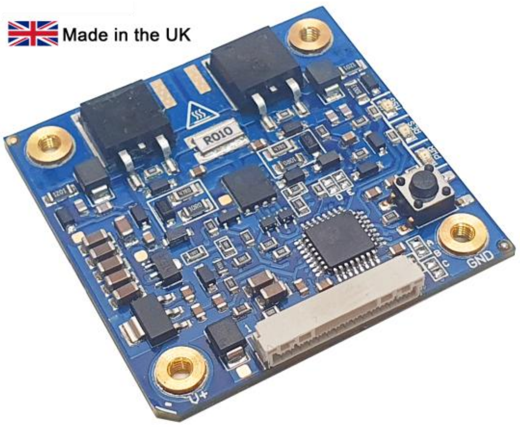
Micro Induction Heater Driver

CRO-SM3 Series

Compact Induction Heating Platform for Embedded and Automated Systems



The CRO-SM3 is a compact, self-resonant induction-heater driver for heating small metal components and workpieces at power levels up to 500 W. It operates from standard 12–24 V DC power supplies and measures only 50 × 50 mm.

Two versions are available. The CRO-SM3-ST provides straightforward standalone operation with four selectable power levels. The CRO-SM3-PRO adds configurable operating modes, serial control and monitoring, and access through a browser-based web application.

Configurable & connected

Set operating modes, limits, timing and control behaviour through onboard registers. Settings are retained, allowing the CRO-SM3-PRO to operate independently once configured.

Connect through the 5 V TTL serial interface for remote control and live monitoring, or use the browser-based web app for setup, dashboards, graphing, calibration and fault diagnostics. The documented serial protocol also simplifies integration with custom controllers and embedded systems.

Serial control & web app only on CRO-SM3-PRO

Compact Design	12 - 24 V DC	Self-Resonant Control
Complete 50 × 50 mm controller for integration into equipment and experimental systems.	Compatible with readily available DC power supplies and battery systems.	Automatically follows the resonant frequency as conditions change. Normally <250 kHz
Up to 500 W	**OEM Integration**	**Modular System**
Designed for efficient induction heating of small components and workpieces.	A ready-made mixed-signal heating controller for integration into products.	Expansion modules provide additional sensing, control and connectivity.

CRO-SM3-ST	CRO-SM3-PRO
Simple standalone control	*Advanced, configurable and connected*
Single push-button operation, four selectable power levels with essential self-monitoring and protection. Best for straightforward induction-heating applications that do not require configuration or communications.	All ST features plus timed cycles, constant-current control, automatic workpiece detection and temperature regulation.
External control can be made via the 5 V I/O port	Configure operation, monitor live values and diagnose faults through the web application or serial interface.

The names CRO-SM3 and SM3 refer to both variants throughout this datasheet; see Appendix H for a feature comparison.

A complete induction heating system will also require an external DC power supply, work coil, tank capacitors and chokes. See Basic induction heater: Quick start for the required parts and example build.

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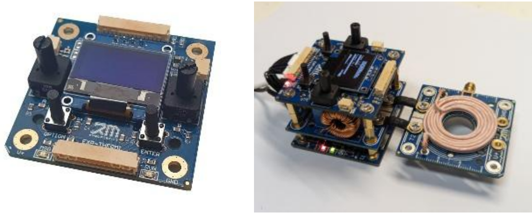
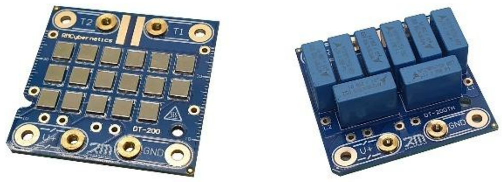
Modular system

The CRO-SM3 combines the power stage, control firmware and external interfaces needed to build a compact induction-heating or resonant-power system. In addition to this; a suitable work coil, tank capacitor, chokes and PSU will be required to assemble a complete working heating system.

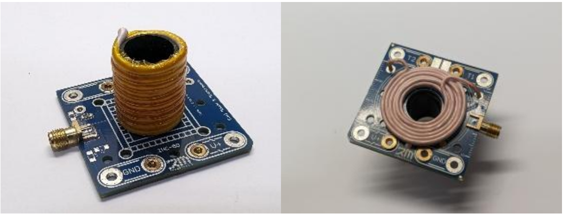
The SM3 will work with third party custom components or the RMCybernetics range of stackable modules designed to make development quick and simple. Below are a few example modules and configurations. See the RMCybernetics website for the latest products and information.



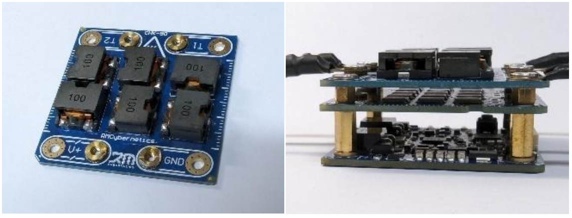
***E*XP-THERM1**
Basic controller with OLED & Thermocouple amplifier



DT-200
Compact capacitor arrays



IHC-50
Work coil mounting platform with integrated feedback coil



CHK-50
Compact choke array

Typical system configurations

The CRO-SM3 can be used in several configurations depending on the required level of local control, monitoring and system integration. Expansion modules may be stacked directly above the controller or connected remotely where this is more suitable for cooling, wiring or enclosure layout.

Standalone controller

Both variants can operate independently without a display, computer or permanent serial connection.

The ST variant operates in NORMAL mode. Output is started and stopped using the onboard button or the 5 V control input, which may be connected to an external switch or controller. The onboard button also selects one of four power levels: 25%, 50%, 75% or 100%.

The PRO variant can first be configured using the web application or serial interface. Operating mode, PWM settings, current limits, heating time and other supported settings are stored in non-volatile memory. Once configured, it can operate without the configuring device and may be started using the onboard button, control input, an external switch or configured automatic behaviour.

Standalone operation is suitable for fixed or repeatable applications where settings do not need to be changed regularly.

Controller with EXP-THERM1

The EXP-THERM1 is a local interface module containing an OLED display, push-button controls, adjustment inputs and a Type-K thermocouple amplifier.

With the ST variant, the display shows operating measurements and fault information. Mode selection, adjustable settings and thermocouple operation are not supported.

With the PRO variant, the module also provides local access to operating modes and adjustable settings, while the thermocouple amplifier enables temperature-controlled operation. This allows the system to be monitored and controlled locally without requiring a computer.

Controller with web application (PRO only)

A compatible 5 V USB-to-TTL serial adaptor (not included) can be used to connect the controller to the browser-based application, accessed by signing in to the RMCybernetics website. The application provides configuration, live measurements, graphs, calibration functions, operating controls and retained fault information. Customers purchasing a CRO-SM3-PRO through the RMCybernetics website must use a registered account. That account provides access to the associated web applications and a downloadable snapshot of the web application source code. The downloaded copy is not updated automatically; a later version may be requested if required.

Embedded control

Both the ST and PRO can be integrated into custom equipment using direct 5 V digital control signals. External switches or compatible logic outputs can start and stop operation and clear fault conditions. The ST provides these basic controls for NORMAL-mode operation.

The PRO additionally supports external potentiometers, configurable analogue and digital AUX functions, and a 5 V TTL serial interface. A microcontroller or computer can read operating values, change settings, select operating modes, start and stop the output, and respond to fault conditions. The AUX connection can be configured for analogue sensing, interlocking, fan control or post-cycle signalling.

Signals using other logic levels, industrial interfaces or powered loads require suitable level conversion, isolation or driver circuitry.

EXP-BOB1 breakout board

The EXP-BOB1 breakout board brings the CRO-SM3 expansion I/O out to terminal breakouts for fast, solderless prototyping. It also includes mounting and connection options for common interfaces such as an Arduino Nano and other components, so developers can interface their own hardware or controller and build custom control systems without designing a separate interface PCB.

Features & applications

The CRO-SM3 provides localised, non-contact heating in a package small enough to build into equipment. The features listed below are described in detail later in this datasheet. The applications are indicative rather than exhaustive, as achievable power and temperature depend on the work coil, tank capacitor and power supply used with the controller. Some features listed are *PRO only*.

