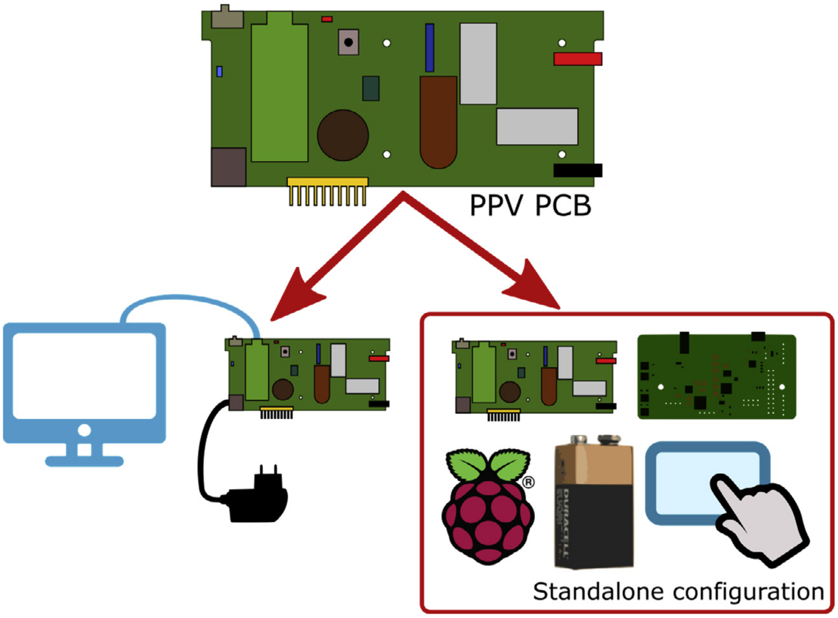

Fig. 1. The PPV project is based on a versatile high voltage power supply board which can be used in multiple configurations. In this article two configurations are described: 1) use of the PPV board with a computer running the provided user interface and an external AC/DC adapter to provide power (left), and 2) A standalone configuration consisting of the PPV board, a touch screen, a Raspberry Pi, a battery, and a power management circuit (right).

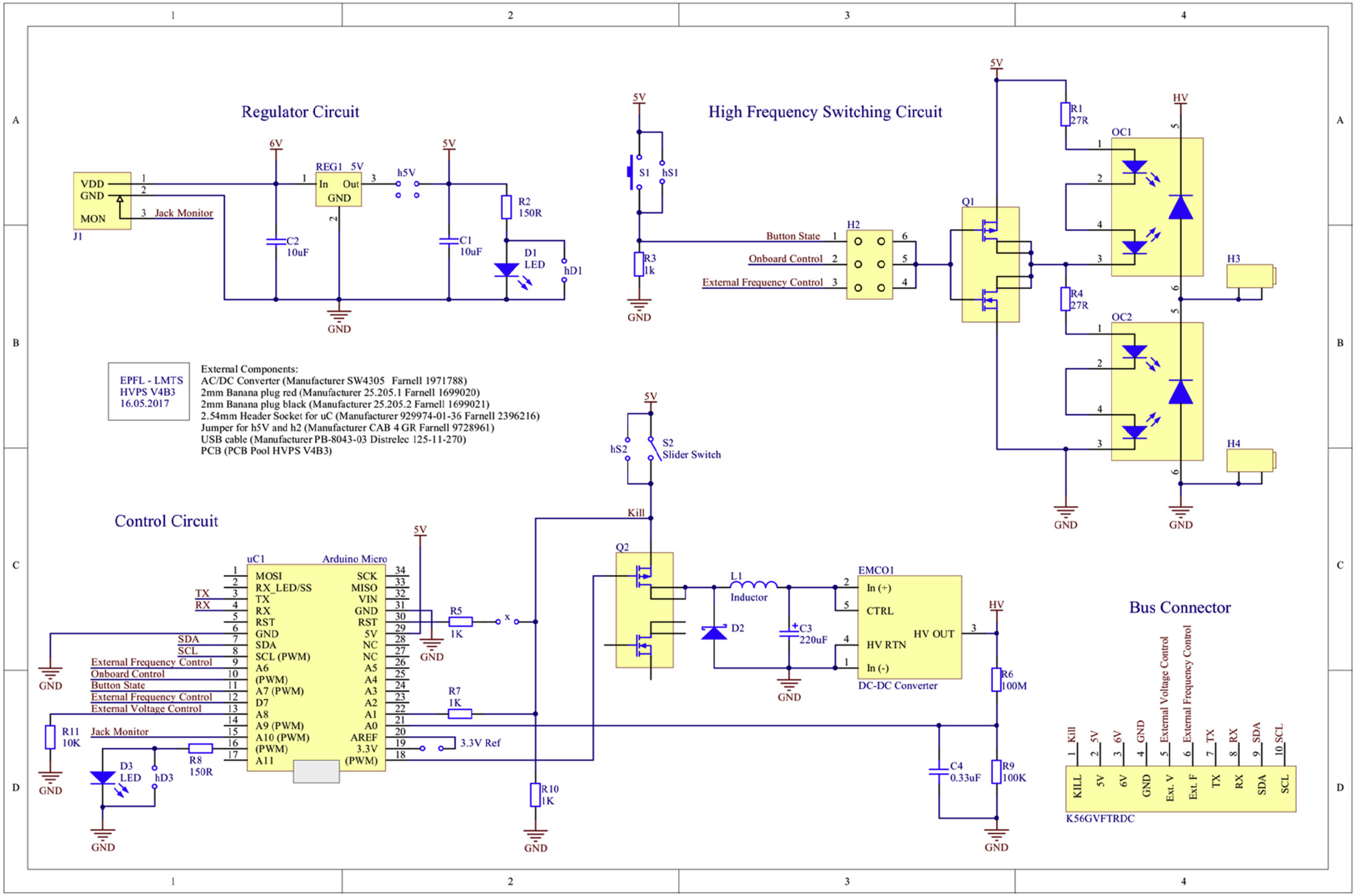

Fig. 2. Schematics of PPV. Refer to the file *PPV-HVPS_PCB.PDF* for a high-resolution version.

and its low-voltage output is fed to a 10-bit analogue input on pin 21 of uC1. A PID controller regulates the high voltage output, by acting on the PWM signal controlling Q2. The values of the resistances forming the resistive divider (R6 and R9) depend on the voltage rating of the converter and are given in the bill of materials. The divider is designed, so that it produces an output voltage of about 4.8 V when the HV converter delivers its full rated output. As the Arduino's analogue input saturates at 5 V, this gives the opportunity to detect over-voltages on the converter.

