AN006: BLOOD PRESSURE MONITORING – DISC PUMP APPLICATION NOTE

1. INTRODUCTION

Disc Pump is a high-performance micropump that 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: A piezoelectric disc pump

1.1. About this Application Note

This Application Note provides practical guidance on how the Disc Pump Development Kit can be used to explore the use of Disc Pump for blood pressure monitoring applications. It outlines:

1. How to set-up a basic system for laboratory testing.
2. How to control the kit via analogue or serial input 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.

2. DISCLAIMER

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3. HEALTH AND SAFETY

WARNING

The Disc Pump Driver PCB Voltage must not exceed 48$V_{r.m.s.}$ (where for a typical square-wave drive $V_{r.m.s.} \approx V_{pk}$) at frequencies between 20 and 22 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. Read the appropriate user manual prior to first operation and take note of all safety notices.

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.

4. FEATURES AND BENEFITS FOR BLOOD PRESSURE MONITORING

The disc pumps offer 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.	• **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.
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.	• **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 is immune to magnetic fields** and **does not generate problematic magnetic fields**	**MRI compatibility** for next generation patient monitors

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

5. PROTOTYPING WITH THE DEVELOPMENT KIT

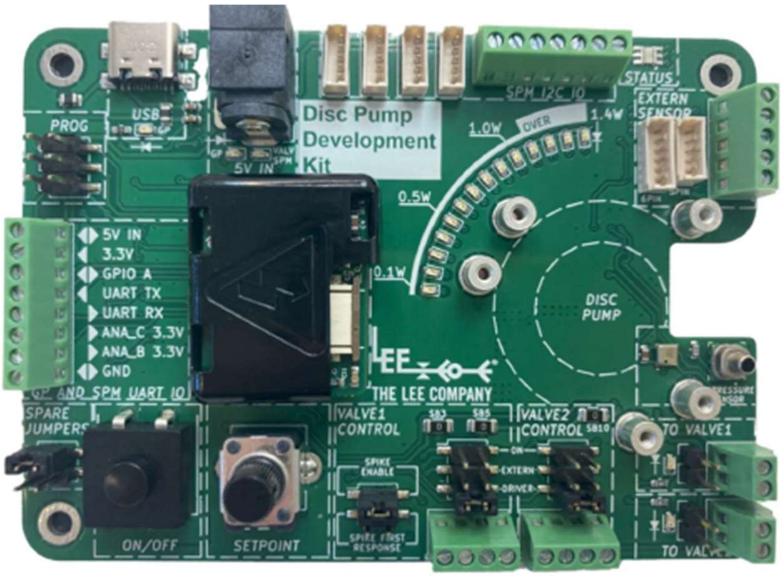


Figure 2. The motherboard and Drive PCB of our Disc Pump Development Kit

5.1. Overview of the Development Kit

The Piezoelectric Disc Pump Development Kit provides a useful platform for configuring the Disc Pump Drive PCB using the Windows PC application. The Drive PCB is mounted on the larger Development Kit motherboard. Drive PCBs can be easily swapped in and out with this interface. Certain Drive PCB pins are made available via the screw terminal block (labelled “GP AND SPM UART IO”) on the motherboard. Those pins relevant for creating a blood pressure monitoring prototype system are shown in Table 2.

Pin Name	Location / Connector	Breakout Description
5V in	DC IN / OUT	5V IN – wired to the 5V IN. can be used to power system. If power supplied by barrel jack, then 5V available here to power other systems.
3.3V	Screw Terminal	3.3V output from Drive PCB, which can be used to power 3.3V devices (max 50 mA).
GND	Screw Terminal	Ground, available through a screw terminal.
GPIO A	Screw Terminal	3.3V-level digital toggle signal IO for enabling / disabling pumping with an external signal. This pin can also be configured as an output via the PC application.

UART TX/RX	Screw Terminal	3.3V-level serial data transmitted from / to the Drive PCB or a Smart Pump Module connected via UART. The Development Kit can be controlled by the customer's host system (e.g. PCB / microcontroller) via these connections.
ANALOG B/C	Screw Terminal	0 to 3.3V analog inputs. The development kit can be configured to be controlled by these signals in the PC application.