- Self-resonant operation
- Adjustable power control
- Soft-start and startup retry
- *Timed* and continuous operation
- *Automatic workpiece detection*
- *Temperature-based control*
- *Live monitoring* and protection
- Fault recording and *retained diagnostics*
- *Browser-based configuration and control*
- *Stored configuration*
- External control options
- *Customer-accessible web app source*

- Annealing
- Heat Treatment & Hardening
- Plastic Moulding
- Heat Sealing
- Wireless Power Transmission
- Robotics & automated assembly
- DC-AC and DC-DC Power Inverters
- 3D Printer Hot End
- Resonant Energy Experiments
- Material Testing
- Flameless sterilising
- Non-contact heating

Advanced configuration, monitoring, calibration and web-app functions are only available on the PRO version and require a compatible 5 V TTL serial connection, such as a USB-to-TTL adaptor. Type-K thermocouple operation requires the EXP-THERM1 or an equivalent thermocouple amplifier.

Electrical characteristics

NB: Figures may vary significantly under different loading conditions and environments. Current is measured only in the DC input supply to the board. The current circulating in the tank circuit is not measured and will typically be many times higher. Voltage is measured both at the input and at T1.

Symbol	Parameter	Min	Typical	Max
V_{in}	Operating Input Supply Voltage	12 V [1]	15 V	25 V [4]
V_{power}	Load Supply Voltage	5 V	15 V	30 V
I_{sup}	Supply Current (no load)	20 mA	30 mA	70 mA
I_{IN}	Continuous DC Input Current	0 A	-	20 A [3]
I_{pulse}	Pulse Current [2]	-	-	70 A
V_{logic}	Logic (High) Voltage	3.3 V	5 V	5.1 V
T_{limit}	Thermal Protection Threshold	-	90 °C	100 °C
$V_{CoilLimit}$	Coil Voltage Protection Threshold	-	85 V	-
$V_{InLimit}$	Input Voltage Fault Thresholds	10 V	-	26 V [4]
I_{limit}	Current Protection Threshold [5]	18 A	20 A	30 A
f_{RES}	Resonant Operating Frequency	-	<250 kHz	ST: 300 kHz PRO: 1 MHz [6]

Table 1: Electrical characteristics

[1] 12 V is absolute minimum. 15 V to 24 V recommended.
[2] Pulse current is transistors max rated DC current at 25 °C.
[3] Max current depends on cooling and operating frequency.
[4] 15 V to 24 V is recommended; the controller will operate up to 25 V. An input above approximately 25.5 V raises an input-voltage fault and the output is inhibited until the input has remained below 24 V for at least one second. 26 V is the absolute maximum continuous input the hardware will tolerate, and continuous input above 26 V may cause permanent damage. The controller cannot block an over-voltage supply; only fast transients are clamped.
[5] Threshold of 20A is fixed on ST. User configuration on PRO allows up to 30A
[6] Default firmware limit on both ST and PRO is 300 kHz. This can be adjusted in PRO modules. Normal operation is below 250 kHz. At higher frequencies, switching losses and component heating significantly increase, so the achievable current and power depend on the tank circuit, supply voltage and cooling. Operation up to 1 MHz may require reduced current or circuit modification and is not guaranteed under all operating conditions.

Important integration and operating requirements

The CRO-SM3 is supplied as a component for incorporation into a complete system. The controller itself does not create a significant hazard when unpowered. Electrical, thermal and electromagnetic hazards arise from the power supply, resonant components, work coil, heated workpiece and installation selected by the system designer.

The completed system must include suitable wiring, connectors, current limiting, fusing, cooling, mechanical protection and electrical insulation for the intended operating conditions.

During operation, the choke, tank capacitor, work coil and associated wiring may carry high alternating currents. Resonant voltages may also be substantially higher than the DC supply voltage. These parts must not be touched, adjusted or disconnected while the system is energised.

The work coil, workpiece, PCBs, heatsink and nearby components may become hot enough to cause burns or damage surrounding materials. Adequate cooling, clearance and guarding must be provided.

The completed system may generate strong alternating magnetic fields and electrical interference. Its effect on nearby electronics, wiring and other equipment must be considered during installation.

Stopping or PWM-modulating a heavily loaded tank circuit can produce fast voltage transients from energy stored in the power chokes. These transients may exceed the MOSFET voltage rating before the controller can detect or respond to them. Systems intended for high-current or strongly coupled loads should be tested under worst-case operating conditions and fitted with external choke clamps where required. See ***Switch-off voltage spikes and external clamping****.*

Firmware protection functions are intended to reduce the risk of damage but must not be treated as the only means of protection. External fusing, power-supply current limiting and any application-specific thermal or interlock protection remain the responsibility of the system designer.

Operate the controller only within the specified electrical and thermal limits. Initial testing of a new work coil or tank circuit should be carried out using a current-limited supply and gradually increased power.

Electrical connections

The main connections for power and the tank circuit (work coil and tank capacitor) are made using the M3 threaded inserts in the corners of the board. Additional connections are available via the 15-way connector at the edge of the PCB. The onboard microcontroller is running at 5 V so all external logic interfaces must be able to work at 5 V. Expansion boards such as the EXP-BOB1 are available for additional connectivity options.

Power cables should be terminated with a suitable M3 crimped ring terminal and fixed to the board using a stainless steel or other non-magnetic M3 Screw.

The screw mounts are only 3 mm deep, so if the PCB is to be fitted to a flat surface, suitably short screws or an appropriate spacer must be used to prevent the screw making contact underneath.

Connectors and mounting kits are available on the RMCybernetics website.

I/O connections can be made using a 15-way, 1.25 mm pitch, JST GH connector. The 15-way female socket on the CRO-SM3 is a JST “SM15B-GHS-TB”. The male plug housing to fit this is JST part number “GHR-15V-S” which uses crimp terminals “SSHL-002TP0.2”. Optionally the EXP-BOB1 breakout board can be used to expand this connection to terminal blocks. Table 3 lists the pinout of this connector.

The CRO-SM3 circuit can be powered from a 12 V to 25 V supply (15 V to 24 V recommended), while the load device itself can be powered from a separate supply of a different voltage if desired. Typically, the circuit and load will both be connected to the same supply for simplicity. A 15 V DC supply is recommended in most cases, with initial tests carried out at this voltage before higher voltages are used. When using a single supply ensure the voltage does not exceed 25 V.

If a separate load supply is used, connect its negative terminal to SM3 GND. Only V_{power} may use the separate 5–30 V supply; V+ must remain within its specified 12–25 V operating range.

Power to the tank circuit is typically delivered via suitable chokes. See Choke selection for guidance on inductance and current rating.

The load supply (V_{power}) should be connected to a suitable DC power supply which is rated for typically 5 A or more (this can be the same connection as V+). For experimental work, a linear bench PSU with current limiting is recommended.

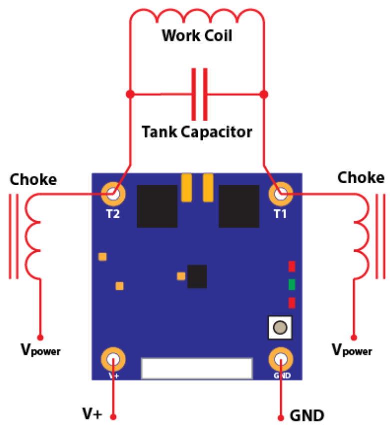


Figure 1: Connection diagram for standard coils

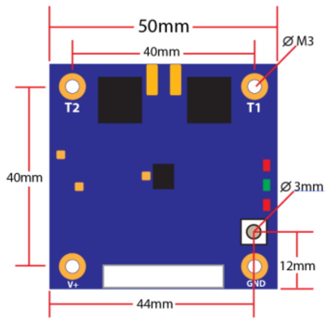


Figure 2: Product dimensions

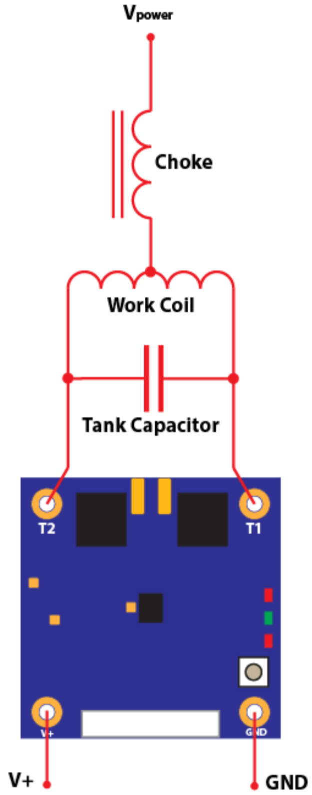


Figure 3: Connection diagram for centre tapped coils

Connection	Description
V+	Circuit positive supply input 12 V to 25 V DC
GND	Circuit ground or negative supply input
V_{power}	Load positive supply (5 V – 30 V) input to choke (connect to V+ for single supply use)
T1, T2	Connection for work coil / tank capacitor
Choke	Power choke. See Choke selection for inductance and current rating.
Tank capacitor	Tank capacitor(s) to form part of the tank circuit.
Work Coil	Work coil, such as an induction coil or transformer primary

Table 2: Connections

The tank circuit connections are labelled T1 and T2 which are for the ends of the work coil and tank capacitor. Note that the terminals do not themselves supply any power. The power for the load must be provided via chokes (inductors) to T1/T2 or the centre connection of a centre tapped coil.