2.2. High voltage switch

A high voltage switch formed by two high voltage photodiodes (OC1 and OC2) makes it possible to quickly switch the potential of the high voltage terminal (H3) between the value of the high voltage power supply and ground. This enables the generation of a DC output voltage, or of a square signal with high slew rate. The high voltage switch can be controlled by three different sources with the header H2: 1) an internal timer that can generate a square signal with a frequency between 1 mHz and 1 kHz. The timing signal is generated on pin 10 of uC1. 2) A push button (S1) for a direct manual control of the output state. The button can either act as a push button (output on while switch is pressed), or as a toggle switch (output changes state at each push of the button). 3) An external 5 V TTL signal. Header H2 can be used to select between the 3 switching sources (selection via hardware). Note that the pushbutton and external TTL control can also be used when the device is software controlled, (H2 is set to on-board control). Regardless of the source, the switching signal is used to control the dual MOSFET Q1, which sends current through the LEDs of OC1 or OC2, thus controlling the output voltage on H3. The DC current transfer ratio of the optocouplers is around 0.3%, leading to an output current of 220 μA. Depending on the voltage rating of EMCO1, the limiting factor for the current output may be the DC/DC converter. For example, the 5 kV unit has a maximal current output of 200 μA, with 50 μA used for the voltage monitoring, thus leaving 150 μA for the load. The output current of a 5 kV PPV is therefore limited by the DC/DC converter.

2.3. Control PPV with simple serial commands

A USB port (on the Arduino) enables communication with PPV. Serial commands can be sent for a low-level control, or for controlling PPV from a computer programme, for example as part of an integrated setup (refer to the file *Serial_commands_for_the_HVPS.pdf* for a list of commands). Alternatively, a graphic user interface can be used to control the power supply manually.

2.4. Freeze high frequency actuation with stroboscopic illumination

PPV can generate a 5 V signal synchronised with the square output voltage, acting as a general-purpose trigger (1 × 10 header pin 7). The trigger signal duration and phase shift relative to the output waveform can be set by the user. If the pulse duration is short, this signal can for example be used to control a stroboscope in order to freeze the motion of the connected actuator. The phase shift between the output and trigger signal can also be auto-incremented at a desired rate, to slow down the apparent motion of the actuator.

2.5. Use PPV without a computer

The parameters of PPV (output voltage, frequency, number of cycles, source of the switching signal, number of cycles, etc.) can be saved into the device's non-volatile memory, making it possible to initialise the power supply to the desired configuration when it is powered up. When this mode is used the PPV can be used without a computer. This feature is convenient for demonstrations when the parameters do not need to be changed.

2.6. Combine multiple PPVs to produce multi-channel high voltage supply

I2C connections on the 10-pin header make it possible to connect up to 4 PPVs together into a multi-channel power supply. The channels can be controlled completely independently or be synchronised at the same frequency. In the latter case, a precise phase shift between the channels can be defined. This is useful for applications that require several synchronised channels, such as peristaltic pumping or multiphase motor.

2.7. Cross platform GUI

PPV is designed to be easy to assemble with a minimum number of components to solders and is therefore devoid of a physical user interface. PPV is meant to be connected to a computer on which a graphic user interface runs. We have designed a cross-platform graphic user-interface in Python that enables direct control of PPV. It can be run on any device equipped with a USB port and able to run Python 3.x. This includes computers running Windows, OSX, or Linux, but also tablets or mini-computers (Raspberry Pi, BeagleBoard, etc.).

3. Design files – PPV

3.1. Design files summary

Design file name	File type	Open source license	Location of the file
Altium_HVPS_V4B3.zip	PCB file, Altium	*GNU GPL v3*	*https://osf.io/2ux79/*
Gerber_HVPS_V4B3.zip	PCB file, Gerber	*GNU GPL v3*	*https://osf.io/2ux79/*
py-hvps-interface_v2.8.zip	Python user interface	*GNU GPL v3*	*https://osf.io/2ux79/*
shvps_8.zip	Arduino sketch	*GNU GPL v3*	*https://osf.io/2ux79/*
Small_enclosure_solidworks.zip	Solidworks CAD	*GNU GPL v3*	*https://osf.io/2ux79/*
Small_enclosure.svg	SVG file	*GNU GPL v3*	*https://osf.io/2ux79/*
Serial_commands_for_the_HVPS.pdf	Pdf document	*GNU GPL v3*	*https://osf.io/2ux79/*
HVPS_GUI.pdf	Pdf document	*GNU GPL v3*	*https://osf.io/2ux79/*
BOM-PPV.xlsx	Excel sheet	*GNU GPL v3*	*https://osf.io/2ux79/*
PPV-HVPS_PCB.PDF	Pdf document	GNU GPL v3	*https://osf.io/2ux79/*

- *Altium_HVPS_V4B3.zip:* Altium project file for the high voltage power supply (HVPS) PCB.
- *Gerber_HVPS_V4B3.zip:* Gerber files to produce the HVPS PCB.
- *py-hvps-interface_v2.8.zip*: Python 3 graphic user interface to control the HVPS. Requires the pySerial module for access to the serial port.
- *shvps_8.zip*: The sketch for the Arduino micro that controls the single channel HVPS
- *enclosure_solidworks.zip:* CAD files (Solidworks) for a protection enclosure.
- *enclosure.svg:* SVG file with the enclosure parts. Can be used to laser-cut the parts in 3 mm thick sheets.
- *Serial_commands_for_the_HVPS.pdf:* List of commands to communicate with the HVPS.
- *HVPS_GUI*.pdf: User manual of the Python Graphic User Interface.
- *BOM-PPV*.xlsx: Bill of material to assemble PPV
- *PPV-HVPS_PCB.PDF:* Schematics and PCB layout of the high voltage power supply.

4. Bill of materials – PPV

The bill of material is available in the repository as a separate file. The excel file is separated in two different tabs:

- *HVPS PCB v4b3*: The first tab lists the components required to assemble the main PCB of the high voltage power supply.
- *Cables and adapters*: The second tab lists additional components required to use PPV (HV rated output cables, power adapter, etc.)

