

Application Note 006: Blood Pressure Monitoring – Prototyping with the Disc Pump Evaluation Kit

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1 REVISION HISTORY

Date	Version	Change
17 June 2020	R200617a	Initial release.

2 INTRODUCTION

Disc Pump is a high-performance micropump which operates by generating a high pressure, ultrasonic standing wave within a carefully designed acoustic cavity. The standing wave is rectified into DC flow by a patented, high-speed passive valve.

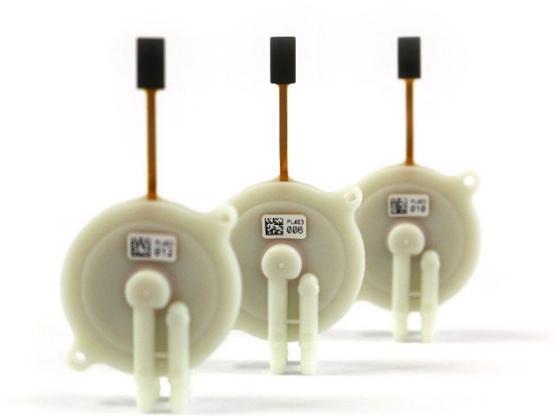


Figure 1 - Disc Pump

2.1 Features and Benefits for Blood Pressure Monitoring

Disc Pump offers a unique set of features with a range of benefits for blood pressure monitoring applications:

Feature	What this enables in BPM	Benefit
Zero pulsation	Measurement on inflation (whilst the pump is running) rather than deflation as in many conventional systems without need for second lumen.	<ul style="list-style-type: none"> • Faster measurement (measurement can end as soon as systolic is detected) • Improved patient comfort
High-precision, responsive control	Constant inflation rate (either mmHg/s or mmHg/beat)	Maximise measurement accuracy by maintaining inflation rate, and through ability to adapt rate to pulse rate.
<ul style="list-style-type: none"> • Compact, lightweight form factor • Silent (ultrasonic), vibration-free operation 	Pump can be integrated into wearable devices (e.g. arm- or wrist worn), directly at the cuff → eliminate the hose / tube between the pump module and cuff for many systems.	<ul style="list-style-type: none"> • Discrete operation (no pump noise or vibration) • Improved patient comfort (no pump noise or vibration; dispense with bulky pump module; no need for pump module strap) • Address risk in ABPM systems that the hose kinks/traps in a way that affects the measurement (no hose needed)
No ferro-magnetic materials	Pump immune to magnetic fields	“Native” MRI compatibility for next generation patient monitors

Table 1 – Features and Benefits of Disc Pump for blood pressure monitoring applications.

For more information, please visit <https://www.ttpventus.com/abpm>.

2.2 Typical Applications

Within the Blood Pressure Monitoring segment, the most suitable applications for Disc Pump include:

- 24-hour Ambulatory Blood Pressure Monitors
- Professional-grade Blood Pressure Monitors
- Professional-grade Blood Pressure Modules

2.3 About this Application Note

This Application Note provides practical guidance on how the Disc Pump Evaluation Kit can be used to explore the use of Disc Pump for blood pressure monitoring applications. In particular, it outlines:

1. How to set-up a basic system for laboratory testing.
2. How to control the kit via analogue input or serial to produce a constant, linear inflation rate (mmHg/s).
3. How to log the measured cuff pressure for subsequent offline analysis.
4. Options for creating a live/real-time measurement system.
5. How to integrate the smaller Disc Pump Driver PCB alone to create compact prototypes
6. Next steps into product development

3 DISCLAIMER

This Application Note is provided "as is" and without any warranty of any kind, and its use is at your own risk. LEE Ventus does not warrant the performance or results that you may obtain by using this Application Note. LEE Ventus makes no warranties regarding this Application Note, express or implied, including as to non-infringement, merchantability, or fitness for any particular purpose. To the maximum extent permitted by law LEE Ventus disclaims liability for any loss or damage resulting from use of this Application Note, whether arising under contract, tort (including negligence), strict liability, or otherwise, and whether direct, consequential, indirect, or otherwise, even if LEE Ventus has been advised of the possibility of such damages, or for any claim from any third party. Use of any products (including software or firmware) provided by LEE Ventus is subject to LEE Ventus' standard terms of sale.