A tank capacitor is essential for proper resonance. These can be fitted externally, or as part of the modular stack using the DT-200 tank capacitor modules.

The work coil and tank capacitor(s) should be connected to each other as close as is practically possible and should also connect very close to the circuit. Long wires can cause problems with oscillations starting up or poorly shaped waveforms, particularly at high power levels.

Basic induction heater: Quick start

This procedure describes an example low power setup using the standard two-choke connection shown in Figure 1. It assumes a single 15 V supply and operation using the onboard Start/Stop button or suitable remote connection. Read Important integration and operating requirements before assembly. If selecting custom components or operating outside the typical starting values below, also read System Design and Component Selection.

Required components

- CRO-SM3 controller
- Current-limited 15 V DC bench supply capable of supplying at least 5 A
- Two suitable power chokes; a pair of 100 µH, 15 A chokes or equivalent provides a versatile starting point
- DT-200-TH tank capacitor board (2640 nF).
- Work coil of approximately 20 turns of 18 A-rated litz wire or larger, wound to an internal diameter of approximately 25 mm. This test coil measured as 5 uH inductance.
- A metal workpiece that is small relative to the work coil (such as an M3 steel bolt)
- A 5 A fuse, wiring, connectors and mounting hardware (mounting kit available)

This arrangement provides a relatively low-power starting tank with a reasonably low unloaded supply current. The DT-200-TH also provides mounting positions for the two power chokes.

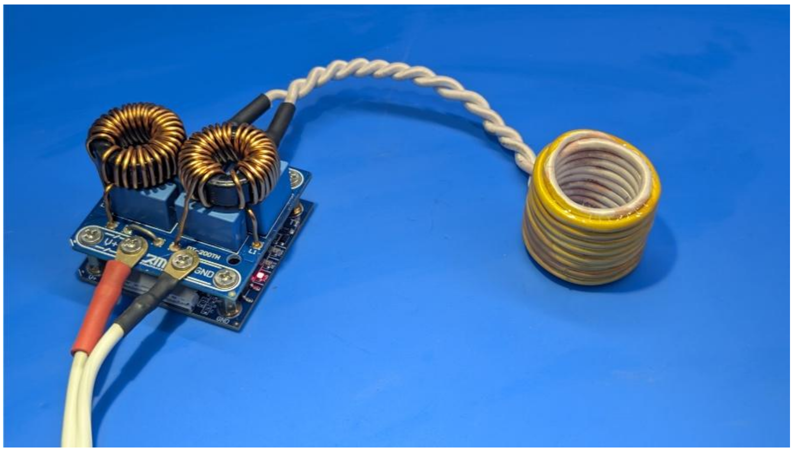


Figure 4: Example induction heating assembly

These values provide an example for a practical starting point rather than universal requirements. Component ratings must be increased where the intended voltage, current, frequency or operating time requires it.

Assembly

1. Ensure that the power supply is switched off and disconnected. Mount the SM3 securely with adequate clearance from conductive surfaces. If a heatsink is fitted, use electrically insulating thermal interface material and ensure that the mounting screws cannot contact the heatsink.
2. Connect the DT-200 tank capacitor board directly to the SM3 using standoffs and screws in the mounting kit.
3. Connect the work coil across T1 and T2, in parallel with the tank capacitor. We twisted the flying leads to the coil as this reduces the effective inductance of that length and makes moving the wires have much less of an effect.
4. Connect one power choke between Vpower and T1 and the second between Vpower and T2, as shown in Figure 1. The chokes may be soldered directly to the positions provided on the DT-200.
5. For single-supply operation, connect both V+ and Vpower to the positive supply through a suitable fuse, and connect GND to the negative supply. If using a DT-200, a wire link can be soldered as shown below for easy single supply operation.
6. Check that all connections are tight, correctly positioned and free from accidental shorts. Do not place a workpiece in the coil for the initial unloaded test.

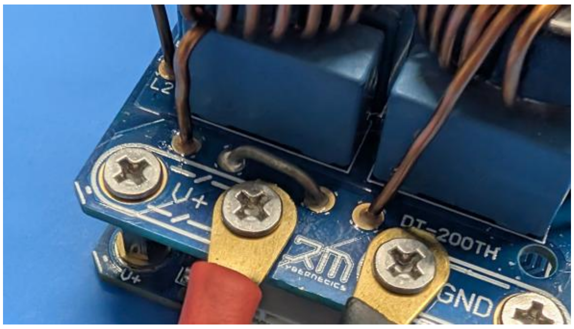


Figure 5: Mounted chokes & wire link for single supply

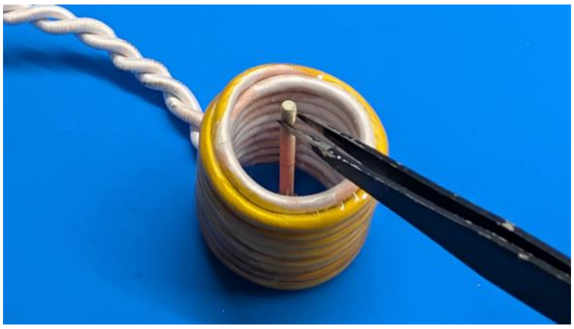


Figure 6: Example of red-hot bolt in a simple litz wire coil

First power-up

1. Set the supply to 15 V with a conservative current limit. Ensure that its output voltage does not collapse when the resonator starts.
2. Apply power and request operation using the onboard Start/Stop button, with nothing inside the work coil. Confirm that no fault is reported and that the supply voltage and unloaded current remain stable. In this example the current should be around 0.7 A. Stop immediately if the current is unexpectedly high, the supply voltage collapses or resonance faults occur repeatedly.
3. Run the unloaded coil only briefly. Stop the output and isolate the power supply before checking the temperature of the SM3, tank capacitor, chokes, work coil and associated wiring. You should not find any significant temperature rise in the SM3, though the work coil may begin to warm up.
4. Once unloaded operation is stable, use a workpiece that is small relative to the coil such as an M3 bolt. With the resonator operating, slowly move the workpiece into the coil using suitable non-metallic and heat-resistant handling or a fixture. Observe the power-supply current as the workpiece enters the coil and coupling increases. Withdraw the workpiece or stop the output if the current rises too rapidly, reaches the supply current limit, causes the supply voltage to fall or produces a fault. The workpiece will rapidly become hot so care must be taken in handling it. Avoid having it touch the coil as it can be hot enough to melt the electrical insulation.

With the example shown, the unloaded coil would resonate with a current draw from the PSU of just 0.7 A. This would increase to around 4 A when an M3 bolt was inserted into the centre before falling back to 3 A once the bolt had become red hot. The later drop in current was due to a lower magnetic coupling as the bolts magnetic properties changed after its curie point.

With only 60W of input power, this setup was able to heat the bolt red hot in under 10 seconds. Heating time could be significantly reduced with an optimised work coil design or higher input voltage.

The CRO-SM3 reported a resonant frequency of 43 kHz and did not require any heatsink or additional cooling during the test. The work coil became quite warm due to the combination of radiated heat from the workpiece and self-heating due to high tank currents. Due to this, heating time was limited and the coil needs to be given time to cool before further heating can commence. To heat items red hot for extended periods, a water-cooled coil is typically required.

Given the tank values of 5 uH and 2640 nF, we can calculate the expected resonant frequency which comes to 43.81 kHz. When loaded with the metal bolt, the inductance changed slightly to 5.15 uH giving a calculated frequency of 43.16 kHz.

Refer to Electrical Connections for terminal details, System Design and Component Selection for custom component selection, and Built-in Protection and LED Indicators for fault information.

System Design and Component Selection

This section explains how to select and arrange the external components that determine the electrical, thermal and resonant behaviour of the completed system. Use it when designing a custom tank circuit, changing the supply voltage or power level, selecting components or investigating unstable operation. The values given in Basic Induction Heater: Quick Start are practical starting points rather than universal requirements.

Power supply selection

At start-up there can be a brief high peak current before resonance starts. It is important that the PSU can deliver this current without dropping voltage otherwise it could fail to operate correctly or even damage the power MOSFETS. The PSU must be rated for at least 5 A for most induction heating applications though it is entirely application specific.