5. Build instructions – PPV

a. Solder the components of the bill of materials (BOM-PPV.xls, tab HVPS PCB v4b3) on the board. Fig. 3 shows a fully assembled board, along with the function of the main components. The names of the components are clearly labelled on the PCB silkscreen and correspond to the names given in the bill of material (column *Designator*). The values of

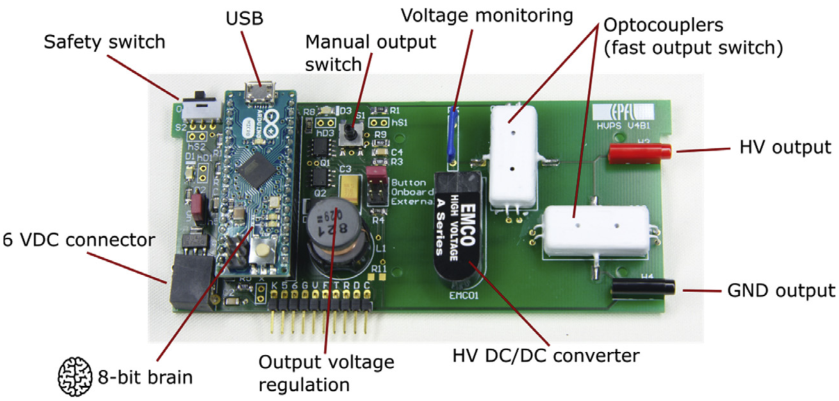

Fig. 3. Assembled PPV board. The left side of the board consists of the low voltage control circuitry. The right side of the board consists of the high voltage components and should not be touched during operation.

Table 2
Voltage divider resistance values (R6 & R9), voltage calibration constant C_1, and PID gains for PPVs of different voltage ratings (corresponding to different DC/DC converters).

Voltage rating (V)	R_6 (MΩ)	R_9 (kΩ)	C_1	k_p	k_i	k_d
5000	100	95.3	1.0503	0.23	2.2	0.004
3000	50	80.6	1.0356	0.36	2.9	0.006
2000	50	120	1.0442	0.35	5	0.004
1200	22	88.7	1.0376	0.51	8	0.006
500	22	215	1.0333	0.2	8	0.006

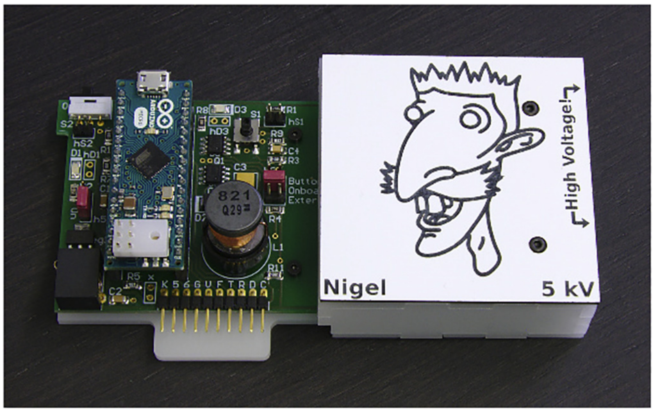

Fig. 4. PPV board with an enclosure covering the high voltage side of the circuit.

resistances R_6 and R_9 depend on the voltage rating of the DC/DC converter. Table 2 lists the respective values for the different voltage ratings of the DC/DC converters. It is better to start with the small SMD components and finish with the large through-hole components. The website http://petapicovoltron.com has an illustrated step-by-step assembly guide and a soldering checklist to help with the assembly process.

b. Insert an Arduino micro on the socket UC1, with the USB socket towards the edge of the PCB (see Fig. 3).
c. Put a jumper on header h5V in the ‘on’ position, and a jumper on h2 in the ‘onboard’ position.
d. Place the assembled board in a protection enclosure to prevent users from touching the high voltage components (Fig. 4). The files enclosure_solidworks.zip and enclosure.svg show an example of enclosure that covers the high voltage components but leaves the low-voltage components accessible. In this configuration, the on-board switches S1 and S2, and LEDs D1 and D3 are easily accessible. It is also possible to place the PCB in a complete enclosure. In this case, the headers hS1, hS2, hD1, and hD2 can be used to link a panel-mounted switch/LED to the PCB.

Safety notice: High voltage is generated on the right side of the board. Even though the output current is limited to below 125 µA, precautions must be taken to prevent users from accidental shock while connecting a load and/or manipulating the PPV high voltage power supply. The switch S2 acts as a mechanical safety switch. Irrespective of whether the power jack or USB cable are plugged, and irrespective of any settings of the GUI or commands sent to PPV via the serial link, **there will be no voltage present at the output of the unit (H3) as long as switch S2 is in the off (0) position**. Consequently, this switch must always be placed on 0 when connecting/disconnecting a load, or when manipulating the board.

6. Initial set-up of PPV

- **Check that the safety switch S2 is in the 0 position**.
- Download and install the Arduino IDE from http://arduino.cc If you are on a Windows computer, you also need to install the drivers that come with the package.
- Connect PPV to the computer with a USB cable.
- Use the Arduino IDE to flash the single channel HVPS sketch (*shvps_8.zip*) to the microcontroller. Don’t forget to select the correct target (Genuino/Arduino Micro) and serial port in the *tools* menu. More information on uploading sketches to Arduino microcontrollers is available on the Arduino website.
- Once you have successfully uploaded the sketch to the microcontroller, establish a serial connection.

  - With the Arduino IDE: Open the serial monitor (Ctrl + shift + M, or Tools → Serial Monitor), and select “carriage return” as end of command character, and 115,200 baud as transmission speed.
  - With any other terminal programme, use the following parameters:

Bits per second	115,200
Data bits	8
Parity	None
Stop Bits	1
Flow Control	None

- You can test communication with PPV by entering *QVer* and pressing the enter key. PPV should reply with the string *slave 8*, where 8 is the version number of the firmware. Each command must be validated by pressing the < enter > key.
- Enter the command *Conf XXXX* where XXXX is the voltage rating of your board, in order to automatically initialize the voltage calibration constant C_1 and the PID coefficients to the values indicated in Table 2. If you have used a DC/DC converter with a different maximal voltage than the entries in the table, you need to enter the configuration coefficients by hand (see *Serial_commands_for_the_HVPS.pdf* for a list of commands).
- GUI configuration: refer to the file HVPS_GUI.pdf for a detailed description of how to install and use the GUI.

7. Operation instructions

- **Check that the safety switch S2 is in the ‘0’ position**. This is a safety measure to be sure that no high voltage is generated by the board.
- Power the PPV with the 6 V adapter and connect PPV to a computer with the USB cable. Connect the device to be tested to the HV output of PPV.
- Launch the Python interface (refer the file HVPS_GUI.pdf for detailed information on how to use the GUI).
- Put safety switch S2 in position ‘1’ to enable the HV output. **From this moment, high voltage may be present at the output of PPV. Do not touch any of the components connected to the high voltage terminals**.
- Perform experiments.
- Place safety switch S2 back in position 0 once you have finished and close the interface.

