THORLABS DSC1 Compact Digital Servo Controller User Guide

Contents

THORLABS DSC1 Compact Digital Servo Controller

Specifications:

- Product Name: DSC1 Compact Digital Servo Controller
- Recommended Use: With Thorlabs' photodetectors and actuators
- Compatible Actuators: Piezo amplifiers, laser diode drivers, TEC controllers, electro-optic modulators
- Compliance: CE/UKCA markings

Product Usage Instructions

Introduction

Intended Use: The DSC1 is a compact digital servo controller designed for general laboratory use in research and industry. The DSC1 measures a voltage, computes a feedback signal according to the user selected control algorithm, and outputs a voltage. The product may only be used in accordance with the instructions described in this manual. Any other use will invalidate the warranty. Any attempt to reprogram, disassemble binary codes, or otherwise alter the factory machine instructions in a DSC1, without Thorlabs consent, will invalidate the warranty. Thorlabs recommends using the DSC1 with Thorlabs' photodetectors and actuators. Examples of Thorlabs actuators that are well suited to use with the DSC1 are Thorlabs' piezo amplifiers, laser diode drivers, thermoelectric cooler (TEC) controllers, and electro-optic modulators.

Explanation of Safety Warnings

NOTE Indicates information considered important, but not hazard-related, such as possible damage to the product.

The CE/UKCA markings on the product are the manufacturer's declaration that the product complies with the essential requirements of the relevant European health, safety, and environmental protection legislation.

The wheelie bin symbol on the product, the accessories or packaging indicates that this device must not be treated as unsorted municipal waste but must be collected separately.

Description
Thorlabs' DSC1 Digital Servo Controller is an instrument for feedback control of electro-optical systems. The device measures an input voltage, determines an appropriate feedback voltage through one of several control algorithms, and applies this feedback to an output voltage channel. Users can choose to configure the operation of the device through either the integrated touchscreen display, a remote desktop PC graphical user interface (GUI), or a remote PC software development kit (SDK). The servo controller samples voltage data with 16-bit resolution

through a coaxial SMB input port at 1 MHz.

To provide more accurate voltage measurements, arithmetic circuitry within the device averages every two samples for an effective sample rate of 500 kHz. The digitized data is processed by a microprocessor at high speed using digital signal processing (DSP) techniques. The user may choose between SERVO and PEAK control algorithms. Alternatively, the user may test a systems response to DC voltage to determine the servo setpoint with the RAMP operating mode, which outputs a sawtooth wave synchronous with the input. The input channel has a typical bandwidth of 120 kHz. The output channel has a typical bandwidth of 100 kHz. The -180 degree phase lag of the input-to-output voltage transfer function of this servo controller is typically 60 kHz.

Technical Data

Specifications

Operating Specifications	
System Bandwidth	DC to 100 kHz
Input to Output -180 Degree Frequency [a]	>58 kHz (60 kHz Typical)
Nominal Input Sampling Resolution	16 Bit
Nominal Output Resolution	12 Bit
Maximum Input Voltage	±4 V
Maximum Output Voltage[b]	±4 V
Maximum Input Current	100 mA
Average Noise Floor	-120 dB V^2/Hz
Peak Noise Floor	-105 dB V^2/Hz
Input RMS Noise[c]	0.3 mV
Input Sampling Frequency	1 MHz
PID Update Frequency[d]	500 kHz
Peak Lock Modulation Frequency Range	100 Hz – 100 kHz in 100 Hz Steps
Input Termination	1 MΩ
Output Impedance[b]	220 Ω

- a. This is the frequency at which the output reaches a -180 degree phase shift relative to the input.
- b. The output is designed for connection to high-Z (>100 kΩ) devices. Connecting devices with lower input termination, Rdev, will reduce the output voltage range by Rdev/(Rdev + 220 Ω) (e.g., a device with 1 kΩ termination will give 82% of the nominal output voltage range).

- c. The integration bandwidth is 100 Hz – 250 kHz.
- d. A low-pass filter reduces digitization artifacts in output control voltage, resulting in an output bandwidth of 100 kHz.

Electrical Requirements	
Supply Voltage	4.75 – 5.25 V DC
Supply Current	750 mA (Max)
Temperature Range[a]	0 °C to 70 °C

- a Temperature range over which the device may be operated without Optimal operation occurs when near room temperature.

System Requirements	
Operating System	Windows 10® (Recommended) or 11, 64 Bit Required
Memory (RAM)	4 GB Minimum, 8 GB Recommended
Storage	300 MB (Min) of Available Disk Space
Interface	USB 2.0
Minimum Screen Resolution	1200 x 800 Pixels

Mechanical Drawings

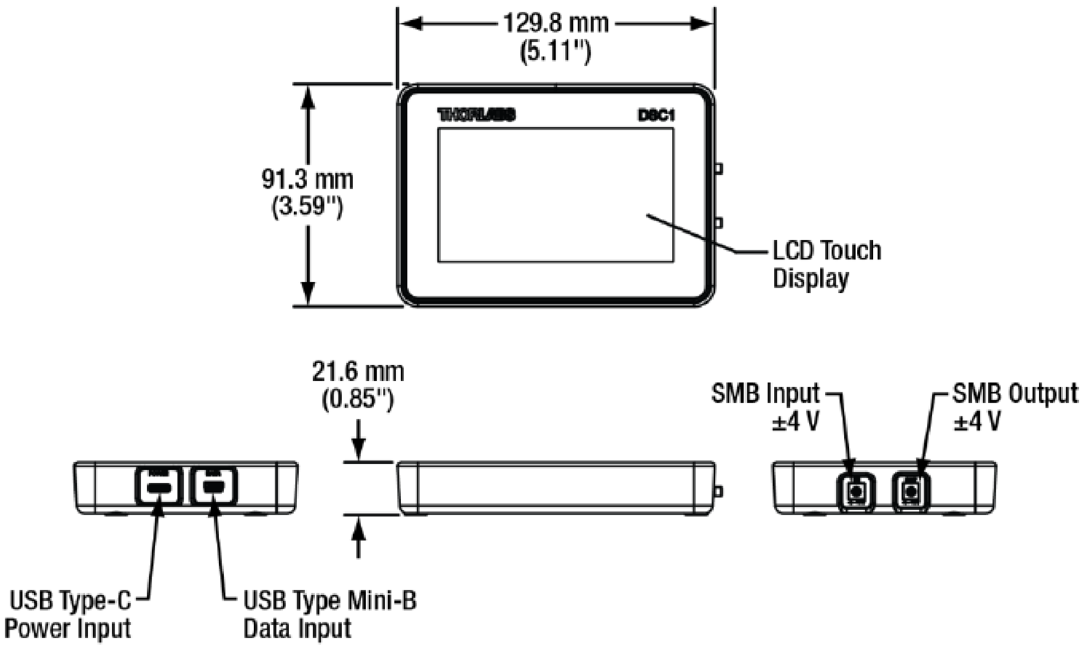


Figure 1 Mechanical Drawing

Simplified Declaration of Conformity
The full text of the EU declaration of conformity is available at the following internet address:
https://Thorlabs.com/newgrouppage9.cfm?objectgroup_id=16794

FCC Designation

Note: This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

Safety Warnings: The CE/UKCA markings indicate compliance with European health, safety, and environmental protection legislation.

Operation

Basics: Familiarize yourself with the basic functions of the DSC1.

Ground Loops and the DSC1: Ensure proper grounding to avoid interference.

Powering the DSC1: Connect the power source following the provided guidelines.

Touchscreen

Launching the Touchscreen Interface
After being connected to power and a brief, less than one second warmup, the DSC1 will illuminate the integrated touchscreen display and the screen will respond to inputs.

Touchscreen Operation in SERVO Mode
The SERVO mode implements a PID controller.