The CRO-SM3 has a built-in soft start feature that PWM ramps up the power over 10 ms at 5 kHz. This can help mitigate problems with high peak currents at startup though in some cases PWM its self can create current spikes. The soft start behaviour can be configured or disabled in the CRO-SM3-PRO.

A linear PSU is usually most reliable, especially when experimenting or developing a system. At higher currents, an SMPS may shut down due to the high peak current on start-up. If using an SMPS it may help to add an additional filtering such as a series choke and/or filter capacitance at the positive output terminal of the PSU.

Tank circuit layout and connections

The tank capacitor must be connected directly across T1 and T2 and mounted as close as practical to the SM3 terminals, using very short, low-inductance connections. Do not mount both the capacitor and work coil remotely at the end of long wires. This places the wiring between the SM3 and the complete tank circuit, which may cause unreliable start-up, parasitic resonance or MOSFET damage.

The work coil itself may be mounted farther from the SM3 if required, provided the tank capacitor remains directly across T1 and T2. In this arrangement, the two leads between the SM3 and work coil are in series with the coil and form part of the inductive branch of the LC tank. Their inductance adds to the work coil inductance, allowing the complete assembly to resonate.

These leads also carry the high circulating tank current. Excess length therefore increases resistance, power loss and heating. Their length, routing and position also affect the total inductance, so they should be kept as short as practical and secured in their final position before testing. Moving or bending them may change the resonant frequency and output power.

Work coil design

The work coil and tank capacitor will affect all aspects of operation including heating power, current draw and resonant frequency.

A larger work coil (more turns, or wider diameter) will lead to a lower resonant frequency and usually lower unloaded power levels. The work coil should be designed to suit the PSU, workpiece and tank capacitor.

The work coil should fit the workpiece as closely as practical if strong coupling is desired. A larger gap weakens magnetic coupling and reduces heating efficiency, although some clearance may be needed to reduce the amount of radiated heat absorbed by the coil.

Work coils normally use a relatively small number of turns to keep the resonant frequency within a range the driver can sustain. A coil with substantially more turns may require an impedance-matching transformer.

Tank capacitor selection

The tank capacitor carries high-frequency alternating current that may be many times greater than the DC supply current. Use low-loss polypropylene film capacitors designed for pulse, resonant or induction-heating applications. Electrolytic capacitors and ordinary power-supply filtering capacitors are unsuitable. A suitable voltage rating or mains-suppression rating alone does not confirm that a capacitor can withstand the required circulating current.

RMCybernetics DT-200 tank capacitor modules provide a convenient ready-made option. Alternatively, a capacitor bank can be assembled from suitably rated individual capacitors.

The total capacitance and the combined inductance of the work coil and its connecting leads determine the resonant frequency:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where *f* is the resonant frequency in hertz, *L* is the total tank inductance in henries and *C* is the total tank capacitance in farads.

Increasing the capacitance lowers the resonant frequency, while reducing it raises the frequency. Select a value that keeps the system within its permitted operating range with both an empty and loaded work coil. See Operating frequency and resonance limits.

The capacitor bank must have adequate peak-voltage and RMS-current ratings, with low ESR and ESL. Several identical capacitors may be connected in parallel to increase the total capacitance and current capability while reducing effective ESR. Connections should be short and arranged so that the current is shared evenly.

During initial testing, begin at low power and check for capacitor heating. Rapid or excessive heating indicates an unsuitable capacitor, insufficient current rating or excessive connection resistance.

Operating frequency and resonance limits

The operating frequency is determined by the inductance and capacitance of the connected tank circuit. The SM3 automatically follows changes in this resonant frequency rather than generating a fixed drive frequency.

The circuit is intended primarily for operation below 250 kHz. Higher-frequency operation significantly increases switching losses and component heating, so the maximum usable current and power generally decrease as frequency rises. Operation at frequencies up to 1 MHz may be possible under suitable conditions, but may require reduced current, additional cooling or circuit modification. This extended frequency capability is application-dependent and is not guaranteed under all operating conditions.

Both SM3 variants are supplied with a maximum permitted frequency (`FMAX`) of 300 kHz. On the ST this setting is fixed, so the tank circuit must remain below 300 kHz under all expected conditions. Allow suitable margin for changes caused by component tolerances, temperature and the presence or position of a workpiece.

The PRO also defaults to 300 kHz, but its `FMIN` and `FMAX` limits can be changed through the serial interface or web application. `FMAX` must be increased before operating the PRO above 300 kHz. Increasing the software limit does not guarantee that the power stage is suitable for the resulting frequency.

The PRO measures resonant frequency from the time between successive oscillation cycles. This time measurement has a resolution of 62.5 ns. At frequencies below 250 kHz, this is small compared with the duration of each cycle and provides good measurement resolution. As frequency increases and each cycle becomes shorter, the same 62.5 ns interval represents a larger proportion of the measurement.

The resulting frequency resolution is approximately 1.6% at 250 kHz, 3% at 500 kHz, 6% at 1 MHz and 10% near 1.5 MHz. Displayed frequency values and `FMIN/FMAX` protection therefore become progressively less precise towards the upper end of the software range and may change in larger steps. Frequencies near the upper limit should be treated as approximate.

These software measurement limits do not define the electrical operating capability of the power stage.

The `FMIN` and `FMAX` settings define the permitted resonance window; they do not set the operating frequency. Set these limits to cover the normal frequency range of the tank circuit, including its unloaded state and the expected range of workpieces or other loads. Allow some margin beyond the lowest and highest frequencies observed during normal operation, but avoid leaving the limits unnecessarily wide.

A suitably restricted frequency window improves detection of abnormal resonance, unsuitable loads and some failing or changed tank components. It also provides a more useful frequency scale in the web application. Review the limits whenever the coil, tank capacitance or intended workpiece is changed.

Workpiece selection and coupling

The size and material of the workpiece will have a significant effect on the power consumption. Magnetic materials like iron will have a very strong reaction and will heat well, whereas non-magnetic materials such as titanium will have only a minimal response.

Placing a workpiece inside the coil can cause a large increase in input current, particularly with strongly coupled iron or steel loads. Begin testing at a reduced Vpower voltage and increase it only after confirming the input current and switching waveform. Starting or stopping at high current also increases the energy stored in the power chokes and the resulting switch-off voltage transient. Where high-current operation is required, provide suitable external clamping as described under Switch-off voltage spikes and external clamping.

Choke selection

Choke selection is not normally critical, as the SM3 operates with a wide range of suitable values. Chokes designed for use with the driver are available from the RMCybernetics website.

The chokes feed DC power into the tank circuit while isolating the power supply from the high-frequency resonant currents.

The standard T1 and T2 connection requires two chokes, with one feeding each side of the tank circuit. A centre-tapped work coil instead requires a single choke connected to its centre tap. The optional PSU output choke described under Power supply is a separate component, which may be added to ease start-up current demand when using an SMPS.

A pair of 100 µH, 15 A chokes or equivalent is a practical starting point for typical installations. Alternatively, the CHK-50 array provides both chokes on one compact board for space-constrained builds. Other values may be selected using the guidance below.

Current rating

The two chokes collectively carry the full DC input current. In the standard two-choke arrangement, this current is shared approximately equally, so each choke normally carries about half the current shown by the power supply.

Allow additional capacity for ripple, imbalance and starting conditions. As a general guide, each choke should have:

- A continuous current rating of at least half the maximum expected input current.
- A saturation current rating of at least 1.5 times this value.

For example, for a system expected to draw up to 10 A, each choke should be rated for at least 5 A continuously, with a saturation rating of approximately 7.5 A or more.

When a choke saturates, its effective inductance falls sharply. This can produce excessive ripple and peak currents, potentially preventing resonance from starting or damaging the MOSFETs.

Chokes with higher current ratings will work correctly at lower currents but will generally be physically larger. Where space is important, choose a rating closer to the expected operating current while retaining suitable saturation margin.

Inductance and operating frequency

The inductance must be sufficient for the chokes to provide a reasonably steady current feed over each resonant cycle. The required value depends on the supply voltage, operating current, resonant frequency and characteristics of the tank circuit, so it cannot be selected from frequency alone.

A pair of 100 µH chokes is a practical general-purpose starting point for most SM3 installations. This is the value used in the Quick Start example, where the completed system operates at approximately 43 kHz and draws approximately 4 A when loaded.

Higher inductance values may be useful at unusually low operating frequencies, higher supply voltages or low operating currents. Lower values may be suitable at higher frequencies or where reduced physical size is important.