8. Voltage calibration

The automatic setup of the power supply performed with the *conf* command provides a basic calibration of the unit based on the nominal values or the resistances R_6 and R_9, as indicated in Table 2. On a 5 kV unit, the default calibration will typically lead to a voltage output within ±100 V (±2%) of the desired value. The calibration can be refined with the help of a high voltage probe and multimeter, to reach a voltage output between ±5 V (±0.1%) of the desired value:

- Reset the calibration to its default value by issuing the 3 following commands:
  - SC0 0
  - SC1 1
  - SC2 0
- Connect the output of PPV to a voltmeter through a high voltage probe (For example Keysight 34136A). Be sure to use a probe rated for the voltage range of your PPV.
- Place PPV in DC mode, and use the GUI to generate voltages between 5% and 100% of the voltage range. For each desired output voltage, record the feedback voltage indicated on the interface, and the real output voltage read by the multimeter (correct for the probe attenuation factor).
- Plot the measured values. Place the feedback voltage indicated by the GUI on the x-axis, and the effective voltage measured by the probe on the y-axis.
- Use a polynomial fit to obtain the correction coefficients (Fig. 5). In a perfect linear world, we physically expect to obtain a curve of the form $y = c1\ x$. However, we have found that a correction equation of the form $y = c0 + c1\ x + c2\ x^2$ leads to much better accuracy. This 2nd order polynomial correction is implemented in PPV with the coefficient c0, c1, and c2. But you can easily use a purely linear correction if you prefer by assigning a value of 0 to c0 and c2.
- Enter the value of the coefficients in PPV. There is a 10E-6 multiplier for coefficient c2. Therefore, for the situation depicted in Fig. 5, the commands to enter are:
  - SC0 17.51
  - SC1 1.045
  - SC2 −7.161

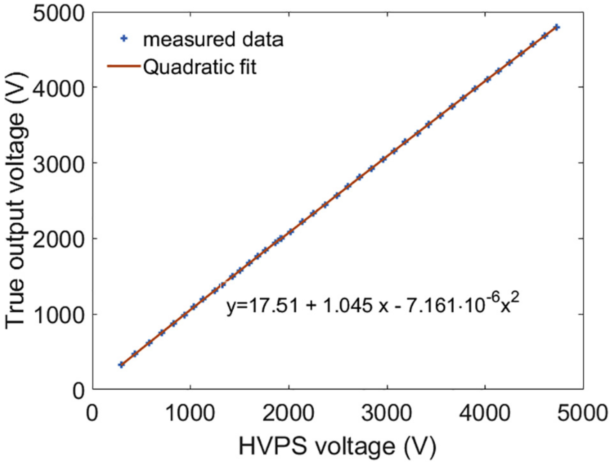

Fig. 5. Calibration of a 5 kV PPV with input voltages between 250 V and 4750 V. A quadratic fit is applied to the experimental data to extract the calibration coefficients c0, c1, and c2.

9. Validation and characterization

The accuracy of the voltage output for a 5 kV PPV is shown in Fig. 6 for three different calibrations. The *default calibration* is the one obtained using a linear correction based on the nominal values of resistances R_6 and R_9 (Table 2). The *linear calibration* shows the error obtained with a linear correction based on experimental data measured with a HV probe. The average error is smaller than when using the default value, and is not linear, showing that a linear calibration is not optimal. The *quadratic calibration* shows the error on the output voltage when using a quadratic calibration (Fig. 5) as described in Section 8. The error of this PPV, when using a quadratic calibration, is comprised between +3.3 V and −1.8 V.

The voltage regulation is shown on Fig. 7. As the high voltage DC/DC converter is non-linear, the dynamic response depends on the target output voltage. It is therefore difficult to define optimal coefficients for the PID regulator. The results shown on Fig. 7 are obtained on a 5 kV PPV, using the default regulator gains shown in Table 2. These have been chosen to reach a trade-off between response speed and overshoot. They can be adapted depending on the priority given to these two characteristics of the system, for example to avoid any overshoot at the cost of a slower response speed. A step down from a starting voltage to 0 V is slower due to the discharge rate of the DC/DC converter. Table 3 shows the rise time, overshoot for the rising edge, and fall time when going back to 0 V for the five different voltage set points shown in Fig. 7.

The characterization of the switching speed of the output optocouplers that generate the square signal is shown in Fig. 8 for a 3 kV PPV. These tests are performed without load apart from the high voltage probe (100 MΩ and 1 pF). Switching between 0 V and the full output voltage (3 kV) is performed at 4 different frequencies ranging between 1 Hz and 1 kHz. The rise time of the generated square signal is 190 μs for all 4 tested frequencies, and the fall time is 160 μs. The slew rate

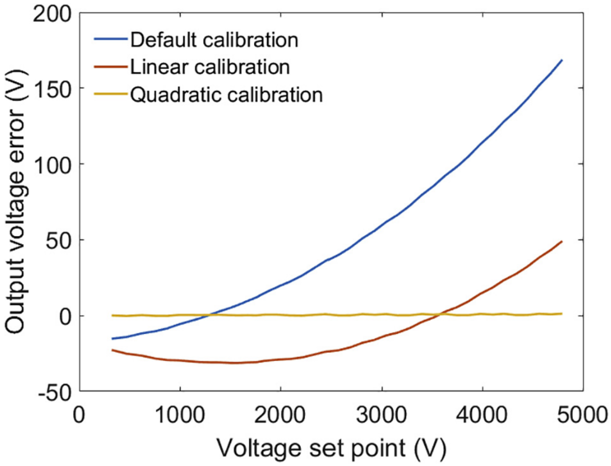

Fig. 6. Output voltage error of a 5 kV PPV with different calibrations.

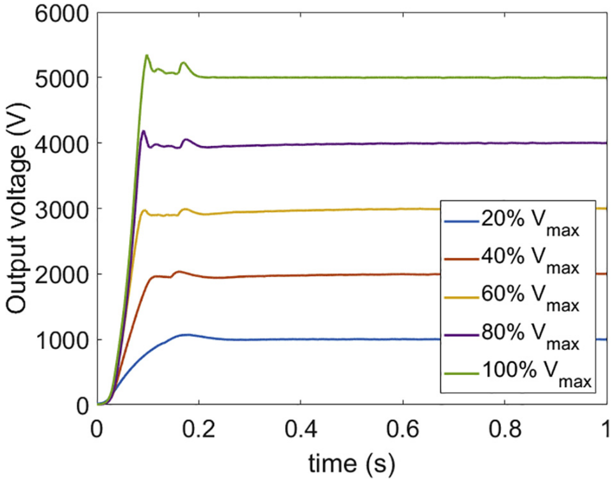

Fig. 7. Closed loop regulation of the output voltage for a step between 0 V and 5 different target values, as measured on a 5 kV PPV.

Table 3
rise time (90% of set point), overshoot and fall time for the tested 5 kV unit.