Table 2 – Useful Disc Pump Driver PCB pins mapped to Development 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 Development 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 Development Kit manual for details on the operation of each of these control modes.

5.2.Setting up a basic laboratory test system

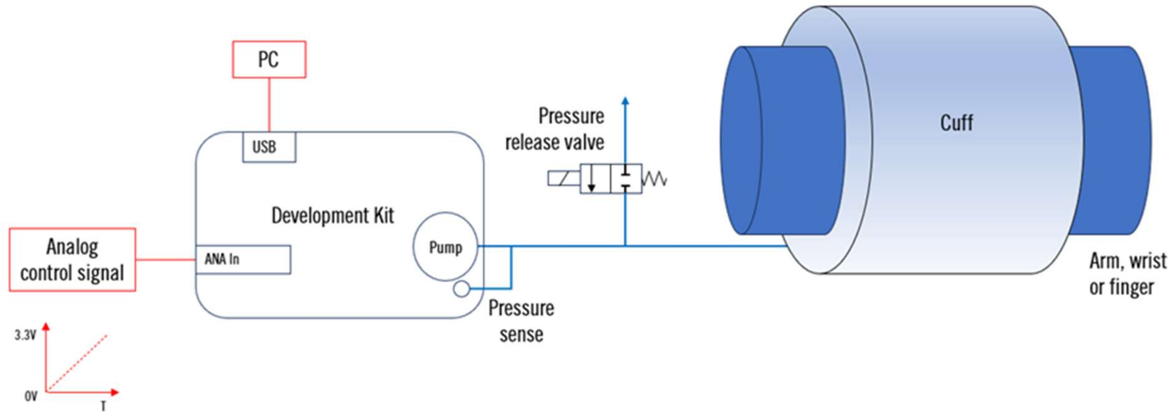


Figure 3 – A basic prototype system using the Piezoelectric Disc Pump Development Kit.

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

- A 0 to 3.3 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 pressure relief 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

  Note that The Development Kit can control certain solenoid valves. Details are provided in the manual–for relieving the pressure in the cuff, the valve can simply be toggled using the PC App. Valve operation requires a mains power supply (P/N: UACX0500950E), which is sold separately by The Lee Company.
- A blood pressure measurement cuff e.g. brachial type.

For the avoidance of doubt, the analog control signal, PC and cuff must be provided by the customer.

The most convenient set-up for initial testing is to control the Development 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 Development Kit via its serial interface – either by PC via the USB-serial interface, or by a host development platform via the UART interface. All three options (analog, USB-serial, UART) are discussed below.

Note that multiple pumps can be used together where rapid inflation and/or higher pressure is required. Pumps can be connected in series (for higher pressure) or parallel (for higher flow) or a combination of both. Performance when operating at altitude or elevated temperature may be reduced; therefore, it is prudent to ensure that the pump system has sufficient headroom to accommodate such derating. The Development Kit can operate up to 5 pumps and 2 valves. See the User Manual for more information.

5.3. Producing constant, linear inflation

5.3.1. By analog control

- Connect equipment as shown in Figure 3.
- Using the Development Kit PC Application, configure the system as follows:
    - If not already connected, select the appropriate Com Port and click Connect.
    - 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 B or C from the Setpoint drop down box
    - Select Digital 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 3.3 V to a pressure setpoint range of 0 to 300 mmHg, use a range value of 300 and an offset of 0.