4 HEALTH AND SAFETY



WARNING

The Disc Pump Driver PCB is capable of producing DC voltages up to 60V, and output AC voltages up to 120V peak- to- peak, at frequencies between 19 and 23 kHz. It is the user's responsibility to ensure that the Disc Pump Driver PCB is used and/or integrated within any product in a safe manner.



WARNING

Take care during use of the Disc Pump Drive PCB not to create short circuits between exposed conductive parts of the board. Short circuits may lead to malfunctioning and heating.

5 PROTOTYPING WITH THE EVALUATION KIT

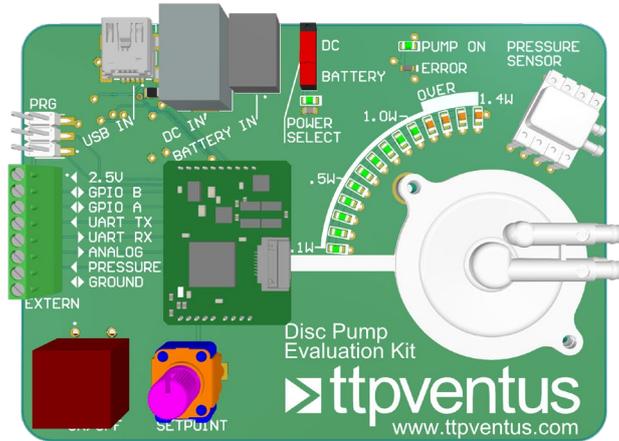


Figure 2 – LEE Ventus Disc Pump Evaluation Kit

5.1 Overview of the Evaluation Kit

The LEE Ventus Evaluation Kit provides a useful platform for configuring the Disc Pump Drive PCB using the Windows PC application bundled with the Evaluation Kit. The Drive PCB is mounted on the larger Evaluation Kit board. Drive PCBs can be easily swapped in and out with this interface. Some useful Disc Pump Driver PCB pins are broken out on the larger “Motherboard” PCB. Those pins relevant for creating a blood pressure monitoring prototype system are shown in Table 2.

Pin Name	Location / Connector	Breakout Description
VCC	DC IN	Main supply voltage. In addition a lithium-ion cell can be connected through the 'battery in' connection.
2.5V	Screw Terminal	2.5V from the on-board voltage regulator.
GROUND	Screw Terminal	Ground, available through a screw terminal.
ANALOG	Screw Terminal	This pin provides 0 to 2.5V analog input control over the system. The analog control signal can be mapped in the PC application to control pump power or the pressure set point.
PRESSURE	Screw Terminal	Connected to the analog pressure sensor on-board the larger Motherboard PCB. This allows the pressure to be independently monitored by a host / master system for real-time measurement and control.
GPIO A	Screw Terminal	Pump enable digital gating signal. Pulled high by default; drive low to override other controls and disable the pump.
UART RX	Screw Terminal	The serial receive connection, broken out through a screw terminal
UART TX	Screw Terminal	The serial transmit connection, broken out through a screw terminal

Table 2 – Useful Disc Pump Driver PCB pins mapped to Evaluation Kit connections.

The Drive PCB can be configured to run in one of three modes: power control (this is akin to an open-loop mode), PID control (closed loop control) and bang-bang pressure control (closed-loop hysteresis control). The most appropriate modes of control for Blood Pressure Monitoring are:

- **PID control** of closed-loop control pressure to create linear inflation ramps
- **Power control** for:
 - Systems executing the pressure control loop independently of the evaluation kit; or,
 - Systems where the more-conventional 'measurement on deflation' protocol is desired, where there is no need for continuous pressure control per-se (other than to turn the pump off once the cuff is inflated).

See the Disc Pump Evaluation Kit manual for details on the operation of each of these control modes.