Voltage set point (V)	Rise time (ms)	Overshoot (%)	Fall time (ms)
1000	94	6.9	442
2000	64	1.8	384
3000	46	0	329
4000	44	5.1	294
5000	48	6.9	263

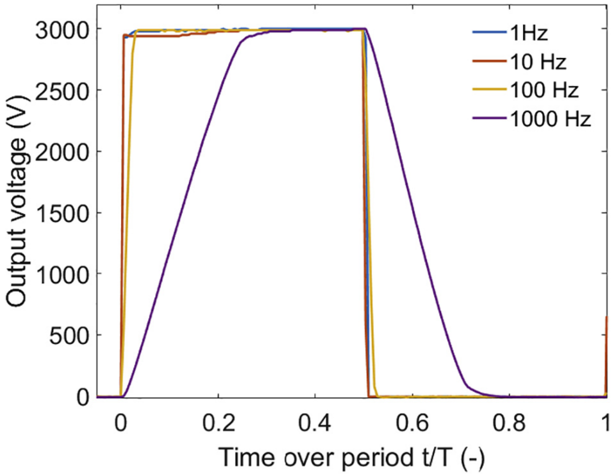

Fig. 8. characterization of the high voltage switch on a 3 kV PPV at full output voltage. The output voltage is plotted as a function of the relative time (time over the signal period) for 4 different switching frequencies. PPV can produce square signals in the range of 1 mHz to 1 kHz. Square signals below 1 Hz have the same profile as the 1 Hz signal, and are therefore not shown on the figure.

is 16 V/μs on the rising edge, and −19 V/μs on the falling edge. These high slew rates allow the generation of high voltage square signals up to a frequency of 1 kHz.

We have successfully used PPV to control dielectric elastomer actuators in different configurations. Three specific cases are described here. 1) we have used PPV to apply periodic strain via a DEA-based cell-stretching device to lymphatic endothelial cells to study strain-induced alignment [4]. In this instance, a square voltage signal of 4 kV was applied at 0.1 Hz for 24 h. 2) We have designed an automated setup to characterise the degradation of the compliant electrodes of DEAs [5]. The measurement setup combines a PPV power supply, a camera, and a digital multimeter controlled by a LabVIEW

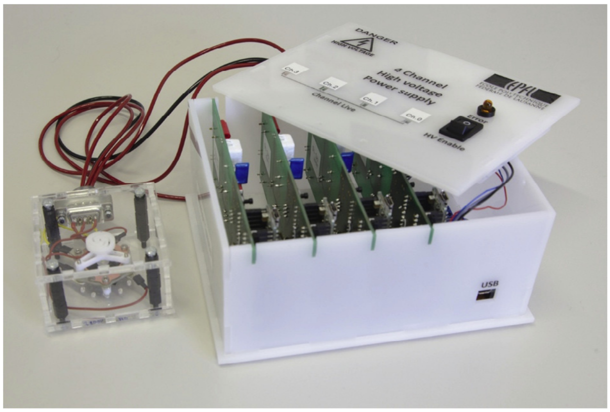

Fig. 9. Several PPV boards can be grouped into a multi-channel unit. The picture above shows a 4-channel power supply used to drive a 3 phase motor (4th channel unused). The channels can be configured to output a synchronized square wave with a defined phase shift.

interface. We make use of the ability of PPV to generate rapid square signals and voltage ramps, and take advantage of the simple communication protocol of PPV to synchronise all the instruments in the setup (multimeter to measure the resistance of the electrode, and camera to measure the strain). In this study, we have also used the trigger function of PPV to freeze the motion of the actuators in order to characterise how the maximal strain is affected by the driving signal frequency [5]. The resistance measurement setup was used to study the degradation of different types of compliant electrodes for DEAs based on carbon black [12]. 3) We have also used the expandability of PPV to produce a multichannel high voltage power supply. The multichannel power supply was used to drive the 3-phase motor described in [13]. Three PPV are synchronised using the I2C bus to generate square signals of 600–700 Hz with a 120° phase shift, which are then connected to each electrode of the motor, thus making the proof mass turn (Fig. 9).

10. Standalone configuration

Here we present an optional configuration that groups PPV, a Raspberry Pi, a 7” touch screen, a battery, and a battery charging circuit into a single package, thus forming a completely independent and portable high voltage power supply with integrated touchscreen (Fig. 10).

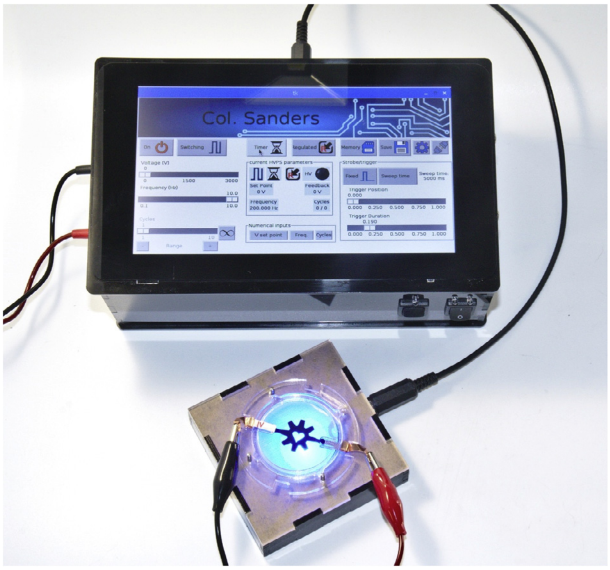

Fig. 10. PPV in standalone configuration with Raspberry Pi, 7” touchscreen and battery. PPV is pictured driving a DEA mounted on a strobe light. PPV provides power to the light, as well as a logic signal synchronized with the high voltage square signal driving the actuator.

One of the important advantages of this configuration is the battery, which allows the unit to be completely independent and portable. In the next sections, we present a custom-designed battery-management circuit for a Lithium polymer battery. The circuit provides the 5 V power required by the PPV, the Raspberry pi, and the LCD screen. We describe the main characteristics of the battery charging circuit, and how to assemble the standalone configuration of PPV. The additional cost of the PPV in the standalone configuration is USD 245, for a total of USD 665.

11. Battery management circuit

The battery charging circuit is required to provide battery power for running the PPV + Raspberry Pi + Screen configuration described in the previous section, in order to make a completely standalone unit. It provides a 5 V supply to power the different components (Raspberry Pi, Screen and PPV). The USB connector on the board can be used to charge the battery, and to send serial commands to PPV).