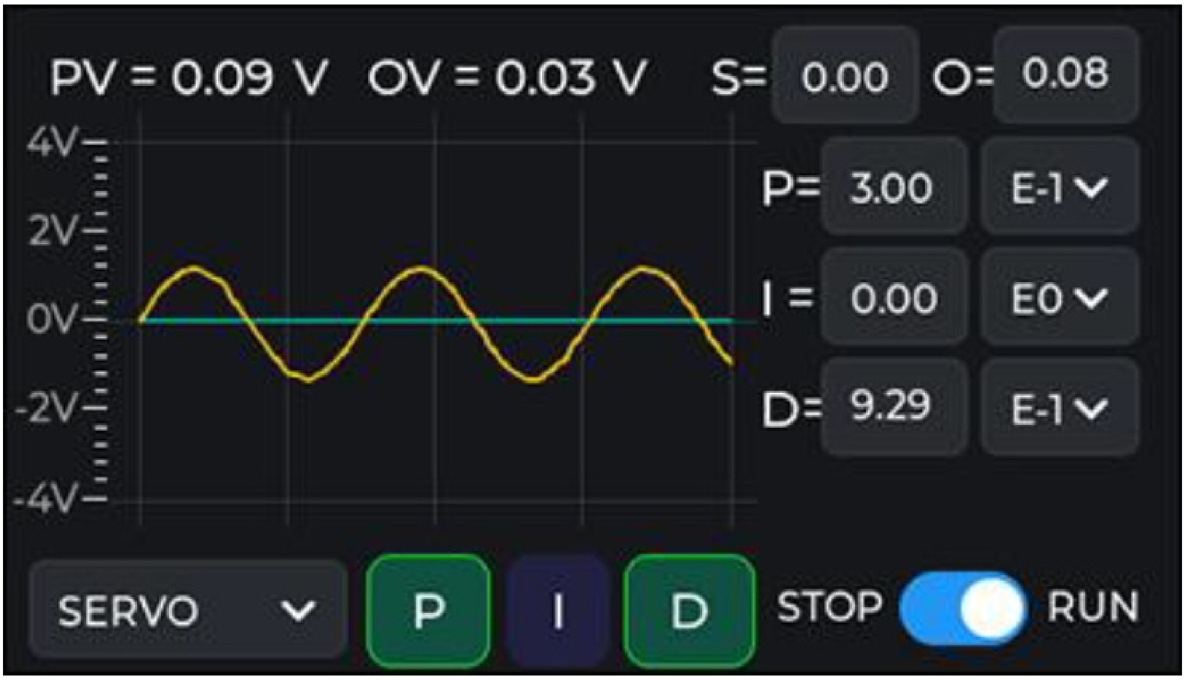


Figure 2 Touchscreen display in the servo operating mode with the PID controller enabled in PI control mode.

- The PV (process variable) numeric value shows the AC RMS voltage of the input signal in volts.

- The OV (output voltage) numeric value shows the average output voltage from the DSC1.
- The S (setpoint) control sets the setpoint of the servo loop in volts. 4 V is the maximum and -4 V is the minimum allowable.
- The O (offset) control sets the DC offset of the servo loop in volts. 4 V is the maximum and -4 V is the minimum allowable.
- The P (proportional) control sets the proportional gain coefficient. This may be a positive or negative value between 10-5 and 10,000, notated in engineering notation.
- The I (integral) control sets the integral gain coefficient. This may be a positive or negative value between 10- 5 and 10,000, notated in engineering notation.
- The D (derivative) control sets the derivative gain coefficient. This may be a positive or negative value between 10-5 and 10,000, notated in engineering notation.
- The STOP-RUN toggle disables and enables the servo loop.
- The P, I, and D buttons enable (illuminated) and disable (dark blue) each gain stage in the PID servo loop.
- The SERVO dropdown menu allows the user to select the operating mode.
- The teal trace shows the current setpoint. Each point is 2 µs apart on the X-axis.
- The golden trace shows the current measured PV. Each point is 2 µs apart on the X-axis.

Touchscreen Operation in RAMP Mode
The RAMP mode outputs a sawtooth wave with user configurable amplitude and offset.

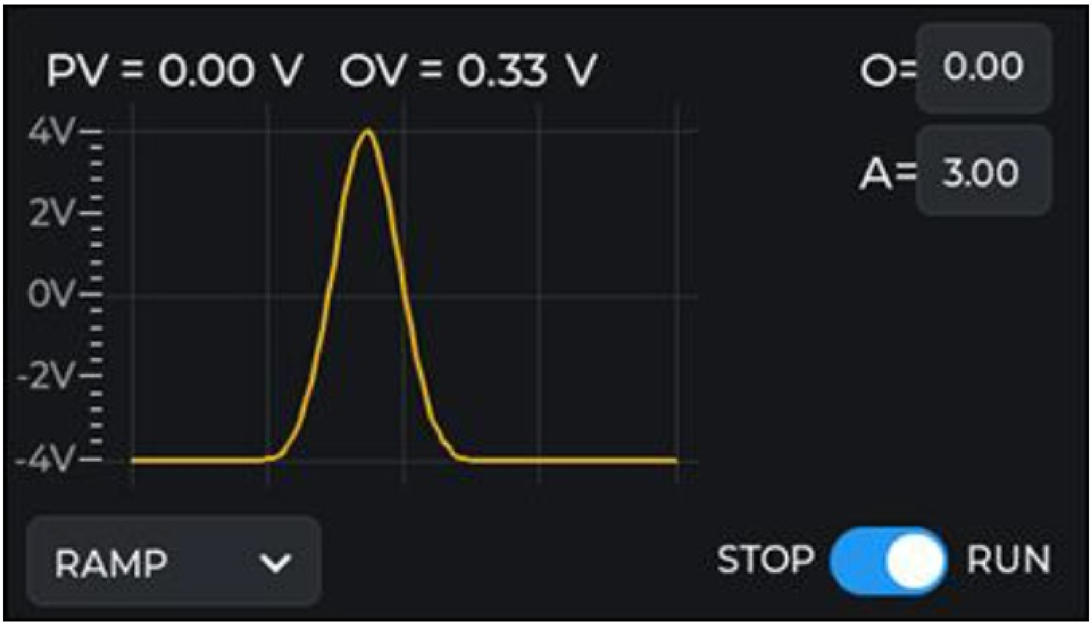


Figure 3 Touchscreen display in the ramp operating mode.

- The PV (process variable) numeric value shows the AC RMS voltage of the input signal in volts.
- The OV (output voltage) numeric value shows the average output voltage applied by the device.
- The O (offset) control sets the DC offset of the ramp output in volts. 4 V is the maximum and -4 V is the minimum allowable.
- The A (amplitude) control sets the amplitude of the ramp output in volts. 4 V is the maximum and -4 V is the minimum allowable.
- The STOP-RUN toggle disables and enables the servo loop respectively.
- The RAMP dropdown menu allows the user to select the operating mode.
- The golden trace shows the plant response synchronized with the output scan voltage. Each point is spaced

195 µs apart on the X-axis.

Touchscreen Operation in PEAK mode
The PEAK mode implements an extremum seeking controller with user configurable modulation frequency, amplitude, and integration constant. Note that the modulation and demodulation is always active when the device is in PEAK mode; the run-stop toggle actives and deactivates the integral gain in the dither control loop.