5.2 Setting up a basic laboratory test system

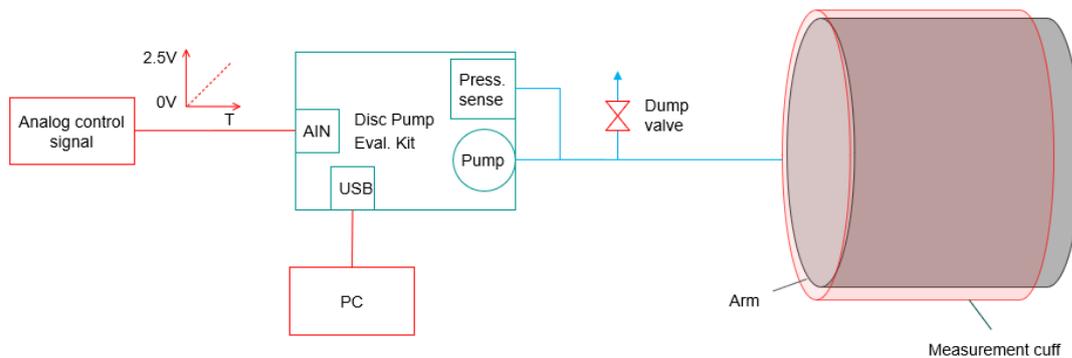


Figure 3 – A basic prototype system using the Disc Pump Evaluation Kit.

Figure 3 shows a basic test laboratory set-up, using the Disc Pump Evaluation Kit, including:

- A 0 to 2.5 V analog control signal. The customer may choose to provide this from a number of common sources, e.g.
 - Laboratory waveform generator
 - A microprocessor development board (e.g. ST Nucleo, Arduino, etc)
- A PC, to enable data logging including the measured pressure, which can then be analysed offline to calculate blood pressure.
- A dump valve to release pressure from the cuff once the measurement is complete (assuming measurement on inflation). This could be:
 - A manual valve e.g. lever-operated ball valve
 - A solenoid valve
 Please note, the valve must be controlled by the customer (or their host system); the Disc Pump Evaluation Kit cannot control valves.
- A blood pressure measurement cuff e.g. brachial type.

For the avoidance of doubt, the Disc Pump Evaluation Kit does not include the analog control signal source, PC, valve or cuff; the customer must provide these.

The most convenient set-up for initial testing is to control the Evaluation Kit via its analog input, and log measured pressure data via the PC Application for subsequent analysis (i.e. estimation of blood pressure). This is the set up shown. Customers may instead prefer to control the Evaluation Kit via its serial interface – either by PC via the USB-serial or by a host development platform via the UART interface. All three options (analog, USB-serial, UART) are discussed below.

5.3 Producing constant, linear inflation

5.3.1 By analog control

1. Connect equipment as shown in Figure 3.
2. Using the Evaluation Kit PC Application, configure the system as follows:
 - If not already connected, select the appropriate Com Port and click connected.
 - If the pump is running, disable it for now.
 - Select the desired pressure unit. mmHg is commonly used for blood pressure monitoring.
 - Select the PID Control tab
 - Select Analog Input from the Setpoint drop down box
 - Select Pressure Sensor from the Input drop down box
 - Set the range and, if needed, offset values for the analog input mapping. For example, to map 0 to 2.5 V to a pressure setpoint range of 0 to 300 mmHg, use a range value of 300 and an offset of 0.