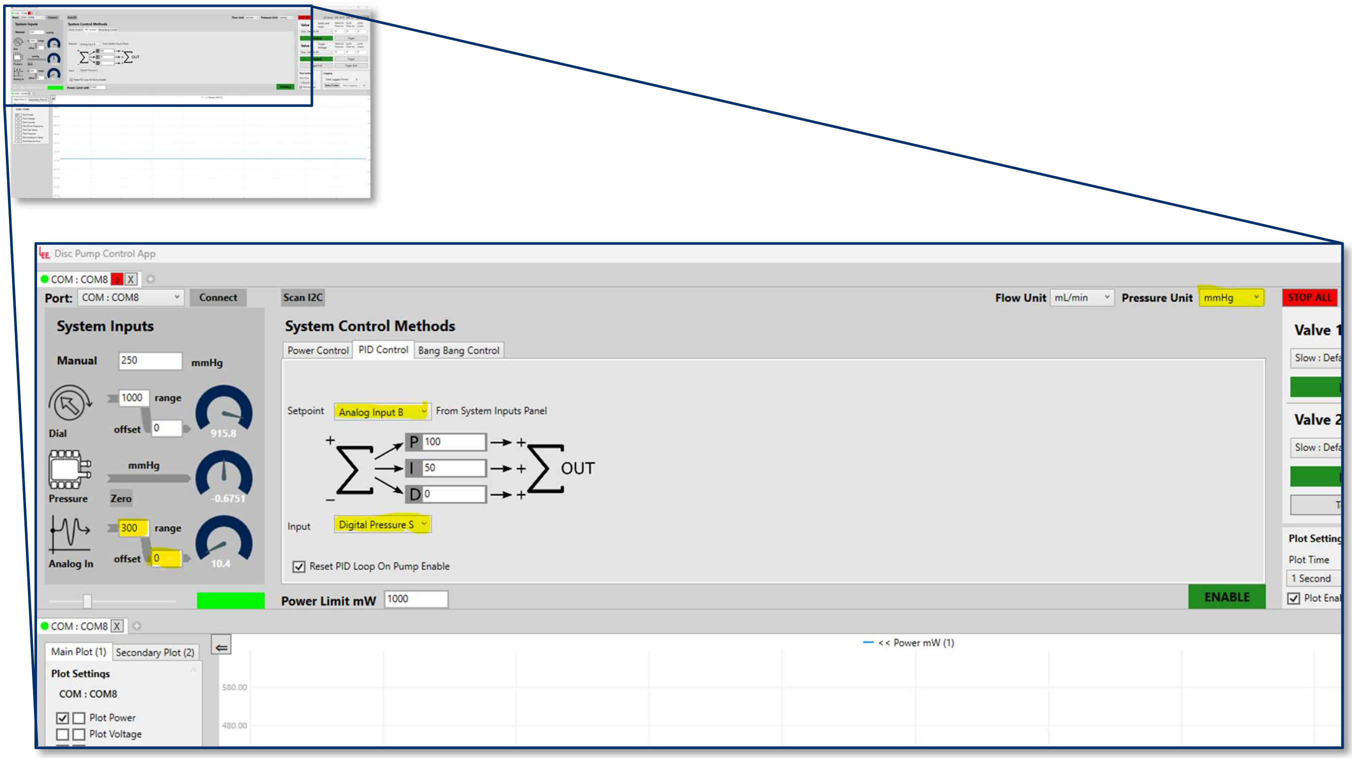
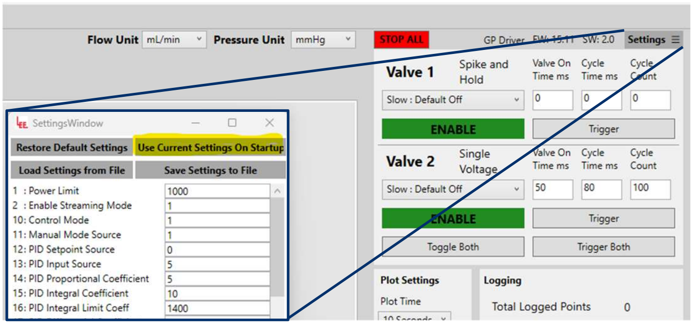


Figure 4 – Configuring the system with the PC Application

- Ensure that the external analog control signal is currently set to 0 volts.
- Now, with the system correctly configured, enable the pump.
- 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.



Click "Settings" to display drop down list

- 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, 3.3 V, by the result from the previous step, e.g. 3.3 / 100 = 0.033, giving the rate at which the analog control voltage needs to be ramped, 0.033 V/s.
- Finally, and whilst ramping the voltage, use the datalogging capability of the PC application as per Section 5.4.1 to log the measured pressure data to file, for subsequent analysis.
- Figure 5 provides the methodology for determining the blood pressure statistics from the measurements i.e. the systolic (132mmHg) and diastolic pressure (75mmHg) estimations.