If the inductance is too low, current ripple and peak current will increase, which may disturb the power supply or make resonance less reliable. Higher inductance provides a steadier current feed but stores more energy at a given current, increasing the energy that must be controlled when operation stops or is PWM-modulated. Use the lowest inductance that provides stable operation across the intended supply, tank and load range.

Switch-off voltage spikes and external clamping

The current flowing through a power choke cannot fall instantaneously. When the resonant output is stopped, the voltage across the choke reverses and rises as the stored magnetic energy attempts to keep the current flowing. The energy stored in each choke is:

$$E = ½LI^2$$

The stored energy therefore increases in proportion to inductance and with the square of choke current. This can become significant when operating at high input current or with a strongly coupled workpiece such as iron or steel.

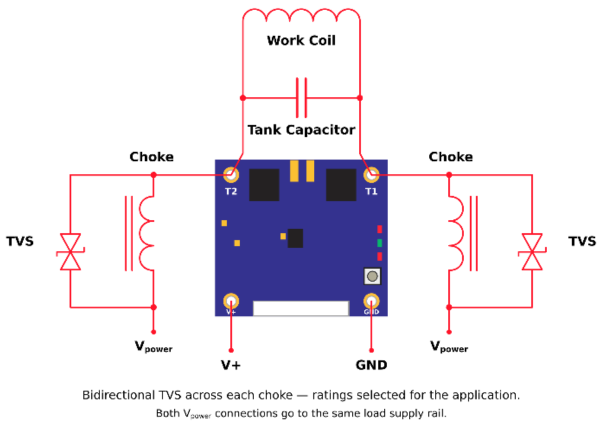


Figure 7: External choke clamp arrangement for limiting T1 and T2 switch-off voltage

During switch-off, this energy can produce a short voltage spike at T1 or T2 above the normal resonant waveform. PWM power modulation causes repeated off-transitions and can therefore produce these spikes many times per second. A sufficiently large transient may exceed the MOSFET drain-voltage rating and cause immediate failure, even when the MOSFET is cool and the average input current is within its permitted range. The firmware voltage measurement and fault response are not fast enough to guarantee protection against very short transients.

The risk can be reduced by:

- Using a lower Vpower voltage where strongly coupled loads cause high input current.
- Limiting the maximum operating current to a value verified with the intended coil and workpiece.
- Using the lowest choke inductance that still provides stable operation and acceptable current ripple.
- Avoiding PWM modulation under heavy-load conditions unless the resulting switching waveform has been verified.
- Reducing or removing the workpiece load before stopping, where the application allows it.
- Fitting an external voltage-clamp network across each power choke.

A suitable clamp provides a controlled path for choke current when T1 or T2 rises excessively above the power rail. This allows the stored energy to circulate back towards the Vpower rail and/or be dissipated by the suppressor instead of appearing across the MOSFET.

The clamp must remain inactive throughout the normal resonant voltage swing. A bidirectional TVS, or a TVS combined with an appropriate blocking or steering diode, may be used. An ordinary diode connected directly across the choke is generally unsuitable because it may conduct during the normal tank waveform and clamp the intended resonant voltage.

Select the suppressor using its maximum clamping voltage at the expected pulse current, rather than its nominal stand-off or breakdown voltage. For a clamp connected between a tank terminal and Vpower, the approximate maximum transistor voltage is:

Maximum T1 or T2 voltage ≈ Vpower + TVS clamping voltage + wiring overshoot

This total must remain below the MOSFET maximum drain voltage (100 V) with a suitable design margin. For example, a nominal “90 V TVS” connected across a choke does not necessarily limit T1 or T2 to 90 V; its voltage is added to Vpower and its actual clamping voltage may be considerably higher than its nominal rating.

The clamp components must also have sufficient peak-power and repetitive-energy ratings for the maximum choke current and modulation frequency. Keep the choke, suppressor and Vpower return connections short and low-inductance. The Vpower rail should have suitable local capacitance and must be able to tolerate any returned pulse energy.

Advanced I/O connections

The 15-way JST GH connector allows for simple interfacing with other devices and sensors. All logic levels are 5 V, so only connect devices that are 5 V tolerant.

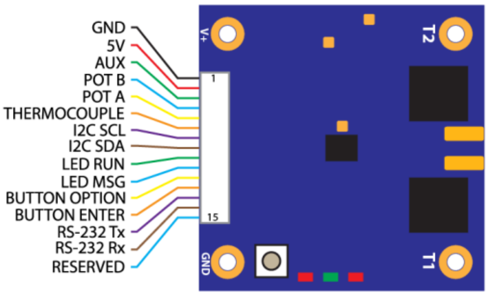


Figure 8: Expansion cable pinout diagram

Pin	Function
1	***GND*** Common connection to ground / 0 V
2	***5 V*** Connects to internal 5 V rail via 10 Ω resistor
3	***AUX [PRO]*** Programmable I/O can be set to use as pulse output, interlock sensor, or analogue input
4	***POT B [PRO]*** ADC input for potentiometer on external control module (analogue 0 - 5 V)
5	***POT A [PRO]*** ADC input for potentiometer on external control module (analogue 0 - 5 V)
6	***THERMOCOUPLE [PRO]*** ADC input from thermocouple amplifier on external control module
7	***I^2C SCL*** Connection for external interfacing. Default setting is for use with standard 128 x 64 OLED display.
8	***I^2C SDA*** Connection for external interfacing. Default setting is for use with standard 128 x 64 OLED display.
9	***LED-RUN*** Signal for RUN LED on external control module (high while the controller is in the ACTIVE run state)
10	***LED-MSG*** Signal for MSG LED on external control module (high while the controller is in the FAULT state)
11	***BUTTON-OPTION*** Input for OPTION button. Active Low with internal pullup enabled
12	***BUTTON-ENTER*** Input for ENTER button. Active Low with internal pullup enabled
13	***5 V TTL Serial Tx [PRO]*** Serial interface for remote control. Connect this to Rx on the controlling device
14	***5 V TTL Serial Rx [PRO]*** Serial interface for remote control. Connect this to Tx on the controlling device
15	***Factory Use Only***

Table 3: Pinout for optional 15-way connector

I/O interfacing

The SM3 can be controlled in several ways using the available I/O connections. Both variants support direct start/stop control and basic status outputs. The PRO variant additionally supports serial communication and external potentiometer controls.

Direct wired control

Pins 9, 10, 11 and 12 provide a basic wired control and status interface through simple 5 V logic pins. All signals are referenced to GND on pin 1. Pins 9 and 10 are 5 V logic outputs intended for high-impedance inputs or indicator LEDs with suitable current-limiting resistors. They must not directly drive relays, solenoids or other power loads.

Pins 11 and 12 are also used together for factory reset. External control hardware should not hold both inputs low simultaneously for an extended period, as this can erase all user settings and calibration data. See Factory Reset for the full procedure.

Pin 12 (BUTTON-ENTER) is an active-low control input with an internal pull-up. Connect a normally open switch between pin 12 and GND, or pull it low using a 5 V logic output, open-collector transistor or open-drain interface. With the default automatic input setting and no compatible EXP module detected, pin 12 operates as a momentary enable: pulling it low requests operation and releasing it stops operation. When an EXP module is detected, the default behaviour changes to toggle operation, where each active-low press changes the run state.

On the PRO, this behaviour can be selected using `TOGGLEMODE`: 0 = momentary, 1 = toggle, and 2 = automatic according to EXP detection.

After a fault condition, clearing the fault and requesting another start are separate actions. Correct the fault condition, return the input to its inactive state, and then issue a new start request.

Power modulation settings are not accessible through the I/O on ST variants. Average heating power may instead be controlled by applying an active-low, time-proportional signal to the control input. A modulation frequency of 0.1–2 Hz is recommended, with ON periods of at least 150 ms. Higher rates may reduce power linearity and bypass normal steady-state resonance monitoring.

Pin 11 (BUTTON-OPTION) is an active-low input with an internal pull-up. Connect a normally open switch between pin 11 and GND, or pull it low using a compatible open-collector or open-drain output. On the ST or PRO, this pin can be toggled to clear a fault. With the PRO and external controls enabled, a short press changes a connected OLED display between the MAIN and INFO pages. Holding the input low for at least one second selects the next operating mode and stops any active operation before changing mode.

Pin 10 (LED-MSG) is held high whenever the SM3 is in a latched FAULT state and remains low during normal operation. It can therefore be connected to an external controller as a fault-status signal. Specific fault information is available through serial communication on the PRO, while basic fault information can be obtained from the flash code displayed by the onboard MSG LED. The flash code is not reproduced on pin 10.