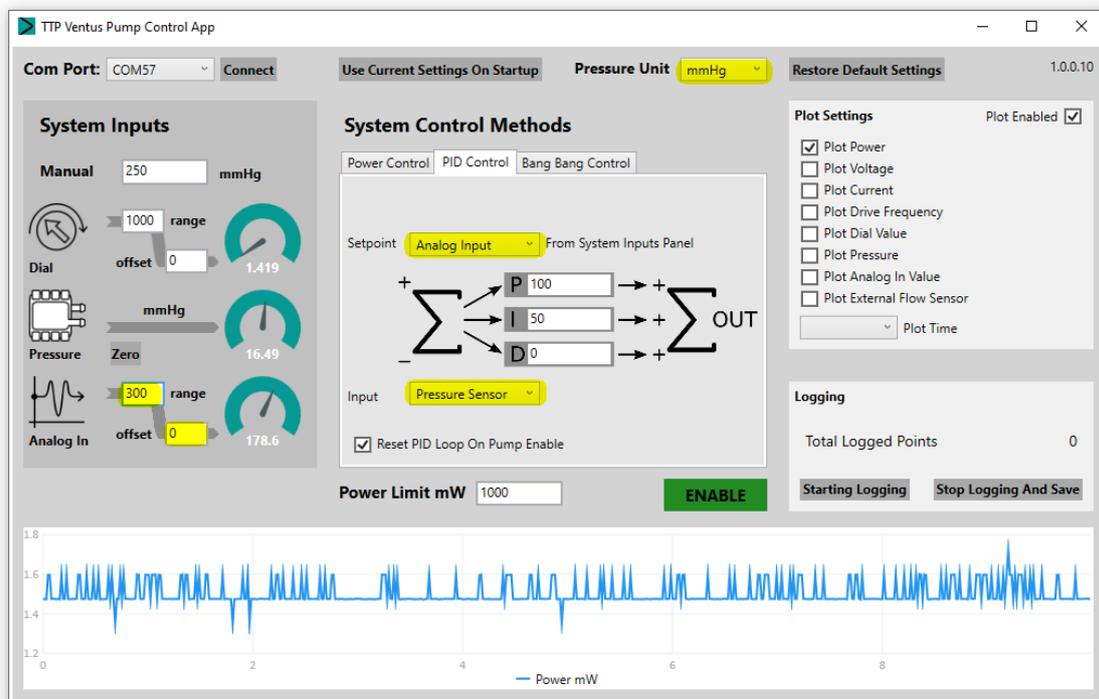


Figure 4 – Configuring the system with the PC Application

3. Ensure that the external analog control signal is currently set to 0 volts.
4. Now, with the system correctly configured, enable the pump.
5. At this point, you may wish you click Use Current Settings On Startup, which will remember these settings next time the system is powered up.
6. Drive a linear voltage ramp on the analog control signal. In response, the system will adjust the pump drive power until the measured pressure equals the pressure set point.

To calculate how fast to ramp the analog control voltage:

- First decide how fast you would like the pressure to ramp during the measurement – for example 3 mmHg/s.
- Divide the analog input range parameter by the target ramp rate – e.g. $300 / 3 = 100$.

- Divide the maximum analog input voltage, 2.5 V, by the result from the previous step, e.g. $2.5 / 100 = 0.025$, giving the rate at which the analog control voltage needs to be ramped, 0.025 V/s.
7. Finally, and whilst ramping the voltage, use the datalogging capability of the PC application as per Section 4.4.1 to log the measured pressure data to file, for subsequent analysis.

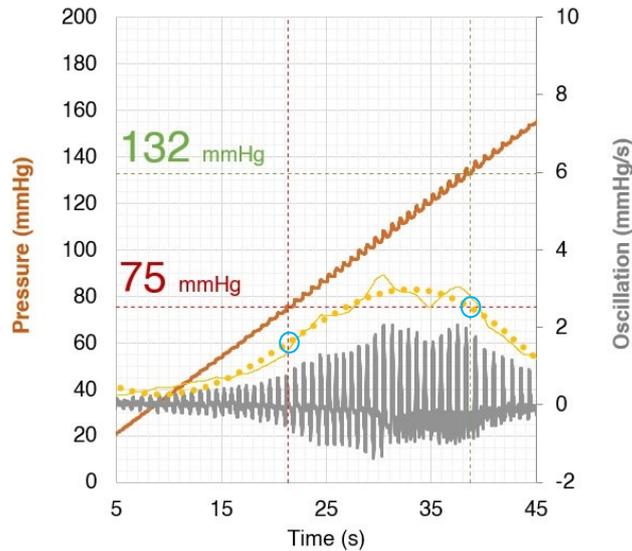


Figure 5 – blood pressure estimation: a linear pressure ramp (orange) is created with the Disc Pump Evaluation Kit, targeting approximately 3 mmHg/s. Oscillations in the measured pressure can be seen in this trace, from which the differential pressure oscillation has been calculated (grey), the oscillation envelope (thin yellow) and a best fit envelope (dotted yellow). Finally, the best fit envelope is used to estimate blood pressure with a standard heuristic.