11.1. Battery charger

The circuit diagram is shown in Fig. 11. The battery charger IC (U2) is a BQ24192 by Texas Instruments. This is a switch mode charger which utilizes an inductor (L2) to buck down the supply voltage and charge the battery at high efficiency. This charger is specifically designed for single cell Li-Po or Li-Ion batteries which have a typical voltage range of 2.6–4.2 V. Any range of battery capacity is acceptable, but it is recommended that a capacity of at least 5000 mAh is used. The charger has inbuilt automatic current limiting: when it detects that the voltage source cannot supply the current it requests, it lowers its charging current. In this design, the default maximum charge current is 3 A and this is set by the value of R15. There are two ways to charge the battery: 1) the high current DC Jack (P5) which can safely tolerate voltages in the range 5–15 V. 2) the micro USB plug (P3). By default the USB current draw is limited to 500 mA. There are two headers for LEDs (P13, P14) which are controlled by the charger IC. These are STAT and !PG, STAT will turn on while charging and blink if anything is wrong, e.g. if no battery is present. !PG is used to show that a charging source is available – when the battery is charged STAT will turn off but !PG will remain on.

The charger has temperature sensor connections (P7, P8) which allows the battery temperature to be sensed to prevent damage to the battery. The temperature sensors must be 10 kΩ NTC thermistors. Only one temperature sensor is necessary,

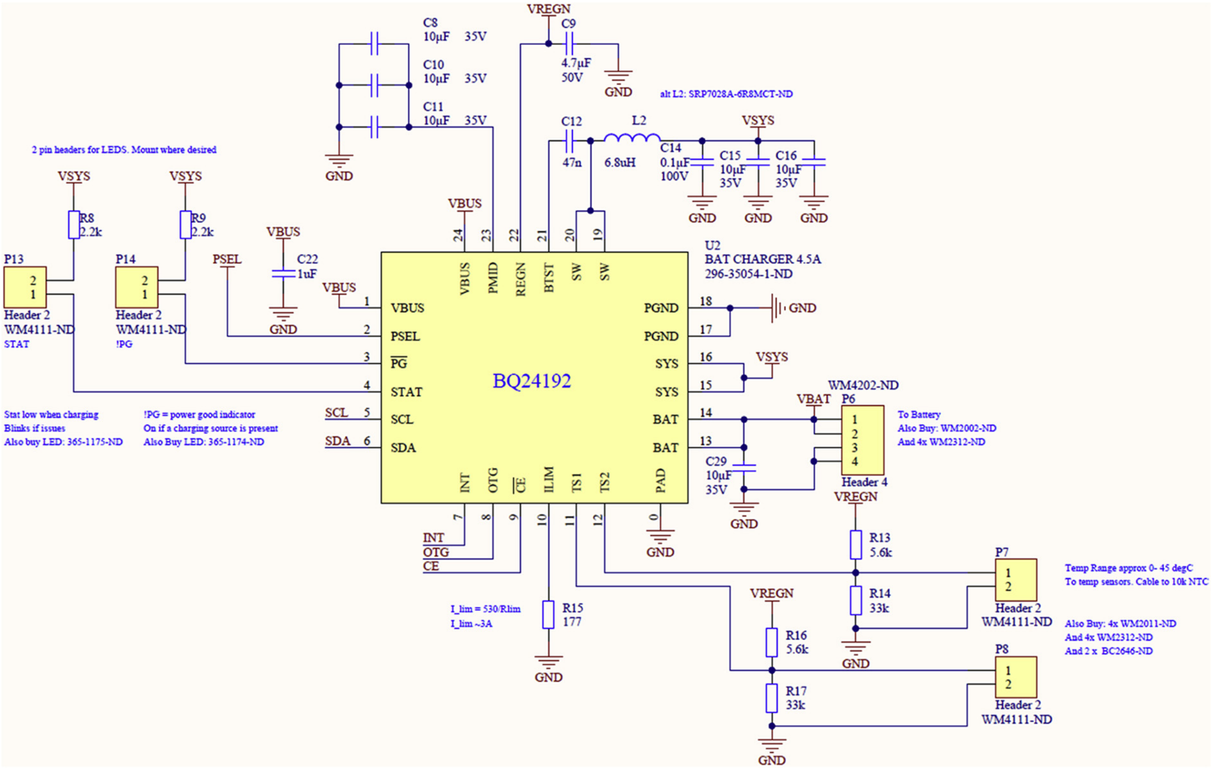

Fig. 11. Circuit diagram of the battery charging IC – BQ24192 (Refer to the file *Battery_management_PCB.pdf* for a high resolution schematics).

but having two allows multiple locations on the battery to be sensed. If one of the sensing resistors in not used, it must be replaced with a 10 kΩ resistor. The charger has built in short circuit current detection. If the VSYS rail draws more than 9 A, the system will disconnect the battery to protect it from short circuit. To reset this, all charging sources must be removed and then reconnected.

11.2. Boost converter – 5 V supply rail

The Boost Converter IC (U3) provides a 5 V supply rail to power the Raspberry Pi, LCD screen, and PPV from the lower battery voltage. It is based on a LTC3872 constant frequency current mode controller by Linear Technology as depicted in Fig. 12. This converter takes the protected battery voltage VSYS and steps this up to 5 V. The voltage to the Boost Converter is passed through a switch header (P9) which allows the 5 V to be turned off and preserve the battery. There is no current sense resistor in this converter, as it uses the MOSFET (Q2) on-state resistance as the sense resistor. This improves efficiency but does put a limit on the adaptability of the system. For the chosen MOSFET, there is a range of temperature-dependent on-state resistances, which puts the output current limit of the 5 V rail at somewhere between 3.9 and 4.8 A, depending on temperature and battery state of charge. If a higher current is drawn, the 5 V rail begins to fall. The 5 V rail is fed to three different locations. Header P2 (see *Battery_management_PCB.pdf*) feeds the 5 V to the Raspberry Pi. Header P10 feeds the 5 V to the Screen. Header P11 feeds the 5 V to PPV.

11.3. USB to serial converter

The Raspberry Pi IO header is connected to the output of a FT231XQ-R USB-to-Serial converter chip made by Future Technology Devices International (Refer to the file *Battery_management_PCB.pdf*). This chip is connected to the micro USB plug (P3) on the input side and converts the USB input data to Serial (UART). It also lowers the serial communication voltage to 3.3 V to make it compatible with the voltage level of the Raspberry Pi I/O. The GUI has a listening mode, which forwards commands sent to the Raspberry pi to PPV. It is therefore still possible to control PPV programmatically with a computer, even in the standalone configuration, in which the USB port of PPV is not accessible.