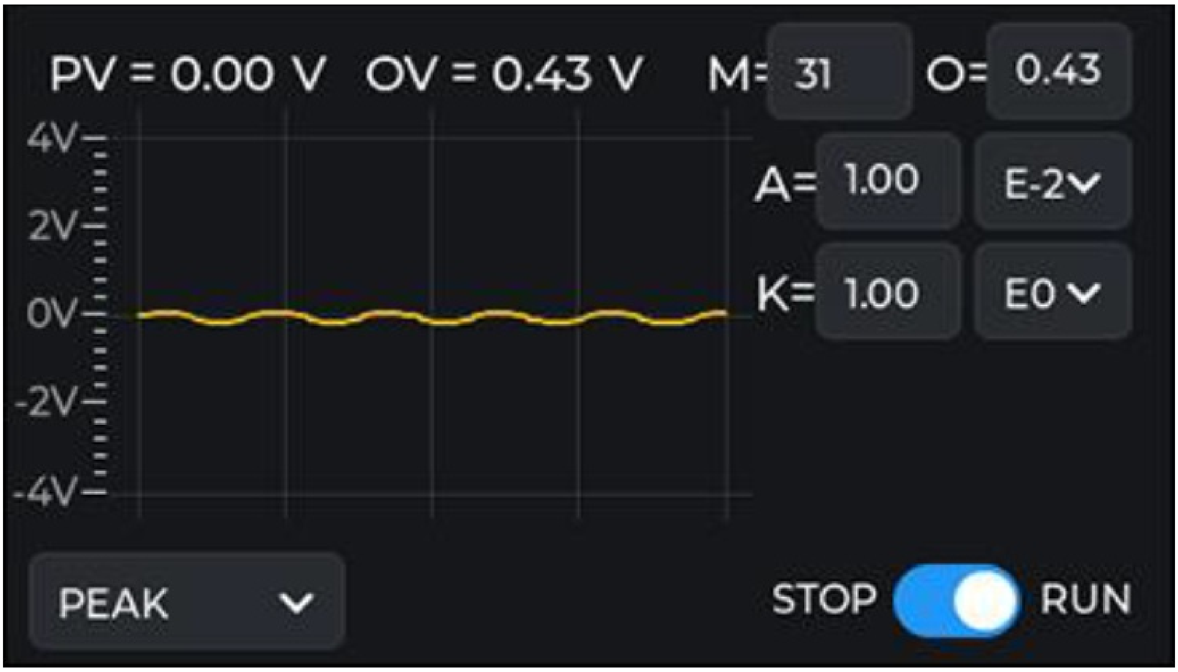


Figure 4 Touchscreen display in the peak operating mode.

- The PV (process variable) numeric value shows the AC RMS voltage of the input signal in volts.
- The OV (output voltage) numeric value shows the average output voltage applied by the device.
- The M (modulation frequency multiplier) numeric value shows the multiple of 100 Hz of the modulation frequency. For example, if M = 1 as shown, the modulation frequency is 100 Hz. The maximum modulation frequency is 100 kHz, with an M value of 1000. In general, higher modulation frequencies are advisable, provided that the control actuator is responsive at that frequency.
- The A (amplitude) control sets the amplitude of the modulation in volts, notated in engineering notation. 4 V is the maximum and -4 V is the minimum allowable.
- The K (peak lock integral coefficient) control sets the integration constant of the controller, with units of V / s, notated in engineering notation. If the user is unsure of how to configure this value, typically starting with a value around 1 is advisable.
- The STOP-RUN toggle disables and enables the servo loop respectively.
- The PEAK dropdown menu allows the user to select the operating mode.
- The golden trace shows the plant response synchronized with the output scan voltage. Each point is spaced 195 µs apart on the X-axis.

Software
The digital servo controller software is designed to both allow for control over basic functionality via a computer interface and provides an expanded set of analysis tools for using the controller. For example, the GUI includes a plot that can display the input voltage in frequency domain. Additionally, data can be exported as a .csv file. This software allows for use of the device in the servo, peak, or ramp modes with control over all parameters and settings. The system response may be viewed as the input voltage, error signal, or both, either in the time domain or frequency domain representations. Please see the manual for more information.

Launching the Software
After launching the software, click “Connect” to list available DSC devices. Multiple DSC devices may be controlled at a time.

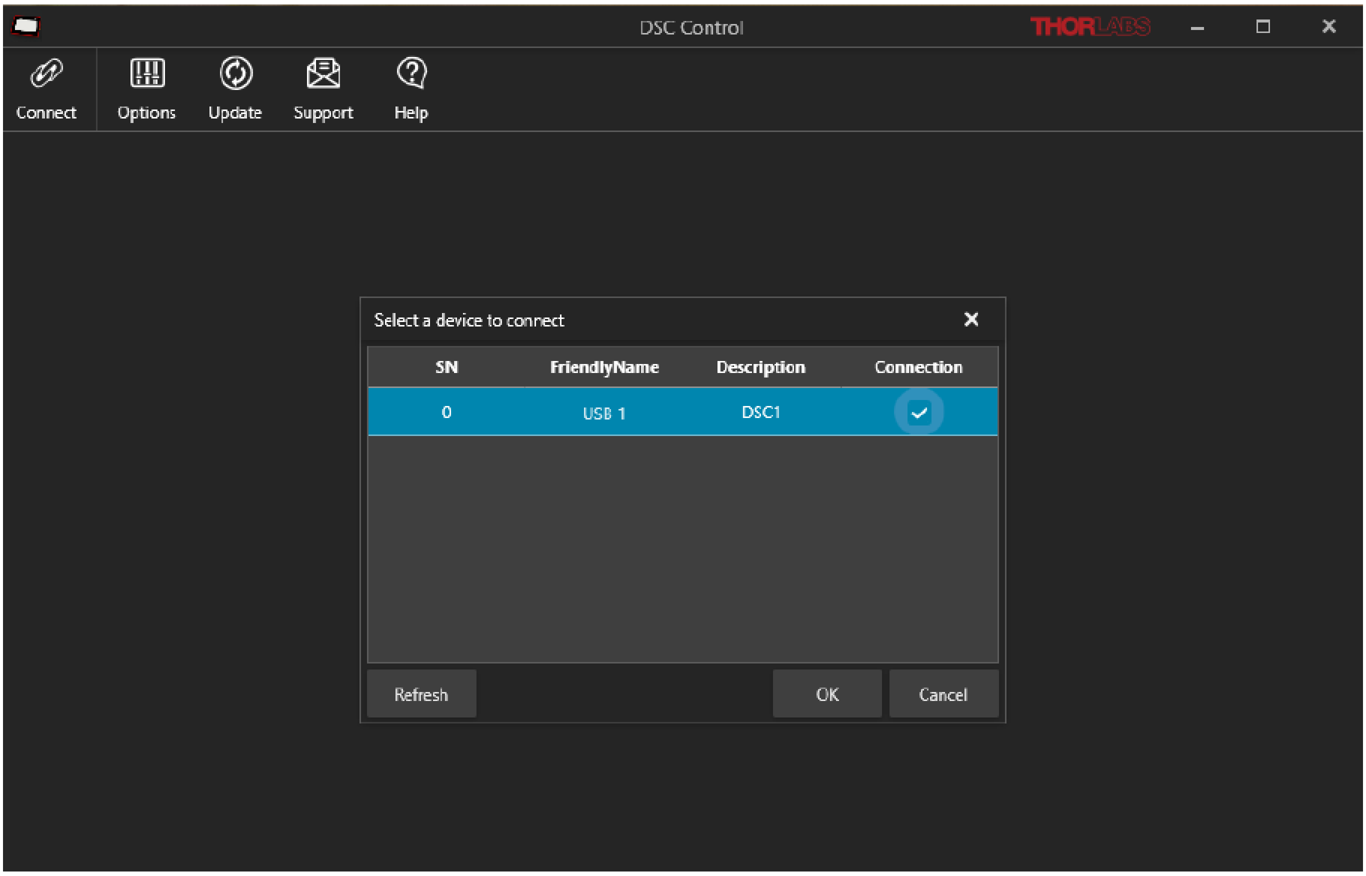


Figure 5
Launch screen for the DSCX Client software.

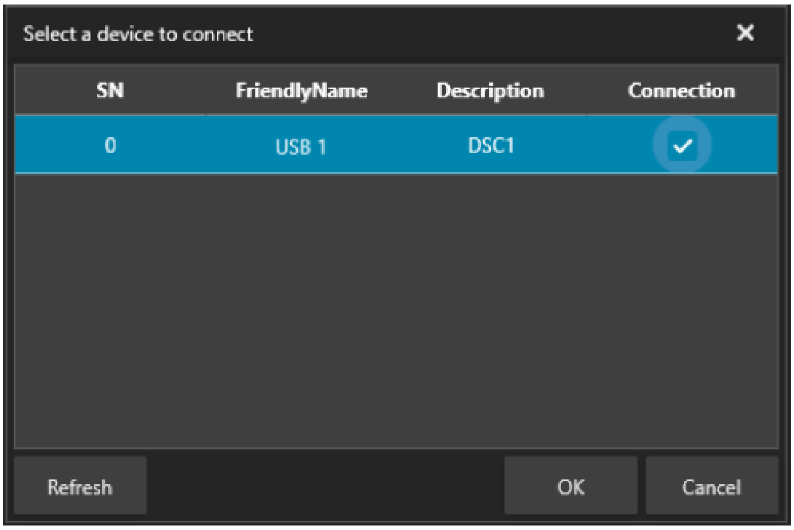


Figure 6 Device selection window. Click OK to connect to the selected device.