5.3.2 By serial control

Customers may prefer to control the Evaluation Kit via its serial interface – either via the UART interface by a host development platform, or by PC (or another USB host) via the USB-serial interface. Note that the Evaluation Kit PC Application cannot be used at the same time, because it communicates with the Evaluation Kit over the same interface.

If using the USB to serial link (provided by the larger Motherboard PCB), connect the Evaluation Kit to your PC via the USB cable and power the system with the mains power supply. If using the UART, please note the voltage levels used are 0 to 2.5 volts. Visit the support section of the LEE Ventus website (<https://www.ttpventus.com/support>) to download the ‘Disc Pump Driver PCB’ application note, which provides further details on the UART interface. One advantage of the UART is that it provides a direct interface to the smaller Disc Pump Driver PCB, meaning that the larger motherboard PCB is not required, thereby supporting the creation of compact prototypes. There is more information on this in Section 4.6.

A single serial command set is used regardless of whether the UART or USB-Serial link is used. Please visit the support section of the LEE Ventus website (<https://www.ttpventus.com/support>) to download the ‘Serial Communications Guide’ for comprehensive details of the communications protocol used. For brevity, example commands are repeated here:

#W0,0\n	Turns the pump off
#W10,1\n	Sets PID control mode
#W12,0\n	Sets PID set point to manual (register 23)
#W13,2\n	Sets PID input source to Analog 2 (pressure sensor)
#W14,100\n	Sets PID proportional coefficient to 100
#W15,50\n	Sets PID integral coefficient to 50
#W16,0\n	Sets PID proportional coefficient to 0
#W23,0\n	Sets the pressure target to 0 mBar*

NB: pressure units can be selected/changed in PC app: check configuration in unsure which unit is currently selected

The serial commands above provide an example of how to configure the PCB prior to creating a ramping pressure set point. To ramp the set point, periodically write to register 23 with the updated set point value.

An example implementation for USB-Serial control in Python is provided below.

```
import serial
import time

import serial
import time

# set up port
serialPort = serial.Serial(port="COM57", baudrate=115200, bytesize=8,
timeout=2, stopbits=serial.STOPBITS_ONE)

# turn off streaming mode
serialPort.write(b"#W2,0\n")

#turn the pump off
serialPort.write(b"#W0,0\n")

# set the pump to use PID control with a manual set point
serialPort.write(b"#W10,1\n")

# sets PID set point to register 23 (manual)
serialPort.write(b"#W12,0\n")

# sets PID input source to Analog 2 (pressure sensor)
serialPort.write(b"#W13,2\n")

# sets PID proportional coefficient to 100.
serialPort.write(b"#W14,100\n")

# sets PID integral coefficient to 50.
serialPort.write(b"#W15,50\n")

# sets PID integral coefficient limit to 55,000.
serialPort.write(b"#W16,55000\n")

# sets PID differential coefficient to 0.
serialPort.write(b"#W17,0\n")

# turns the pump on
serialPort.write(b"#W0,1\n")

# loop ramping pressure between 0 and 300 mBar at 3 mBar/s
for pressure in range(0, 300, 1):

    # create string to send
    str = f"#W23,{pressure}\n"
```

```
# convert string to bytes
str = bytes(str, 'utf8')

# write pressure control string
serialPort.write(str)

#sleep
time.sleep(0.33)

# set the pressure setpoint back to zero
serialPort.write(b"#W23,0\n")

# turn the pump off
serialPort.write(b"#W0,0\n")
time.sleep(0.1)

serialPort.close()
```

5.4 Capturing measured pressure data

The Evaluation Kit includes a pressure sensor mounted onboard the larger Motherboard PCB, which enables the closed-loop pressure control function. Measurement values from this pressure sensor can be captured for analysis, enabling estimation of blood pressure.