Pin 9 (LED-RUN) is active high while the controller is in the ACTIVE run state. It may operate a status LED or provide a run-state signal to another controller. It indicates that an operating cycle is active, not that the resonant output is continuously energised.

In AUTO mode, it remains high while workpiece detection is active, including the periods between coil pings. In THERMO mode, it remains high while regulation is active, including periods when heating has stopped because the target has been reached.

AUX input and output modes (PRO only)

Pin 3 (AUX) is a configurable 5 V analogue or digital I/O controlled by the `AUXMODE` register. The selected mode determines whether the pin operates as an input or output. `AUXMODE` can only be changed while the SM3 is stopped.

When configured as an output, pin 3 provides a logic-level signal only. Fans, relays, solenoids and other loads must not be connected directly. Use a suitable transistor, MOSFET or driver circuit, with flyback protection where required for inductive loads. When configured as an input, the applied signal must remain within the 0–5 V range.

AUXMODE = 0 — Analogue Input
Pin 3 operates as a 0–5 V ADC input with a returned range of 0–1023 counts. It can be used as the feedback source for THERMO mode by setting `REGSRC` to 1.

The regulation target is set by AUX, or by POT B when external controls are enabled. `AUXMIN` and `AUXMAX` define the potentiometer adjustment range. `HYSTERESIS` is expressed in ADC counts when the AUX input is used for regulation.

This mode allows a suitable 0–5 V sensor, such as a pressure, position or optical sensor, to control the heating cycle.

AUXMODE = 1 — HIGH blocks operation
Pin 3 becomes a digital interlock input with an internal pull-up. Pulling the input LOW permits operation; allowing it to become HIGH or open blocks operation.

For example, a normally closed guard or lid switch can be connected between pin 3 and GND. Opening the switch, disconnecting the cable or removing power from the external circuit blocks operation.

AUXMODE = 2 — LOW blocks operation
Pin 3 becomes a digital interlock input without an internal pull-up. A HIGH input permits operation and a LOW input blocks operation. An external bias resistor or actively driven 5 V logic signal is required to prevent the input from floating.

For example, a microcontroller or PLC can provide a 5 V permissive signal. An external pull-down resistor can ensure that a disconnected or unpowered controller produces the blocked state.

For either interlock mode, an unsatisfied interlock prevents a new heating cycle from starting but does not latch a fault. If the interlock becomes unsatisfied while the SM3 is active, the output stops immediately and an AUX fault is latched. The fault must then be cleared before another start is requested.

The firmware interlock is intended for process control and equipment coordination. It is not a safety-rated emergency-stop circuit.

AUXMODE = 3 — Fan / Cooling Output
Pin 3 becomes an active-high digital output used during THERMO operation. It goes HIGH during the cooling phase, when THERMO remains active but heating is not currently requested. It returns LOW when heating resumes or the operating cycle stops.

AUXMODE = 4 — Completion Pulse Output
Pin 3 becomes an active-high post-cycle output. When a timed NORMAL heating cycle reaches its programmed end, pin 3 goes HIGH for the period set by `AUXPULSEMS`, from 1 to 10,000 ms, and then returns LOW.

This allows the SM3 to initiate an action automatically after heating has finished. Example applications include:

- Activating a pneumatic or solenoid-operated workpiece ejector
- Signalling a PLC or external controller to advance to the next machine operation
- Operating a completion warning light or audible indicator
- Running a cooling fan for a fixed period after heating
- Releasing a clamp or triggering a material-handling mechanism

The completion pulse is generated only when a timed NORMAL cycle finishes naturally. It is not generated following a manual stop, fault, continuous cycle, AUTO operation or THERMO operation.

External potentiometer control (PRO only)

Pins 4 and 5 (POT B and POT A) allow the PRO to use external potentiometers as live adjustment controls such as is done with the EXP-THERM1 addon. External controls can be enabled by setting `EXTCTRLS` to 1, or selected automatically by setting it to 2 and connecting a compatible detected EXP module. Setting `EXTCTRLS` to 0 disables the potentiometer inputs.

A 10 kΩ linear potentiometer is suitable. Connect its ends between 5 V on pin 2 and GND on pin 1, with its wiper connected to the applicable analogue input. Movement towards 5 V increases the selected value. Do not leave a potentiometer input floating while external controls are enabled.

The function of the POT inputs will vary depending on the operating mode currently active.

Input	Operating Mode	Controlled Value
Pin 5 (POT A)	Fixed-duty PWM	Duty target between `PWMMIN` and `PWMMAX`
Pin 5 (POT A)	Constant-current mode	Current target between `PWMAMPSMIN` and `PWMAMPSMAX`
Pin 4 (POT B)	NORMAL	Heating time between `TIMEMIN` and `TIMEMAX`; continuous operation at the top of the range
Pin 4 (POT B)	AUTO	Detection/hold-current target between `HOLDAMIN` and `HOLDAMAX`
Pin 4 (POT B)	THERMO	Temperature target between `HOLDTMIN` and `HOLDTMAX`, or AUX target between `AUXMIN` and `AUXMAX`

Table 4: External input functions

When external controls are enabled, the potentiometers provide the live operating targets in place of the corresponding stored register values. Serial communication may still be used for monitoring and for configuring the permitted adjustment ranges. To resume control from the stored register values, set `EXTCTRLS` to 0.

Thermocouple input (PRO only)

Pin 6 (THERMOCOUPLE) is a 0–5 V analogue input intended to receive the conditioned output from a thermocouple amplifier. A thermocouple must not be connected directly to this input.

The EXP-THERM1 addon module uses an AD8495 cold-junction-compensated amplifier for Type-K thermocouples. Its nominal output is 5 mV/°C, corresponding approximately to 0–1000 °C across the 0–5 V ADC range. A custom amplifier may be used provided that its output remains within 0–5 V and follows a compatible temperature-to-voltage relationship. Cold-junction compensation should be included where accurate temperature measurement is required.

The firmware filters the ADC reading and calculates the reported temperature using:

Temperature = filtered ADC value × `THERMOCAL` ÷ 1024

`THERMOCAL` defaults to 1000 and can be adjusted from 500 to 1500 to correct gain tolerances in the amplifier, ADC and associated components. A one-point correction can be calculated using:

New `THERMOCAL` = existing `THERMOCAL` × reference temperature ÷ displayed temperature

Calibration should be performed near the intended operating temperature. `THERMOCAL` provides gain correction only and cannot correct an amplifier offset or nonlinear response.

The thermocouple value is available for monitoring and can be selected as the feedback source for THERMO mode. The associated target, input selection and hysteresis settings are described under THERMO Mode.

The thermocouple input is intended for process regulation and monitoring. Independent overtemperature and sensor-failure protection must be provided where uncontrolled heating could create a hazard.

I²C display interface

Pins 7 and 8 provide a 5 V I²C interface intended primarily for the OLED display used by the EXP-THERM1. The SM3 operates as the I²C controller and directly generates the display contents; the display does not contain any SM3-specific firmware.

A compatible replacement display must have all the following characteristics:

- SSD1306 display controller
- 128 × 64 pixel resolution
- I²C address 0x3C
- 5 V-compatible supply and logic interface

Displays using a different controller, resolution or I²C address will not operate correctly without custom SM3 firmware, even if they have a similar physical appearance.

Connect the display using pin 1 for GND, pin 2 for 5 V, pin 7 for SCL and pin 8 for SDA. The pin order on an OLED module may differ, so connections must be confirmed from the module documentation rather than inferred from its connector position.

The SDA and SCL lines require pull-up resistors to 5 V. Suitable pull-ups are normally fitted to the display module; values between 4.7 kΩ and 10 kΩ are suitable. The SM3 detects a connected EXP module by checking for these pull-ups and enables the display automatically.

EXP detection can also affect other automatic control settings. On the PRO, `EXTCTRLS` = 2 enables the external potentiometer controls when the display pull-ups are detected. If a display is connected without potentiometers, set `EXTCTRLS` to 0 to prevent floating POT inputs from affecting operation. `TOGGLEMODE` = 2 also changes pin 12 to toggle operation when EXP detection is active.

The I²C connection is not a general-purpose expansion bus. The standard firmware supports the specified OLED display and does not provide an interface for arbitrary I²C sensors or peripheral devices.

Keep the display wiring short and route it away from the work coil, tank capacitor and other high-current resonant wiring to reduce electrical interference.