Servo Software Tab
The Servo tab allows a user to operate the device in servo mode with additional controls and displays beyond those provided by the embedded touchscreen user interface on the device itself. On this tab, either time or frequency domain representations of the process variable are available. The system response may be viewed as either the process variable, error signal, or both. The error signal is the difference between the process variable and the setpoint. Using control analysis techniques, the impulse response, frequency response, and phase

response of the device can be predicted, provided certain assumptions about the system's behavior and the gain coefficients are made. This data is displayed on the servo control tab so that users can preemptively configure their system, before beginning control experiments.

Figure 7 Software interface in Ramp mode with the frequency-domain display.

- Enable X Gridlines: Checking the box enables X gridlines.
- Enable Y Gridlines: Checking the box enables Y gridlines.
- Run / Pause Button: Pressing this button commences / stops the update of graphical information on the display.
- Frequency / Time Toggle: Switches between frequency-domain and time-domain plotting.
- PSD / ASD Toggle: Switches between power spectral density and amplitude spectral density vertical axes.
- Average Scans: Toggling this switch enables and disables averaging in the frequency domain.
- Scans In Average: This numeric control determines the number of scans to be averaged. The minimum is 1 scan and the maximum is 100 scans. The up and down arrows on a keyboard increase and decrease the number of scans in the average. Similarly, the up and down buttons adjacent to the control increase and decrease the number of scans in the average.
- Load: Pressing this button in the Reference Spectrum panel allows a user to select a reference spectrum saved on the client PC.
- Save: Pressing this button in the Reference Spectrum panel allows a user to save the currently displayed frequency data to their PC. After clicking this button, a save file dialog will allow the user to choose the storage location and enter the file name for their data. The data saves as a Commas Separated Value (CSV).
- Show Reference: Checking this box enables display of the last selected reference spectrum.
- Autoscale Y-Axis: Checking the box enables automatic setting of the Y Axis display limits.
- Autoscale X-Axis: Checking the box enables automatic setting of the X Axis display limits.

- Log X-Axis: Checking the box toggles between a logarithmic and linear X axis display.
- Run PID: Enabling this toggle enables the servo loop on the device.
- O Numeric: This value sets the offset voltage in volts.
- SP Numeric: This value sets the setpoint voltage in volts.
- Kp Numeric: This value set the proportional gain.
- Ki Numeric: This value sets the integral gain in 1/s.
- Kd Numeric: This value sets the derivative gain in s.
- P, I, D buttons: These buttons enable the proportional, integral, and derivative gain respectively when illuminated.
- Run / Stop Toggle: Toggling this switch enables and disables the control.

The user may also use the mouse to change the extent of the displayed information:

- The mouse wheel zooms the plot in and out towards the current position of the mouse pointer.
- SHIFT + Click changes the mouse pointer to a plus sign. Thereafter the left-mouse button will zoom in on the position of the mouse pointer by a factor of 3. The user may also drag and select a region of the chart to zoom to fit.
- ALT + Click changes the mouse pointer to a minus sign. Thereafter the left-mouse button will zoom out from the position of the mouse pointer by a factor of 3.
- Spread and pinch gestures on a mouse pad or touch screen will zoom in and out of the chart respectively.
- After scrolling, clicking the left-mouse button will allow the user to pan by dragging the mouse.
- Right clicking the chart will restore the default position of the chart.

Ramp Software Tab
The Ramp tab provides comparable functionality to the ramp tab on the embedded touchscreen display. Switching to this tab puts the connected device in ramp mode.

Figure 8
Software interface in Ramp mode.

In addition to the controls available in Servo mode, the Ramp mode adds:

- Amplitude Numeric: This value sets the scan amplitude in volts.
- Offset Numeric: This value sets the scan offset in volts.
- Run / Stop Ramp Toggle: Toggling this switch enables and disables the ramp.

Peak Software Tab
The Peak Control tab provides the same functionality as the PEAK mode on the embedded user interface, with additional visibility into the nature of the return signal from the system. Switching to this tab switches the connected device to the PEAK mode of operation.

Figure 9 Software interface in Peak mode with the time-domain display.

In addition to the controls available in Servo mode, the Peak mode adds:

- Amplitude numeric: This value sets the modulation amplitude in volts.
- K numeric: This is the peak lock integral coefficient; the value sets the integral gain constant in V/s.
- Offset numeric: This value sets the offset in volts.
- Frequency numeric: This sets the modulation frequency multiplier in increments of 100 Hz. The minimum allowable value is 100 Hz is the maximum is 100 kHz.
- Run / Stop Peak toggle: Toggling this switch enables and disables the integral gain. Note, whenever the device is in PEAK mode, the output modulation and error signal demodulation is active.

Saved Data
Data is saved in Comma Separated Value (CSV) format. A brief header retains pertinent data from the data being saved. If the format of this CSV is altered, the software may be unable to recover a reference spectrum. Therefore, the user is encouraged to save their data in a separate spreadsheet file if they intend to do any independent analysis.

	A	B	C	D	E
1	Timestamp	09.16.2024:09:19:11			
2	Scans an avera	1			
3	Termination	10000			
4	AC_RMS	0.000246982			
5	V_DC	-8.23E-08			
6	Frequency (Hz)	PSD (dBV^2 / Hz)	ASD (dBV / sqrt(Hz))	Sample Point(Time Domain)	Volts(Time Domain)
7	0	-130.3402866	-65.17014329	0	-0.000366211
8	122.0703	-120.6731671	-60.33658353	2	-0.000488281
9	244.1406	-119.9602799	-59.98013993	4	-0.000732422
10	366.2109	-124.711872	-62.35593601	6	-0.000610352
11	488.2813	-130.7534212	-65.37671061	8	-0.000488281
12	610.3516	-127.0521684	-63.52608422	10	-0.000244141
13	732.4219	-124.1439653	-62.07198267	12	-0.00012207
14	854.4922	-120.735596	-60.36779799	14	-0.000610352

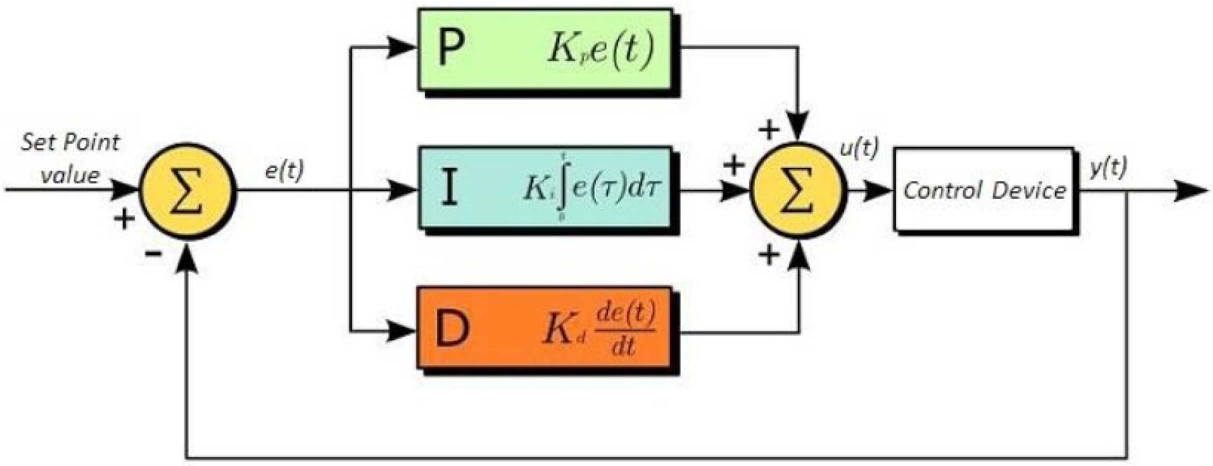
Figure 10 Data in .csv format exported from the DSC1.