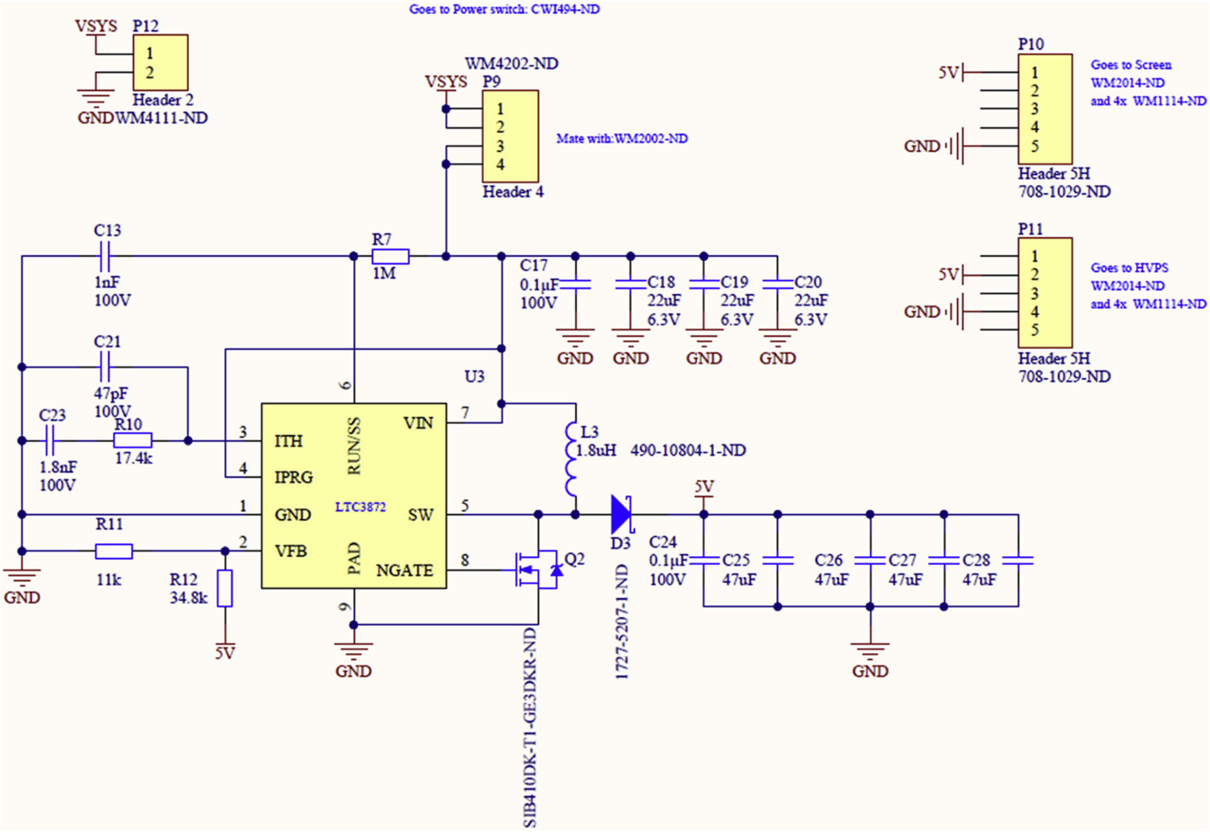

Fig. 12. Circuit diagram of the Boost Converter – LTC3872 (Refer to the file *Battery_management_PCB.pdf* for a high resolution schematics).

12. Design files for the standalone configuration

12.1. Design files summary

Design file name	File type	Open source license	Location of the file
Altium_Battery_PCB.zip	PCB file, Altium	GNU GPL v3	*https://osf.io/2ux79/*
Gerber_Battery_PCB.zip	PCB file, Gerber	GNU GPL v3	*https://osf.io/2ux79/*
standalone_config_solidworks.zip	Solidworks CAD	GNU GPL v3	*https://osf.io/2ux79/*
BOM.xlsx	Excel file	GNU GPL v3	*https://osf.io/2ux79/*
Battery_management_PCB.pdf	Pdf document	GNU GPL v3	*https://osf.io/2ux79/*

- *Altium_Battery_PCB.zip:* Altium project file for the battery charger PCB.
- *Gerber_Battery_PCB.zip:* Gerber files for the production of the battery charger PCB.
- *standalone_config_solidworks.zip:* CAD files (Solidworks) for the enclosure of the standalone configuration.
- *BOM-standalone.xlsx*: Bill of materials for the standalone configuration.
- *Battery_management_PCB.pdf:* Schematics and PCB layout of the battery management circuit.

13. Bill of materials for the standalone configuration

The bill of material is available in the repository as a separate file. The components for the standalone configuration are located on two different tabs:

- *Battery management PCB*: List of the components required to assemble the battery management PCB, which is required if you want to assemble the stand-alone configuration with integrated touch screen and battery
- *Touchscreen configuration*: Additional components required to assemble the standalone configuration (USB cable, Buttons, Raspberry Pi, etc.).

14. Build instructions for the standalone configuration

- You need a functioning and calibrated PPV PCB first. Follow the instructions given in Sections 3 to 8 prior to assembling the power supply into the standalone configuration.
- Connect PPV to a computer and send command SPowJack 0 to PPV. This will tell PPV that the power will not come through the power jack, so it will not check if the jack is plugged in.
- On the PPV PCB, move jumper h5V from the ‘on’ to the ‘off’ position.
- Connect the Raspberry Pi to a monitor and install the python graphic user interface (py-hvps-interface_v2.8.zip). The interface uses the entire screen, so it is recommended to auto-hide the taskbar of the Raspberry Pi. To auto-hide the taskbar, right-click on it and select “Panel Settings”. Click on the “Advanced” tab, and check “Minimize panel when not in use”.
- Connect PPV to one of the Raspberry Pi USB ports, and check that the interface and PPV are communicating.
- Solder the components of the bill of materials of the battery management PCB (Tab *Battery management PCB*) on the board. The names of the components are clearly labelled on the PCB silkscreen and correspond to the name given in the bill of material (column *Designator*).
- The file *standalone_config_solidworks.zip* contains a Solidworks CAD model of an enclosure specifically designed to house all of the components (PPV, Raspberry Pi, battery, battery PCB, LCD screen). The file *complete_assembly.SLDASM* shows how all the components are assembled. All plastic parts are designed to be laser cut into 3 mm-thick plastic sheets, except for part *HVPS_support* which needs to be cut from a 6 mm thick plastic sheet. The folder *laser_cutting* contains SVG files which are ready for laser-cutting. Glue is required to assemble the plastic parts together (e.g. cyanoacrylate-based adhesive).
- The Raspberry Pi is fixed on the screen controller using the spacers provided with the touch screen, and the PPV PCB is fixed on the Raspberry Pi using the 30 mm spacer (refer to the Solidworks assembly file) (Fig. 13). The battery is fixed with double-sided tape to the bottom plate. It is recommended to add a thin PET sheet on top of the battery to provide electrical insulation from the high voltage produced by PPV. The battery management PCB is located on the screen holder. Use the right-angle short USB cable to connect any USB port of the Raspberry Pi to the PPV Arduino.
- Assemble the 4 sides of the enclosure. There are two openings for on/off buttons that can be snapped in place, and 3 holes for LEDs, which should be glued in the holes beneath the switches (Fig. 14 left). Button 1 is the main power switch and connects to P9 on the battery management PCB. LED 2 is the Power good LED (green) and connects to P14 on the battery PCB. It turns on when the circuit is connected to an external power supply. LED 3 is the status LED that connects to P13. It turns on when the battery is charging, or blinks if there is an error. Button 4 is the high voltage safety switch which connects to header S2 on the PPV PCB, and the LED 5 (red) indicates the presence of HV on the output, which must be connected to hD3 on the PPV PCB. The on-board LED D3 should be removed from the PPV PCB.