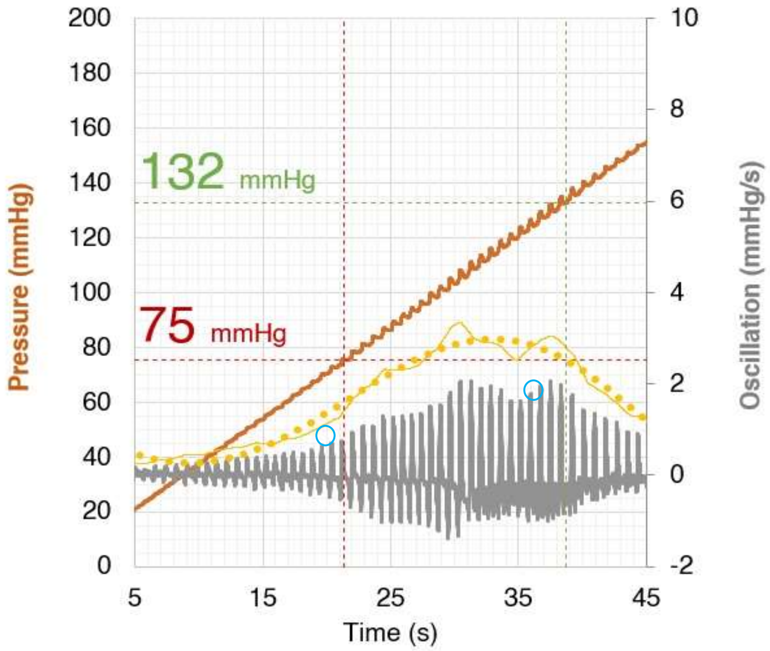


Figure 5 – blood pressure estimation: a linear pressure ramp (orange) is created with the Disc Pump Development Kit, targeting approximately 3 mmHg/s. Oscillations in the measured pressure can be seen in this trace, from which the differential pressure oscillation has been calculated (grey), the oscillation 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 Development 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 Development Kit PC Application cannot be used at the same time, because it communicates with the Development Kit over the same interface.

If using the USB to serial link (provided by the larger motherboard PCB), connect the Development Kit to your PC via the USB cable and power the system with the mains power supply. If using UART, please note the voltage levels used are 0 to 3.3 volts. Visit The Lee Company website (https://www.theleeco.com/disc-pumps/) to download 'TG003: Communications Guide Guide' and manuals, which provide 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 5.6.