Theory of Operation

PID Servo Control

The PID circuit is often utilized as a control loop feedback controller and is very common in servo circuits. The purpose of a servo circuit is to hold the system at a predetermined value (set point) for prolonged periods of time. The PID circuit actively holds the system at the set point by generating an error signal that is the difference between the set point and the current value and modulating an output voltage to maintain the set point. The letters making up the acronym PID correspond to Proportional (P), Integral (I), and Derivative (D), which represent the three control settings of a PID circuit.

The proportional term is dependent upon the present error, the integral term is dependent upon the accumulation of past error, and the derivative term is the prediction of future error. Each of these terms are fed into a weighted sum which adjusts the output voltage of the circuit, u(t). This output is fed into the control device, its measurement is fed back into the PID loop, and the process is allowed to actively stabilize the circuit's output to reach and hold the set point value. The block diagram below illustrates the action of a PID circuit. One or more of the controls can be utilized in any servo circuit depending on what is needed to stabilize the system (i.e., P, I, PI, PD, or PID).



Please note that a PID circuit will not guarantee optimal control. Improper setting of the PID controls can cause the circuit to oscillate significantly and lead to instability in control. It is up to the user to properly adjust the PID parameters to ensure proper performance.

PID Theory

PID Theory for a Continuous Servo Controller: Understand the PID theory for optimal servo control.
The output of the PID control circuit, u(t), is given as

$$u(t) = K_P\, e(t) + K_i \int e(\tau)d\tau + K_d \frac{d}{dt} e(t)$$

Where:

- ?? is the proportional gain, dimensionless
- ?? is the integral gain in 1/seconds
- ?? is the derivative gain in seconds
- ?(?) is the error signal in volts
- ?(?) is the control output in volts

From here we can define the control units mathematically and discuss each in a little more detail. Proportional control is proportional to the error signal; as such, it is a direct response to the error signal generated by the circuit:
? = ???(?)
Larger proportional gain results in larger changes in response to the error, and thus affects the speed at which the controller can respond to changes in the system. While a high proportional gain can cause a circuit to respond swiftly, too high a value can cause oscillations about the SP value. Too low a value and the circuit cannot efficiently respond to changes in the system. Integral control goes a step further than proportional gain, as it is proportional to not just the magnitude of the error signal but also the duration of any accumulated error.

$$I = K_i \int_0^t e(\tau)d\tau$$

Integral control is highly effective at increasing the response time of a circuit along with eliminating the steady-state error associated with purely proportional control. In essence, integral control sums over any previously uncorrected error, and then multiplies that error by Ki to produce the integral response. Thus, for even a small sustained error, a large aggregated integral response can be realized. However, due to the fast response of integral control, high gain values can cause significant overshoot of the SP value and lead to oscillation and instability. Too low and the circuit will be significantly slower in responding to changes in the system. Derivative control attempts to reduce the overshoot and ringing potential from proportional and integral control. It determines how quickly the circuit is changing over time (by looking at the derivative of the error signal) and multiplies it by Kd to produce the derivative response.

$$D = K_d \frac{d}{dt} e(t)$$

Unlike proportional and integral control, derivative control will slow the response of the circuit. In doing so, it is able to partially compensate for the overshoot as well as damp out any oscillations caused by integral and proportional control. High gain values cause the circuit to respond very slowly and can leave one susceptible to noise and high frequency oscillation (as the circuit becomes too slow to respond quickly). Too low and the circuit is prone to overshooting the set point value. However, in some cases overshooting the set point value by any significant amount must be avoided and thus a higher derivative gain (along with lower proportional gain) can be used. The chart below explains the effects of increasing the gain of any one of the parameters independently.

Parameter Increased	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
Kp	Decrease	Increase	Small Change	Decrease	Degrade
Ki	Decrease	Increase	Increase	Decrease Significantly	Degrade
Kd	Minor Decrease	Minor Decrease	Minor Decrease	No Effect	Improve(for small Kd)

Discrete-Time Servo Controllers

Data Format

The PID controller in the DSC1 receives a 16-bit ADC sample, which is an offset binary number, that can range from 0-65535. 0 maps linearly to a negative 4V input and 65535 represents a +4V input signal. The "error" signal, ?[?], in the PID loop at a timestep ? is determined as ?[?] = ? – ?[?] Where ? is the setpoint and ?[?] is the voltage sample in the offset binary scale at a discrete time step, ?.

Control Law in the Time Domain

Three gain terms are computed and summed together.
?[?] = ??[?] + ??[?] + ??[?] ?? = ???[?] ?? ≈ ?? ∫ ?[?] ?? = ??(?[?] – ?[? – 1])
Where ??[?], ??[?], and ??[?] are the proportional, integral, and derivative gains comprising the control output ?[?] at a timestep ?. ??, ??, and ?? are the proportional, integral, and derivative gain coefficients.

Approximating the Integral and the Derivative

The DSC1 approximates an integrator with an accumulator.
∫ ?[?] = ?[?] + ∫ ?[? – 1] Consideration of the interval of integration, the timestep width, is wrapped into the integral gain coefficient ?? such that: ?? = ?′?*h*
Where ?′? is the nominally entered integral gain coefficient and *h* is the time between ADC samples. We make a similar approximation to the derivative as the difference between ?[?] and ?[? – 1] again assuming that ?? also contains a 1 / h scaling.

$$\frac{d}{di}(e[i]) = e[i] - e[i-1]$$

As previously mentioned, now consider that the integral and derivative approximations did not include any consideration of the timestep (sample interval), hereafter *h*. Traditionally we say a first-order, explicit, approximation to a variable ?[?] with $\frac{du}{di}$ = ?(?, ?) based on the terms in a Taylor series expansion is ?[?] ≈ ?[? – 1] + *h* ?(?, ?)
This is often referred to as a Backwards Euler Integration Scheme or an Explicit First-Order Numerical Integrator. If we solve for the derivative, ?(?, ?), we find:

$$\frac{u[i] - u[i-1]}{h} \approx f(u, i)$$

Note the similarity of the numerator in the above to our proceeding approximation to the derivative in the control equation. This is to say, that our approximation to the derivative is more appropriately scaled by *h*–1.

It also intuitively mimics the Fundamental Theorem of Calculus:

$$f(x) = \lim_{h \to 0} \frac{A(x+h) - A(x)}{h} \stackrel{\text{def}}{=} A'(x).$$

Now if we say that ? is the integral of the error signal ?, we can make the following substitutions.
?[?]=∫?[?] ?(?,?)= ?[?] And we obtain from the first-order Taylor series approximation to a function ?: ∫?[?]=∫?[? −1]+*h* ?(?)
By simply assuming ∫?[?]=0 for ?=0, the proceeding approximation to an integral practically condenses to an accumulator.

Therefore we adjust our prior derivation of the control law to:

$$u[i] = K_p e[i] + hK'_i \left(e[i] + \int e[i-1]\right) + \frac{K'_d}{h}(e[i] - e[i-1])$$

Control Law in the Frequency Domain

Although the equation derived in the proceeding section informs the time-domain behavior of the discrete-time PID controller implemented in the DSC1, it says little about the frequency domain response of the controller. Instead we introduce the ? domain, which is analogous to the Laplace domain, but for discrete rather than continuous time. Similar to the Laplace transform, the Z transform of a function is most often determined by assembling tabulated Z-transform relationships, rather than substituting the Z-transform definition (shown below) directly.

$$X(z) = \sum_{n=0}^{\infty} x[n]\, z^{-n}$$

$$z = Ae^{j\emptyset}$$

Where ?(?) is the Z-domain expression of a discrete time variable ?[?], ? is the radius (often treated as 1) of the independent variable ?, ? is the square root of -1, and ∅ is the complex argument in radians or degrees. In this case, only two tabulated Z-transformations are necessary.
?[?] = ?[?] ?[? − 1] = ?[?]?−1
The Z-transform of the proportional term, ??, is trivial. Also, please accept for a moment that it's useful to us to determine the error to control transfer function, ?(?), rather than simply ?(?).

$$u_p(z) = K_p e[i] = K_p e(z)$$

$$\frac{u(z)_p}{e(z)} = K_p$$

The Z-transform of the integral term, ??, is more interesting.
Recall our explicit Euler integration scheme in the previous section: ??(?) = ?? ∫ ?[?] = ?? (∫ ?[? − 1] + *h* ?(?))
∫ ?(?) = ∫ ?(?) ?−1 + *h*?(?)
∫ ?(?) − ∫ ?(?) ?−1 = *h*?(?)