Serial interface (PRO only)

Pins 13 and 14 provide connections for 5V TTL serial communication. For connection to a PC use a standard USB-to-5 V-TTL serial adaptor. Connect adaptor TX to SM3 RX (pin 14), adaptor RX to SM3 TX (pin 13), and GND to GND (pin 1). Leave the adaptor's 5 V connection disconnected during normal operation. Pin 2 may be powered from the adaptor only when configuring a bare, otherwise unpowered SM3.

I/O configuration pads

A number of empty pads on the PCB are available for custom modifications or testing. These are used for things like performing a factory reset of the internal registers, or setting alternative operating modes.

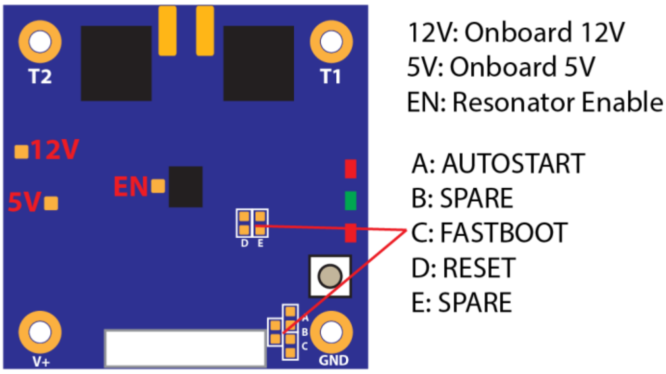


Figure 9: Optional I/O configuration pads & test points

Pad	Function
12 V	Test point for onboard 12 V regulator
5 V	Test point for onboard 5 V regulator
EN	Test point for MOSFET driver IC Enable status
A	`AUTOSTART`: Short the two pads with solder or fit an 0805 link or resistor to force `AUTOSTART` setting 2. The selected operating mode starts automatically when power is applied and is requested again whenever operation stops, unless prevented by a fault or interlock.
B	Unused: Available for factory customisation
C	`FASTBOOT`: Short the two pads with solder or 0805 resistor to set the CRO-SM3 to skip the LED flash sequences on start-up.
D	FACTORY RESET: Short the two pads for approximately 2 seconds to factory reset all customisable registers. A successful reset will be indicated by the normal LED bootup sequence (only if `FASTBOOT` is not used).
E	Unused: Available for factory customisation

Table 5: Optional I/O configuration pads & test point descriptions

Mechanical installation and cooling

The CRO-SM3 is built on a high-density PCB with copper filled vias to maximise passive heat dissipation so that in many cases, no additional heatsink is required. For high currents and / or frequencies additional cooling may be required and can be fixed to the back side of the PCB using electrically isolating thermal adhesive.

Heat is transferred to the heatsink through copper-filled thermal vias on the PCB which have high thermal resistance vs directly mounted transistors. Therefore, large increases in power level may cause the transistor temperature to rise faster than heat can be removed or detected by the onboard sensor.

The underside of the PCB is flat so that it can be mounted to metal surfaces for cooling (with suitable interface material), or to be fixed directly into a larger system.

When mounting the PCB to a heatsink or other metal surface, use electrically insulating thermal interface material. Do not rely on thermal paste alone. Use suitably short screws or spacers and ensure that no mounting or terminal connection screw can contact the metal surface.

Examples of mounted heatsinks, available on the RMCybernetics website, are shown in Figure 10. The heatsink required will vary depending on various factors such as ambient air temperature and the operating frequency. Forced air cooling (a fan) may also be mounted to cool the component side to improve the power handling capability.

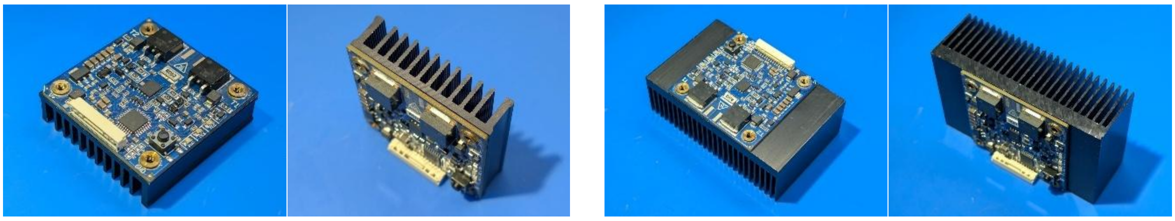


Figure 10: Standard heatsinks

Stacked module mounting

The M3 threaded inserts near the PCB corners carry the main electrical connections and also provide mounting points for compatible stackable modules. Conductive M3 standoffs mechanically support each module while making the required electrical connections between adjacent boards.

Product dimensions including mount points can be found in Figure 2.

The SM3 is normally fitted at the bottom of the stack so that a heatsink or other cooling hardware can be attached to its underside. A module mounted above the SM3 may obstruct the onboard button. Compatible modules provide an access hole through which a suitable non-conductive 3 mm-diameter button extension may be fitted. Alternatively, use the external I/O or, on the PRO, serial control.

The Quick Start example shows a typical arrangement in Figure 5, with the tank-capacitor board and chokes mounted above the SM3 on short standoffs. Only the power-supply and work-coil connections then require cables.

Operation

The CRO-SM3 is designed for simple intuitive operation while having a range of optional advanced features available to the system designer.

Basic usage

The system can be activated by a push button built onto the PCB, or can be connected to an external switch or microcontroller. One press of the onboard button will activate/deactivate the resonant power output while a long press can be used to cycle through the power modulation modes. Onboard LEDs or the optional display will indicate the output mode and status.

When the output is initialised a range of checks will occur to ensure it is safe to resonate. If any checks fail, it will go into to error mode and disable output power. If everything passes, the output will be driven at resonance. The circuit will automatically drive at resonance even if the resonant frequency changes such as when a metal object is placed inside an work coil. The default accepted range of resonant frequencies is very large for compatibility. On the PRO the permitted frequency range can be adjusted using `FMIN` and `FMAX`. These should be configured to suit the normal frequency range of the completed tank circuit, as described under Operating frequency and resonance limits.

Automatic start behaviour

Automatic start is available on both variants. The ST provides the always-on behaviour through configuration pad A, while the PRO provides three selectable behaviours through `AUTOSTART`:

0 — Disabled. A start request is always required.
1 — Issues one start request after each power-up.
2 — Always on. Starts automatically when power is applied and requests another start whenever operation stops, unless a fault or interlock prevents it.

`AUTOSTART` set to 1 starts the selected operating mode once after power-up. A subsequent stop request, completed timed cycle or cleared fault leaves the controller stopped.

AUTOSTART set to 2 attempts to keep the selected operating mode active. It will restart following a stop request or completed timed cycle, and will start again after a fault has been manually cleared. It does not bypass the AUX interlock or other protection systems.

Shorting configuration pad A sets AUTOSTART to 2 during every startup and provides automatic operation on either the ST or PRO. On the PRO, AUTOSTART can instead be configured through the serial interface while the controller is stopped.
Automatic start can energise the resonator without any local button input when power is applied or restored. It should only be used as part of a system with suitable independent guarding, interlocks and emergency stopping arrangements.

Power modulation

The effective heating power of the system can be adjusted by simply changing the supply voltage. Alternately, the CRO-SM3's built in modulation function can be used which allows for an adjustment between 20% and 100%. Using the serial interface or external controller this adjustment can be in 1% steps (PRO only), or using the onboard button it can be changed to a power level of either 25%, 50%, 75%, or 100%. To select a power level with the onboard button, hold the on/off button until the MSG LED flashes. The number of flashes indicates the power level selected, as listed in Table 6. Keep holding the button down to cycle through the available power levels.

The power level selected is stored in memory and will be retained even after the circuit powers off.

Flashes	Power Level
1	25%
2	50%
3	75%
4	100%

Table 6: LED flashes and power levels

The percentage setting represents PWM modulation duty, not a calibrated percentage of electrical input or heating power. Actual power depends on the supply, tank circuit, workpiece and operating conditions and may not vary linearly with duty.

PWM modulation repeatedly interrupts the current flowing through the power chokes. Each off-transition can produce a voltage spike as the stored choke energy attempts to maintain current. This effect becomes more severe at high input current and with strongly coupled loads. Reduced PWM duty must not be assumed to produce a proportionally lower peak voltage. Avoid PWM modulation near the maximum current or voltage limits unless the T1 and T2 waveforms have been verified and suitable choke clamping is fitted. See Switch-off voltage spikes and external clamping.