A single serial command set is used regardless of whether the UART or USB-Serial link is used. Please visit The Lee Company website to download the Technical Guide 'TG003: PCB 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)
#W13,5\n	Sets PID input source to digital 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 integral coefficient limit to 55,000
#W17,0\n	Sets PID differential 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 (no valve control is included in the code) – **note the COM port number under the "# set up port" comment (shown as "COM1" below) will need to be modified to match the relevant port on your system.**

```
import serial
import time

import serial
import time

# set up port
serialPort = serial.Serial(port="COM1", 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 Digital pressure sensor
serialPort.write(b"#W13,5\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 measure pressure data

The Development Kit includes a pressure sensor mounted on board 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 Development Kit independently via the USB-Serial / UART interface, as this interface is required for the PC Application.

To log data (see below also):

1. Configure the system as desired.
2. Once the Com port is connected, click on the new plot window icon, below the System Inputs
3. Select attributes to plot e.g. Pressure and Power by click in the boxes
4. Select the location for file storage
5. Click the Start Logging button.
6. Confirm that the Total Logged Points counter is now incrementing.
7. 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).

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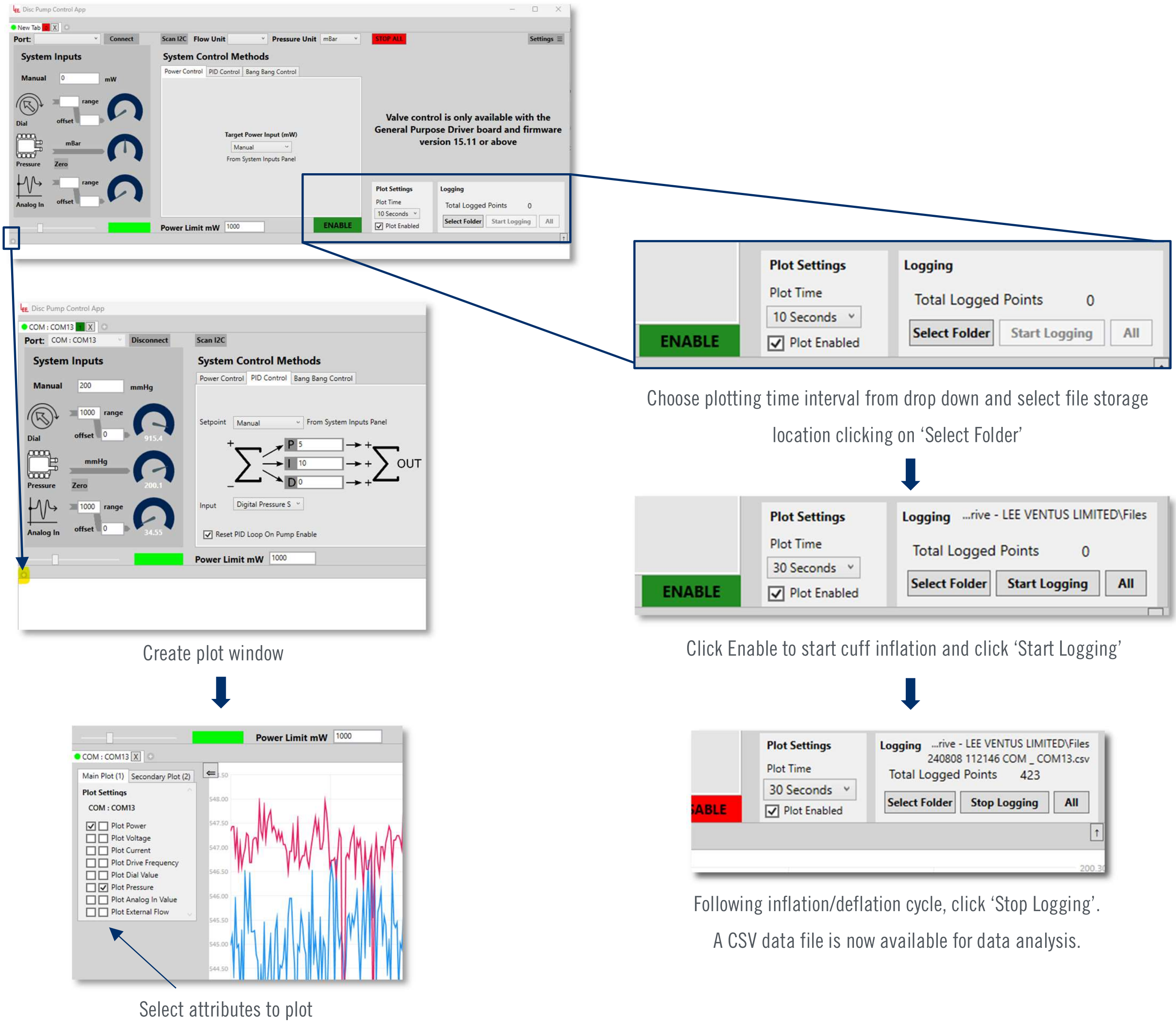

Figure 6 – Enabling datalogging in the PC Application

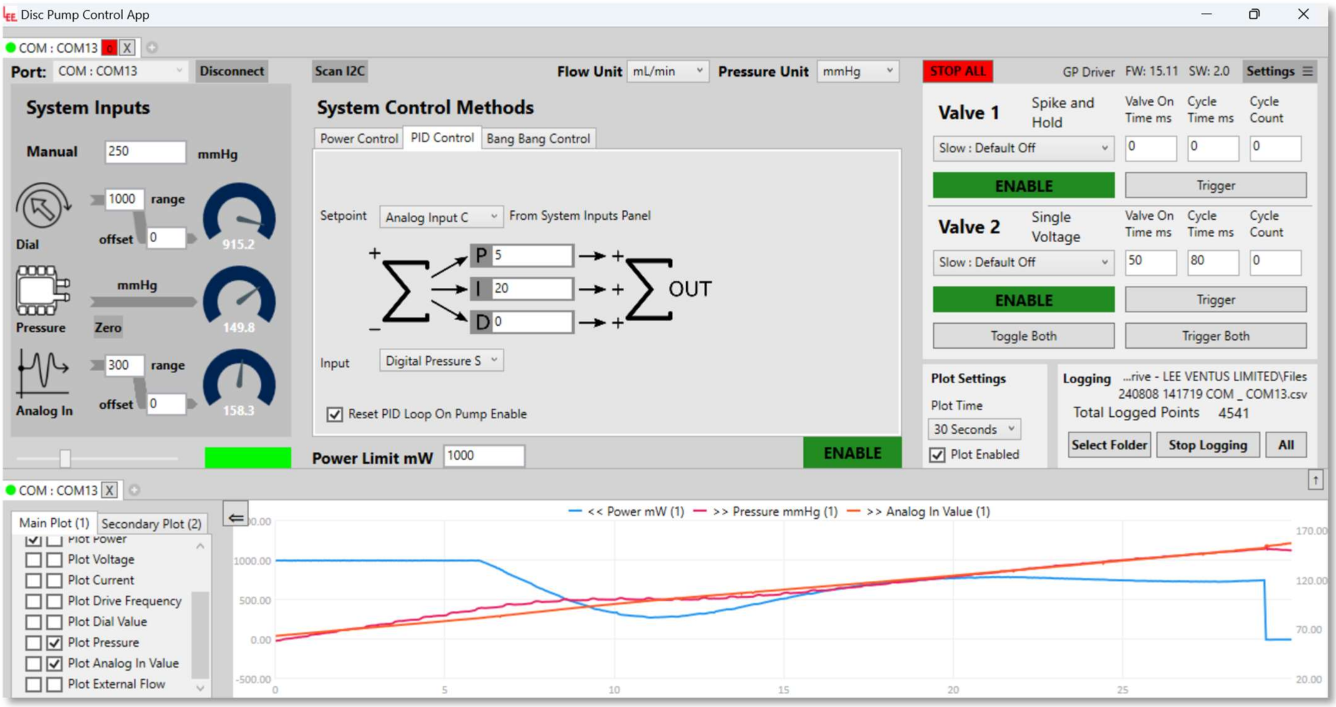

Figure 7: Typical plot during inflation and datalogging

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\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>\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 Development 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\n
```