$$\frac{\int e(z)\left(1-\frac{1}{z}\right)}{h} = e(z)$$

$$\frac{\int e(z)}{e(z)} = \frac{h}{\left(1-\frac{1}{z}\right)} = \frac{hz}{z-1}$$

$$\frac{u_i(z)}{e(z)} = K_i h\left(\frac{z}{z-1}\right)$$

Finally, we look at the derivative gain, ??:

$$u_d(z) = K_d \frac{d}{dt}(e[i]) \approx \frac{K_d(e[i]-e[i-1])}{h}$$

$$\frac{d}{dt}(e[i]) = \frac{(e(z)-e(z)z^{-1})}{h}$$

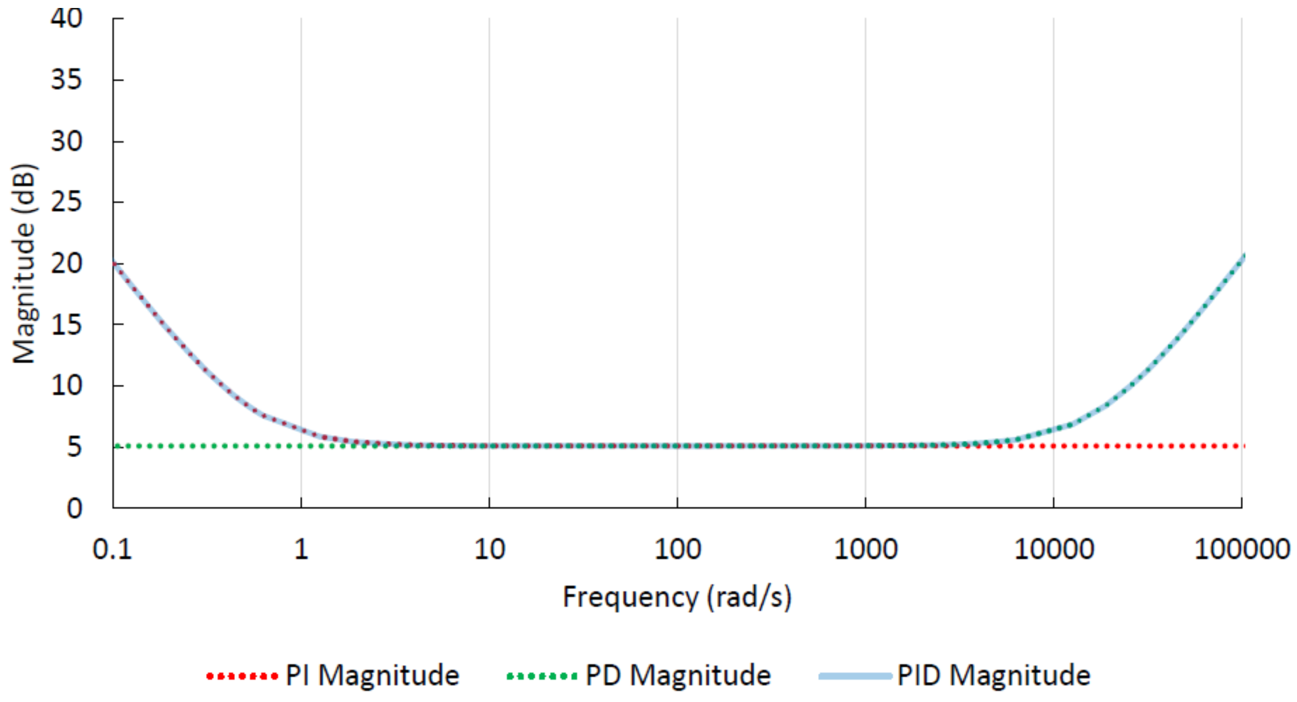
$$\frac{\frac{d}{dt}(e[i])}{e(z)} = \frac{\left(1-\frac{1}{z}\right)}{h} = \frac{1}{h}\left(\frac{z-1}{z}\right)$$

$$\frac{u_d(z)}{e(z)} = \frac{K_d}{h}\left(\frac{z-1}{z}\right)$$

Assembling each of the above transfer functions, we arrive at:

$$\frac{u(z)}{e(z)} = K_p + hK_i\left(\frac{z}{z-1}\right) + \frac{K_d}{h}\left(\frac{z-1}{z}\right)$$

With this equation, we may numerically compute the frequency domain response for the controller and display it as a Bode plot, such as below.
PID Transfer Functions, Kp = 1.8, Ki = 1.0, Kd = 1E-4



Note how the PI controller gain approaches solely the proportional gain and hi-frequency and how the PD controller gain approaches solely the proportional gain at low frequencies.

PID Tuning

In general, the gains of P, I, and D will need to be adjusted by the user in order to optimize the performance of the system. While there is not a static set of rules for what the values should be for any specific system, following the general procedures should help in tuning a circuit to match one's system and environment. In general, a properly tuned PID circuit will typically overshoot the SP value slightly and then quickly damp out to reach the SP value and hold steady at that point. The PID loop can lock to either a positive or negative slope by changing the sign of the P, I, and D gains. In the DSC1, the signs are locked together so changing one will change them all.

Manual tuning of the gain settings is the simplest method for setting the PID controls. However, this procedure is done actively (the PID controller attached to the system and the PID loop enabled) and requires some amount of experience to achieve good results. To tune your PID controller manually, first set the integral and derivative gains to zero. Increase the proportional gain until you observe oscillation in the output. Your proportional gain should then be set to roughly half this value. After the proportional gain is set, increase the integral gain until any offset is corrected for on a time scale appropriate for your system.

If you increase this gain too much, you will observe significant overshoot of the SP value and instability in the circuit. Once the integral gain is set, the derivative gain can then be increased. Derivative gain will reduce overshoot and damp the system quickly to the set point value. If you increase the derivative gain too much, you will see large overshoot (due to the circuit being too slow to respond). By playing with the gain settings, you can optimize the performance of your PID circuit, resulting in a system that quickly responds to changes and effectively damps out oscillation about the set point value.

Control Type	**Kp**	**Ki**	**Kd**
P	0.50 Ku	–	–
PI	0.45 Ku	1.2 Kp/Pu	–
PID	0.60 Ku	2 Kp/Pu	KpPu/8

While manual tuning can be very effective at setting a PID circuit for your specific system, it does require some amount of experience and understanding of PID circuits and response. The Ziegler-Nichols method for PID tuning offers a more structured guide to setting PID values. Again, you'll want to set the integral and derivative gain to zero. Increase the proportional gain until the circuit starts to oscillate. We will call this gain level Ku. The oscillation will have a period of Pu. Gains are for various control circuits are then given in the chart above. Note that when using the Ziegler-Nichols tuning method with the DSC1, the integral term determined from the table should be multiplied by 2·10-6 to normalize to the sample rate. Similarly, the derivative coefficient should be divided by 2·10-6 to normalize to the sample rate.

Ramping

Users may often need to determine the large-signal operating point or useful setpoint for a system. To determine either the large-signal operating point (hereafter referred to as DC offset) or optimal servo setpoint, a common technique is to simply stimulate the system repeatedly with a linearly increasing voltage signal. The pattern is commonly referred to as a sawtooth-wave, for its resemblance to the teeth of a saw.