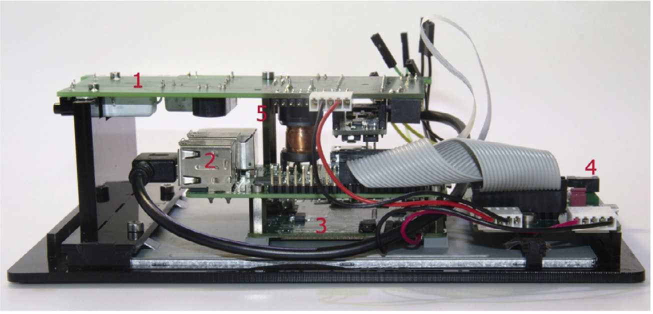

Fig. 13. Touchscreen assembly. 1) PPV PCB, 2) Raspberry Pi, 3) LCD screen with controller, 4) Battery management PCB, and 5) 30 mm spacer. The battery is fixed to the bottom of the enclosure and not shown in this picture.

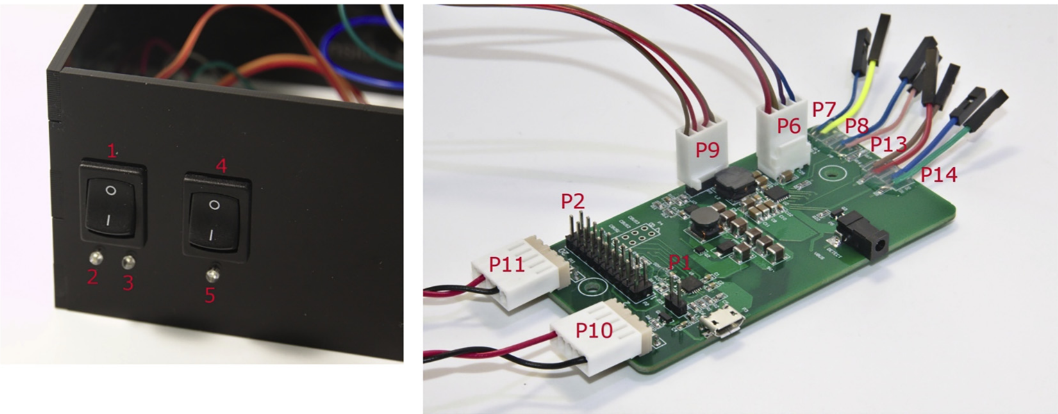

Fig. 14. Left: Buttons and LEDs on the side of the enclosure. Right: connectors on the battery management PCB. On the PCB file, P7, P8, P13, and P14 have been replaced by 2-pin headers.

- Connect the components to the battery management PCB (Fig. 14 right):
  - P1: Place a jumper on P1 to enable charging via the USB port.
  - P2 brings power and logic signals to the Raspberry Pi. Use a flat cable to connect to pins 1 to 20 of the Raspberry Pi. If you use a 20-pin connector on the Raspberry Pi side, you will need to cut pins 21 and 22 of the GPIO port. You can also use a 40-pin connector and clamp the 20-wire cable on pins 1–20.
  - P6 is the battery connector. To handle the high current, two wires should be connected in parallel. Pins 1 and 2 connect to the positive pole of the battery and pins 3 and 4 to the negative pole. P6 is polarised and prevents plugging the battery in the wrong way. Take care to solder P6 with an orientation matching the battery plug.
  - P7 and P8 connect to 10 kΩ NTC thermistors that must be applied on the battery to monitor its temperature.
  - P9 is the connector for the main power switch and connects to switch 1 in Fig. 14 left. To handle the large current, two wires are used for each contact, with pins 1 and 2 sending VSYS to the switch, and pins 3 and 4 receiving the return signal (c.f. Fig. 12).
  - P10 powers the LCD screen controller. 5 V is on pin 1, and GND on pin 5. It connects to connector J1 on the screen controller.
  - P11 powers PPV. 5 V is on pin 2, and GND on pin 4. 5 V connects to pins 2 and GND connects to pin 4 of the 10-pin header on the PPV PCB.
  - P13 connects to the status LED (marked 3 in Fig. 14 left). It is on when the battery is charging
  - P14 connects to the *power good* LED (marked 2 in Fig. 14 left). It is on when the unit is connected to a source of power.

15. Operation instructions of the standalone configuration

- **Check that the safety switch (Switch 4, Fig. 14 left) is in the '0' position**.
- Place main switch (Switch 1, Fig. 14 left) in position '1' and wait until the Raspberry Pi has started.
- Start the interface (file install.txt has instructions to place a shortcut on the desktop, or to have the interface launched automatically on start up. Refer the file HVPS_GUI.pdf for detailed information on how to use the GUI.)

- Put safety switch (Switch 4, Fig. 14 left) in position ‘1’ to enable the output. **From this moment, high voltage may be present at the output of PPV. Do not touch any of the components connected to the high voltage terminals**.
- Perform experiments
- Place safety switch (Switch 4, Fig. 14 left) back into position ‘0’ and close the interface.
- Shutdown Raspberry Pi.
- When the screen goes blank, wait for about 10 s and turn off the unit using the main power switch (Switch 1, Fig. 14 left).

16. Conclusion

We have presented an open-source portable high voltage power supply designed to drive dielectric elastomer actuators. This project combines a compact power supply capable of generating voltages up to 5 kV with a user-friendly graphic interface and a simple communication protocol. The power supply was specifically tailored for the development of DEAs for which there are no commercially available products with a similar set of functionalities. It can be assembled for USD 420, and for an additional cost of USD 245, it can be turned into a standalone battery-powered unit with an integrated touch screen.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ohx.2018.e00039.

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