There are various methods of acquiring measurement values dependent on your particular set-up configuration.

5.4.1 Logging the measured pressure by the PC Application

This method applies where the pump is connected to a PC with the PC Application running. Note that this method cannot be used where you intend to control the Evaluation Kit independently via the USB-Serial / UART interface, as this interface is required for the PC Application.

To log data:

1. Configure the system as desired.
2. Click the Start Logging button.
3. Confirm that the Total Logged Points counter is now incrementing.
4. When you have captured sufficient data, click Stop Logging And Save to save the data to file. The saved data file format is Comma-Separated Variable (CSV).

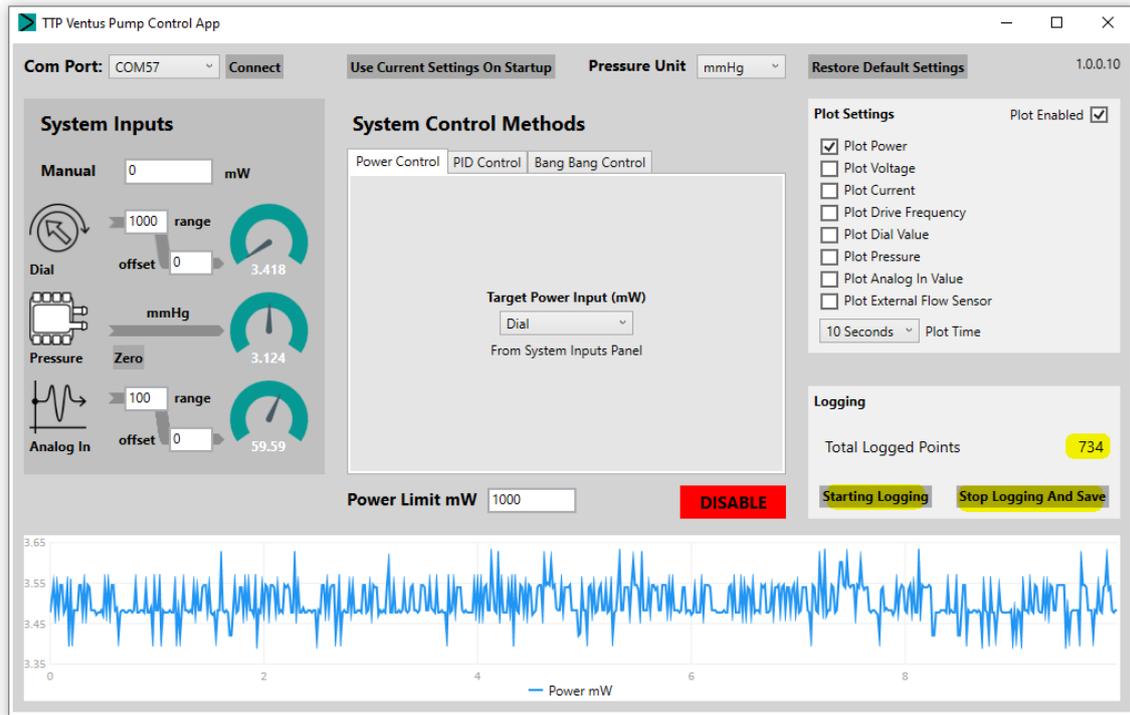


Figure 6 – Enabling datalogging in the PC Application

5.4.2 Reading pressure data via the serial interface

Pressure measurement data can be read independently via the serial interface (USB-serial or UART).

This may be accessed with the following command:

```
#R8\r\n          Read register 8, which is the Analog 2 register
```

Following writing this comment, the serial port should then be read. The returned message is formatted as:

```
#R8,<register value>\r\n
```

Note that the register value returned is offset and scaled by the Analog 2 Offset register (26) and Analog 2 Gain register (27), respectively. The gain and offset registers are initially set during a calibration process when Evaluation Kits are assembled at LEE Ventus. They are further updated anytime the user zeros the pressure sensor or changes the working pressure units via the PC Application, or indeed writes to registers 26 or 27 independently via the serial interface.