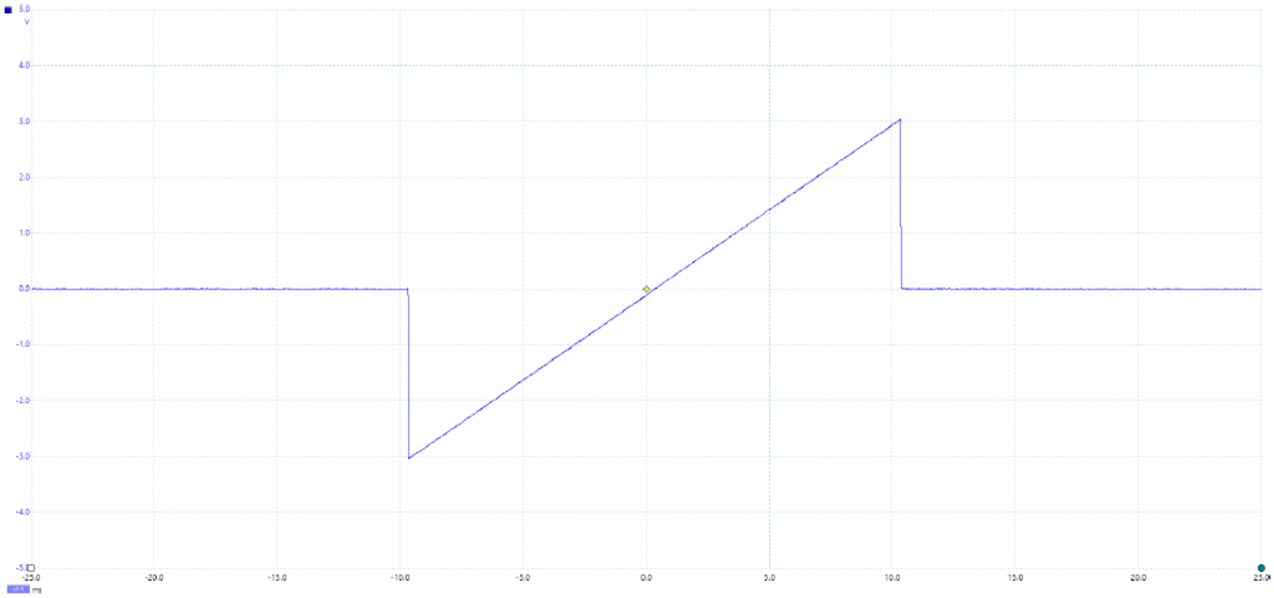


Figure 11 Oscillogram of a single cycle of the ramp mode waveform with amplitude set to 3.0V and offset set to 0.0V.

Peak Lock Mode

The peak lock mode implements a dither locking algorithm also known as an extremum seeking controller. In this mode of operation, the control value is superimposed on a sine wave output. The measured input voltage is first digitally high-pass filtered (HPF) to remove any DC offset. Then the AC coupled signal is demodulated by multiplying each measured voltage by the outgoing sine wave modulation value. This multiplication operation creates a demodulated signal with two principal components: a sine wave at the sum of the two frequencies and a signal at the difference of the two frequencies.

A second digital filter, this time a low pass filter (LPF), attenuates the sum-of-two frequencies signal, and transmits the low frequency difference-of-two frequencies signal. Signal content at the same frequency as the modulation appears as a DC signal post demodulation. The final step in the peak lock algorithm is to integrate the LPF signal. The integrator output, combined with the outgoing modulation, drives the output voltage. The accumulation of low frequency demodulated signal energy in the integrator pushes the offset control voltage of the output higher and higher until the sign of the LPF output reverses and the integrator output begins to diminish. As the control value approaches the peak of the system response, the result of the modulation on the input signal to the servo controller becomes smaller and smaller, since the slope of a sinusoidal wave form is zero at its peak. This in turn means that there is a lower output value from the low-pass-filtered, demodulated signal, and therefore less to accumulate in the integrator.

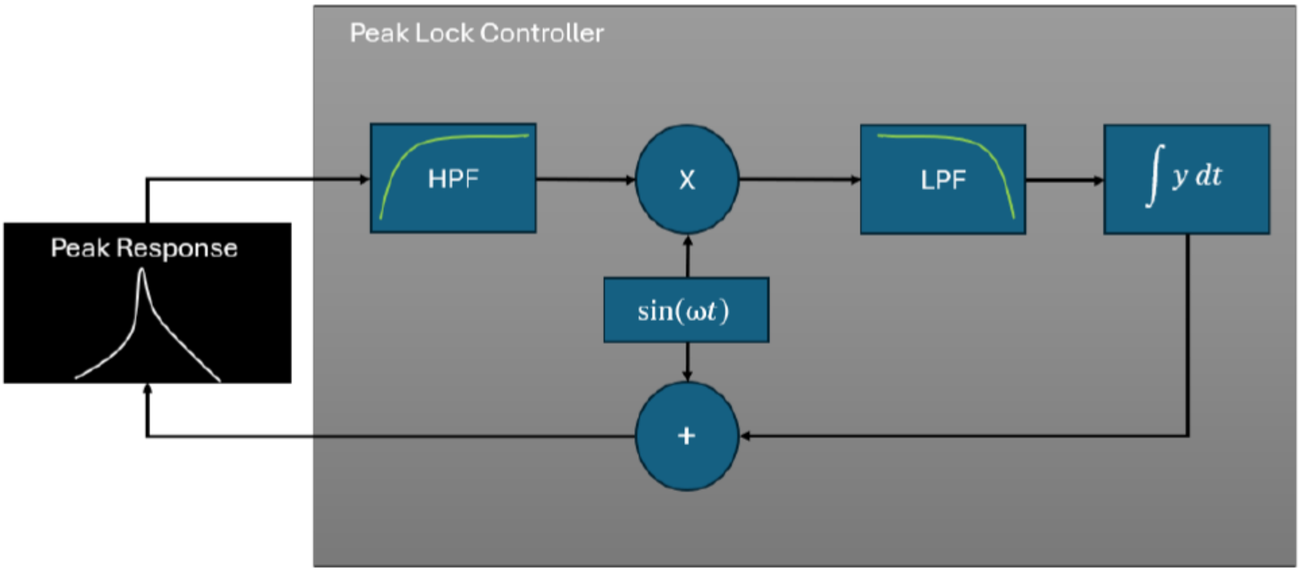


Figure 12 Block diagram of a peak locking controller. The input signal from the peak responsive plant is digitized, then high-pass filtered. The HPF output signal is demodulated with a digital local oscillator. The output of the demodulator is low-pass filtered and then integrated. The integrator output is added to the modulation signal and output to the peak responsive plant. Peak locking is a good control algorithm to choose when the system the user wishes to control does not have a monotonic response around the optimal control point. Examples of these sorts of systems are optical media with a resonant wavelength, such as a vapor cell, or an RF band-reject filter (notch filter). The central characteristic of the peak locking control scheme is the algorithm's tendency to steer the system towards the zero-crossing of the error signal which coincides with a peak in the measured signal, as if the error signal were the derivative of measured signal. Note that the peak may be positive or negative. To get started with the peak locking mode of operation for the DSC1, you may follow this procedure.

1. Make sure that there is a peak (or valley) of the signal you are locking to is within the control voltage range of the actuator, and that the peak position is relatively stable with time. It is helpful to use the RAMP mode to visualize the signal over the control voltage range of interest.
2. Note the control voltage position of the peak (or valley).
3. Estimate how broad the peak (or valley) is in control voltage at half of the height of the peak. This width, in volts, is commonly referred to as the Full-Width Half-Max or FWHM. It should be at least 0.1V wide for good results.
4. Set the modulation amplitude (A) to 1% to 10% of the FWHM voltage.
5. Set the offset voltage as close as possible to the position of the peak (or valley) that you desire to lock to.
6. Set the modulation frequency to the desired frequency. On the touch screen this is affected through the M, modulation frequency parameter. The modulation frequency is 100 Hz times M. The best modulation frequency selection depends on the application. Thorlabs recommends values around 1 kHz for mechanical actuators. Higher frequencies may be used to electro-optic actuators.
7. Set the peak lock integral coefficient (K) to 0.1 times A. K can be positive or negative. Generally, positive K locks to a peak of the input signal, while negative K locks to a valley of the input signal. However, if the actuator or system being locked has more than 90 degree phase delay at the dither frequency, the sign of K will invert and positive K will lock to a valley, and negative K will lock to a peak.
8. Press Run and verify that the control voltage output changes from the original offset (O) value and does not run away to a an extreme. Alternatively, monitor the process variable using an oscilloscope to verify that the DSC1 is locking to the peak or valley desired.