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 Development Kit

- The Development 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 Development 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 0-3.3V.
- The host system analog output should be fed into the Development Kit analog input, to control pump pressure setpoint and therefore cuff inflation. Use the PC application supplied with the Development kit to map the analog input range onto the desired pressure setpoint range: we recommend 0-3.3V is mapped to 0-300 mmHg. See the Development kit manual for more information on how to do this.

- The cuff pressure is measured by the digital pressure sensor on the Development kit motherboard, connected by teeing off from the pump exhaust.
- 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 or the drive function into a system PCB

Ultimately, the Disc Pump Development 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 Development 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. Visit The Lee Company website to download the resource 'TG001: Disc Pump Drive Guide' that offers guidance on how to integrate the Disc Pump Drive PCB into your product designs. Alternatively, the reference design package for the drive electronics can also be downloaded from the website, to facilitate the integration of the drive electronics into a system PCB. If you have any further questions, please contact your Lee Sales Engineer.

6. ADDITIONAL SUPPORT

The Lee Company Website (https://www.theleeco.com/disc-pumps/) provides advice on:

- Getting Started
- Applications
- Development Process
- Downloads (including datasheets, manuals, application notes, case studies and 3D models)
- Frequently Asked Questions

The Lee Company 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 your Lee Sales Engineer.

7. REVISION HISTORY

Date	Version	Change
September 2024	09/24	Updated for Development Kit
June 2023	06/23	Rebranded document
17th June 2020	R200617a	Add images for background to pump operation and clarify ground time in more detail