You may prefer to switch off “streaming mode” prior to reading pressure measurements, so that you do not need to discard other data normally streamed from the board to the PC application. To do this, send the following command:

```
#W2,0\r\n
```

5.4.3 Monitoring the pressure pin

The Evaluation Kit Motherboard (the larger PCB) has a pin labelled PRESSURE on its screw terminal block. This pin provides access to an amplified analog voltage proportional to the value

output by the onboard pressure sensor (Honeywell TSCDRR015PDUCV). The transfer function is as follows:

0.00 V = -745 mmHg (differential between ports)

1.25 V = 0 mmHg

2.50 V = 745 mmHg

5.5 Options for creating a live/real-time measurement system

A next useful step is to create a live / real-time system. This requires that a 'host' system is cued to control cuff inflation at the same time as capturing pressure readings. There are a number of approaches that can be taken as follows.

Option 1 – serial-controlled evaluation kit

- The evaluation kit serial interface is used for both pump operation (and therefore cuff inflation) and for reading back measured pressure.
- The host (control) system could be a separate PCB or development board (e.g. Arduino, ST Nucleo, Raspberry Pi, etc), in which case the evaluation kit UART interface may be of interest.
- Alternatively, a PC can be used, in which case the USB-Serial interface may be of interest.
- Linear cuff inflation is achieved as per section 5.3.2.
- Simultaneously, cuff pressure must be read back from the board at reasonably high bandwidth: we recommend 10 Hz.
- The host system can then perform the necessary calculations in real time to extract the oscillatory signal and estimate blood pressure. See Section 6 for resources on this.

Option 2 – analog-controlled kit

- The host (control) system will need one analog output, and one analog input, both in the range 0-2.5 V.
- The host system analog output should be fed into the evaluation kit analog input, to control pump pressure setpoint and therefore cuff inflation. Use the PC application supplied with the evaluation kit to map the analog input range onto the desired pressure setpoint range: we recommend 0-2.5 V is mapped to 0-300 mmHg. See the evaluation kit manual for more information on how to do this.
- The cuff pressure is provided as an analog signal on the "PRESSURE" pin (see Section 5.4.3). Connect this pin to the host system analog input.
- Linear cuff inflation is achieved as per section 5.3.1. Simultaneously, cuff pressure must be captured by the host system analog input at reasonably high bandwidth: we recommend a minimum of 10 Hz.
- The host system can then perform the necessary calculations in real time to extract the oscillatory signal and estimate blood pressure. See Section 6 for resources on this.

5.6 Prototype next steps: integrating the smaller Disc Pump Drive PCB

Ultimately, the Disc Pump evaluation kit may be too large for integration with a wearable prototype. Customers may instead prefer to integrate only the pump and the small postage-stamp sized drive PCB, which comes mounted on the larger 'motherboard' PCB as part of the evaluation kit.

The driver board provides serial, digital and analog control options. The host system will need to provide power to the driver board, and an independent means to measure pressure. LEE Ventus provides an application note ('AN004: Disc Pump Driver PCB') that offers guidance on how to integrate the Disc Pump Drive PCB into your product designs. Please visit the support section of the LEE Ventus website (<https://www.ttpventus.com/support/>) to download the latest version of this application note.

6 FURTHER SUPPORT

The support section of LEE Ventus website (<https://www.ttpventus.com/support>) provides technical information, FAQs, a “How To” video on the operation of the evaluation kit and documentation for download.

Specific resources that may be of interest in creating blood pressure measurement systems:

- **AN001: Disc Pump Drive Guide:**
Application note covering the basics of the lock-in circuit, including recommended drive waveforms, drive algorithms, and a reference circuit. We are also able to provide reference firmware.
- **AN003: PCB Serial Communications Guide:**
Application note covering the serial communications protocol that you can use to control the Disc Pump Drive PCB from your own software.
- **AN004: Disc Pump Driver PCB:**
Application note providing information to aid the integration of the Disc Pump Drive PCB with your system.

LEE Ventus is happy to discuss next steps beyond prototyping including system design. If you would like to discuss this with us, or for any other additional support, please contact us at support@ttpventus.com.