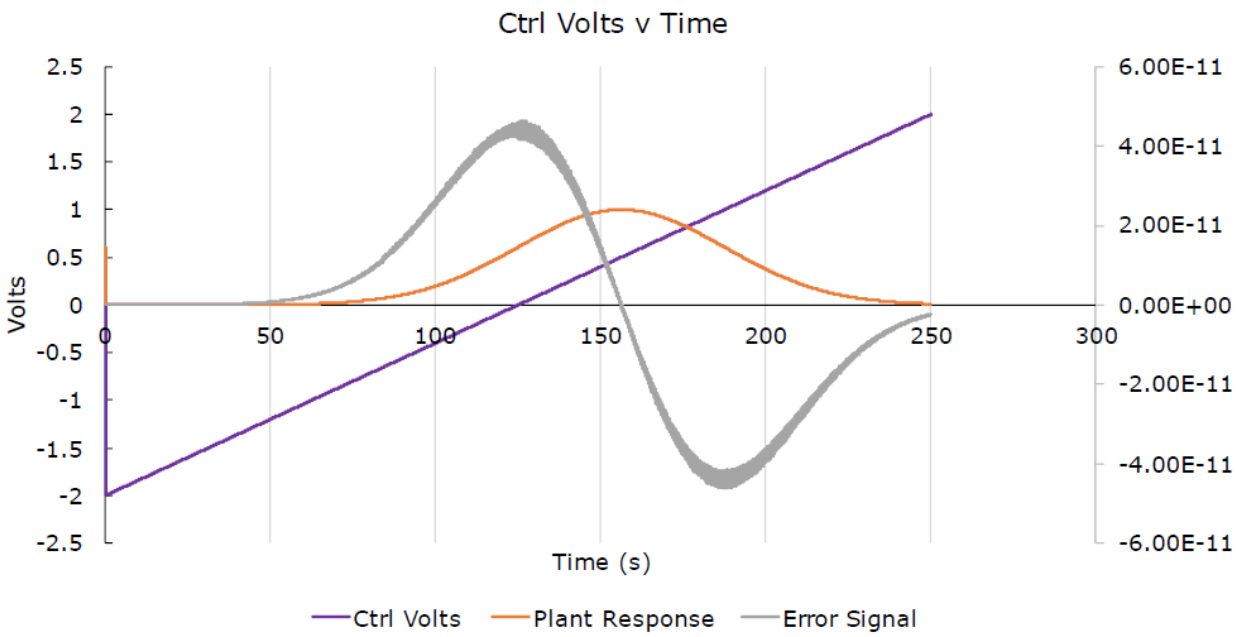


Figure 13 Example data from ramping the output offset voltage with a continuous sine wave, imposed on a peak response plant. Note the error signal zero crossing aligns with the peak of the plant response signal.

Maintenance and Cleaning

Regularly clean and maintain the DSC1 for optimal performance. The DSC1 requires no regular maintenance. Should the touchscreen on the device become dirty, Thorlabs recommends gently cleaning the touchscreen with a soft, lint-free cloth, saturated with diluted isopropyl alcohol.

Troubleshooting and Repair

If issues arise, refer to the troubleshooting section for guidance on resolving common problems. The below table describes typical issues with the DSC1 and Thorlabs recommended remedies.

Issue	**Explanation**	**Remedy**
The device does not turn on when plugged into USB Type-C power.	The device requires as much as 750 mA of current from a 5 V supply, 3.75 W. This may exceed the power capabilities of some USB-A connectors on laptops and PCs.	Use Thorlabs DS5 or CPS1 power supplies. Alternatively, use a USB Type-C power supply such as is typically used to charge a phone or laptop that is rated to output at least 750 mA at 5 V.
The device does not turn on when the data port is plugged into a PC.	The DSC1 only draws power from the USB Type-C power connector. The USB Type Mini-B connector is data only.	Connect the USB Type-C port to a power supply rated to output at least 750 mA at 5 V, such as Thorlabs DS5 or CPS1.

Disposal

Follow proper disposal guidelines when retiring the DSC1.

Thorlabs verifies our compliance with the WEEE (Waste Electrical and Electronic Equipment) directive of the European Community and the corresponding national laws. Accordingly, all end users in the EC may return “end of life” Annex I category electrical and electronic equipment sold after August 13, 2005 to Thorlabs, without incurring disposal charges. Eligible units are marked with the crossed out “wheelie bin” logo (see right), were sold to and are currently owned by a company or institute within the EC and are not dissembled or contaminated. Contact Thorlabs for more information. Waste treatment is your own responsibility. “End of life” units must be returned to Thorlabs or handed to a company specializing in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site. It is the user's responsibility to delete all private data stored on the device prior to disposal.

FAQ:

Q: What should I do if the DSC1 is not powering on?
A: Check the power source connection and ensure it meets the specified requirements. If the issue persists, contact customer support for assistance.

Safety

NOTICE
This instrument should be kept clear of environments where liquid spills or condensing moisture are likely. It is not water resistant. To avoid damage to the instrument, do not expose it to spray, liquids, or solvents.

Installation

Warranty Information
This precision device is only serviceable if returned and properly packed into the complete original packaging including the complete shipment plus the cardboard insert that holds the enclosed devices. If necessary, ask for replacement packaging. Refer servicing to qualified personnel.

Included Components

The DSC1 Compact Digital Servo Controller is delivered with the following components:

- DSC1 Digital Servo Controller
- Quick Start Card
- USB-AB-72 USB 2.0 Type-A to Mini-B Data Cable, 72″ (1.83 m) Long
- USB Type-A to USB Type-C Power Cable, 1 m (39″) Long
- PAA248 SMB to BNC Coaxial Cable, 48″ (1.22 m) Long (Qty. 2)

Installation and Setup

Basics
Users may configure the device with a computer using the USB interface or through the integrated touchscreen. In either case, power must be provided through the 5V USB-C connection. When using the desktop GUI, the servo controller must be connected with a USB 2.0 cable (included) from data port of the device to a PC with the Digital Servo Controller software installed.

Ground Loops and the DSC1
The DSC1 includes internal circuitry to limit the likelihood of ground loops occurring. Thorlabs suggests using either the transformer isolated DS5 regulated power supply or the CPS1 external battery pack. With either the DS5 or CPS1 power supplies, the signal ground within the DSC1 floats with respect to the earth ground of a wall outlet. The only connections to the device that are common to this signal ground are the signal ground pin of the USB-C power connector and the outer, return path on the output SMB coaxial cable. The USB data connection is isolated. The input signal has a ground-loop break resistor between the signal return path and the signal ground within the instrument which typically prevents ground loop interference. Importantly, there are no two direct paths to the device signal ground, minimizing the occurrence of ground loops.

To further mitigate the risk of ground-loop interference, Thorlabs suggests the following best-practices:

- Keep all power and signal cables to the device short.
- Use either a battery (CPS1) or transformer isolated (DS5) power supply with the DSC1. This ensures a floating device signal ground.
- Do not connect other instruments' signal return paths to one another.
    - A common example is a typical benchtop oscilloscope; most often the outer shells of the BNC input connections are directly connected to earth ground. Multiple ground clips connected to the same ground node in an experiment can cause a ground loop.

Although the DSC1 is unlikely to cause a ground loop in of itself, other instruments in a user's lab may not have ground loop isolation and thus could be a source of ground loops.

Powering the DSC1
The DSC1 Digital Servo Controller requires 5 V power through the USB-C at up to 0.75 A peak current and 0.55 A in typical operation. Thorlabs offers two compatible power supplies: the CPS1 and DS5. In applications where noise sensitivity is less constrained or where runtimes of greater than 8 hours are required, the DS5 regulated power supply is recommended. The CPS1 battery power supply is recommended when optimal noise performance is desired. With the CPS1 fully charged and in good health, the DSC1 can operate for 8 hours or more without recharging.

Thorlabs Worldwide Contacts

For further assistance or inquiries, refer to Thorlabs' worldwide contacts. For technical support or sales inquiries, please visit us at **www.thorlabs.com/contact** for our most up-to-date contact information.

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Documents / Resources

	THORLABS DSC1 Compact Digital Servo Controller [pdf] User Guide DSC1, DSC1 Compact Digital Servo Controller, DSC1, Compact Digital Servo Controller, Digital Servo Controller, Servo Controller, Controller

References

- Thorlabs - Photonics Products & Solutions
- Thorlabs - Photonics Products & Solutions
- Thorlabs - Photonics Products & Solutions
- User Manual