The modulation frequency defaults to 5 kHz. This is fixed on the ST, while the PRO allows it to be changed using PWMFRQ. The default is suitable for most applications, but adjustment may help avoid unwanted resonances involving the chokes and supply filtering, reduce audible noise or current ripple, move modulation-related emissions away from sensitive frequencies during EMC testing, or prevent interaction with other switching regulators and control systems. After changing the frequency, verify stable operation across the required power and load range.

Fixed-duty and constant-current control (PRO only)

PWMMODE selects how the CRO-SM3-PRO controls its fast PWM modulation:

PWMMODE = 0 selects fixed-duty operation.
PWMMODE = 1 selects constant-current operation.

In fixed-duty mode, `PWMDUTY` sets the requested PWM duty from 20% to 100%. The selected duty remains constant while the output is operating. When external potentiometer controls are enabled, POT A provides the live duty setting and `PWMMIN` and `PWMMAX` define its adjustment range.

Fixed-duty operation provides predictable modulation but does not compensate for changes in current caused by the workpiece, work coil, tank capacitor or supply voltage.

In constant-current mode, `PWMAMPS` sets the target current in 0.1 A units. For example, a value of 30 represents a target of 3.0 A. The controller continuously measures the input current and adjusts PWM duty towards this target.

When external potentiometer controls are enabled, POT A provides the live current target. `PWMAMPSMIN` and `PWMAMPSMAX` define the available adjustment range.

`PWMFRQ` sets the modulation frequency used by both control methods. `PWMMODE` and `PWMFRQ` can only be changed while the SM3 is stopped.

Constant-current control is available in NORMAL and THERMO modes but is not used in AUTO mode. It is intended to regulate average input current and should not be treated as a precision current source.

`MAXAMPS` remains the independent overcurrent fault limit in either control mode. It should be set above the intended operating current but within the safe limits of the SM3, power supply, work coil and associated wiring.

Advanced operating modes

The ST operates only in NORMAL mode. The PRO also provides AUTO and THERMO modes, giving three operating modes in total. On the PRO, the operating mode can be selected through the serial interface or compatible external controls. The selected mode is stored in `LASTMODE` and restored when the controller is next powered.

NORMAL:

The standard operating mode and the only operating mode available on the ST variant. The ST supports direct start/stop control, while the PRO also supports timed operation in NORMAL mode. Heating continues until a stop is requested or a fault occurs. On the PRO, a timed cycle also stops when the configured timer expires.

On the PRO, `TIMEVAL` sets the heating duration in 0.1-second units; for example, a value of 150 represents 15.0 seconds. Each new start request begins a complete timed cycle. When the timer expires, the output switches off automatically.

`TIMEMIN` and `TIMEMAX` define the permitted adjustment range. When external potentiometer controls are enabled, POT B adjusts the heating time between these limits. Otherwise, the duration is taken from `TIMEVAL`. Selecting a value above `TIMEMAX` enables continuous operation. This is shown as INF in the web application and on a compatible OLED display. Heating then continues until a stop is requested or a fault occurs.

NORMAL supports both fixed-duty and constant-current power control on the PRO. Timed operation is suitable for repeatable processes such as heat sealing, brazing, annealing or heating a component for a defined period. Continuous operation is more appropriate where the cycle duration is controlled manually or by external equipment.

When `AUXMODE` is set to 4, the natural completion of a timed NORMAL cycle can also generate a completion pulse for external sequencing. No pulse is produced following a manual stop, fault or continuous cycle.

AUTO:

Intended for applications where heating should begin automatically when a suitable workpiece is inserted into the work coil. While AUTO is active but unlatched, the SM3 sends short detection pulses to the coil approximately once per second and measures the resulting input current. Normal heating begins when the measured current reaches or exceeds the threshold set by `HOLDA`.

`HOLDA` is expressed in 0.1 A units; for example, a value of 40 represents 4.0 A. The threshold should be set above the input current measured when pinging an empty work coil, but below the input current produced by the intended workpiece. `MEASURED AMPS`, available as read-only operating value 3, reports the most recent ping input current while AUTO is unlatched and can be used when establishing a suitable threshold.

Once latched, the SM3 continues heating until the measured input current falls below `HOLDA` minus `HYSTERESIS`. `HYSTERESIS` is also expressed in 0.1 A units. For example, with `HOLDA` set to 40 and `HYSTERESIS` set to 5, heating starts at 4.0 A and stops if the current falls below 3.5 A. `HYSTERESIS` should normally be set lower than `HOLDA`.

When external potentiometer controls are enabled, POT B provides the live detection threshold between `HOLDAMIN` and `HOLDAMAX`. Otherwise, `HOLDA` provides the threshold.

AUTO uses the selected fixed-duty output and does not use constant-current regulation. Detection behaviour will vary with the work coil, workpiece material, workpiece position, supply voltage and selected output power. Establish the threshold experimentally on the completed system and confirm that there is a clear difference between the empty-coil and workpiece-present readings.

THERMO:

This mode provides basic on/off regulation using either the thermocouple input on pin 6 or the AUX analogue input on pin 3. The feedback source is selected by the `REGSRC` (Regulation Source) register:

`REGSRC` = 0: Thermocouple input
`REGSRC` = 1: AUX analogue input

When the thermocouple is selected, the target temperature is set by `HOLDT`. If external potentiometer controls are enabled, POT B provides the live target instead, with its adjustment range defined by `HOLDTMIN` and `HOLDTMAX`.

When AUX regulation is selected, the target is set by AUX, or by POT B when external controls are enabled. `AUXMIN` and `AUXMAX` define the available potentiometer adjustment range.

Heating stops when the measured value reaches the target and resumes when it falls to the target minus `HYSTERESIS`. Hysteresis is expressed in degrees Celsius when using the thermocouple input and in ADC counts when using the AUX input. The minimum effective hysteresis is 1 °C or one ADC count.

THERMO uses on/off regulation rather than PID control. Thermal inertia and delays between the heated part and sensor may therefore cause the measured temperature to overshoot the selected target.

See the *Thermocouple input* section for amplifier requirements, electrical connection and temperature calibration.

Soft start & startup retry

When the resonator starts, soft start initially limits the modulation duty to 20% and then increases it to the selected operating level. This reduces the sudden current demand placed on the power supply and switching components. It does not change the final operating power.

The PRO soft-start duration is set by `SOFTSTART` in milliseconds, from 0 to 1,000 ms. Setting `SOFTSTART` to 0 disables the ramp. The ST uses the default soft-start configuration of 10 ms.

Immediately after enabling the output, the SM3 checks that oscillation has started. If no oscillation is detected, the output is switched off briefly before another startup attempt is made. `STARTRETRY` sets the number of additional attempts from 0 to 5. For example, `STARTRETRY` set to 1 allows the initial attempt followed by one retry. The ST always allows one additional attempt.

If oscillation cannot be established after all permitted attempts, the SM3 enters a latched frequency fault. Startup retry only applies when oscillation fails to begin; faults occurring after startup, and other fault types such as overcurrent or incorrect supply voltage, are not automatically retried.

Built-in protection & LED indicators

Three LEDs are used to indicate the operational status of the CRO-SM3. A red “PWR” LED indicates the board has power applied to the inputs and is not digitally controlled.

The green “RES” indicator illuminates while the resonator output is active and resonance has been established. It remains steadily illuminated during normal PWM operation and turns off when the resonator output is disabled, including regulated idle periods and fault conditions. During startup, it may illuminate briefly while resonance is being verified. In AUTO mode, it also follows the brief load-detection pulses.

The red “MSG” LED is used to indicate errors and modes of operation, and other changes. You can also see additional fault information with the expansion board or compatible OLED display.

On the application of power, the CRO-SM3 will perform a Power On Self Test. If external modules such as the EXP-THERM1 are connected (before power up), the board will flash LEDs to indicate it successfully detected it. The LEDs also indicate which version of the module is fitted (ST or PRO), as listed in Table 7. Detection of the EXP-THERM1 module is based on checking for pullup resistors on the I^2C pins.

	ST	**PRO**
MSG LED (red)	Flashes	ON if EXP detected
RES LED (green)	On if EXP detected	Flashes

Table 7: Power on self-test LED status

The CRO-SM3 has a range of built in protection systems to prevent accidental damage and to provide reliable operation. Fault conditions are indicated by a repeating sequence of flashes from the red “MSG” LED. The number of flashes identifies the fault, as listed in Table 8, with the final flash held on for longer to mark the end of the sequence. In any fault condition, the output is disabled. To restart the circuit, press the Start/Stop button to clear the fault, the press again to enable the output.

Both variants monitor the resonant feedback signal while the output is active. The ST uses the full protection configuration, while the PRO allows the checks and frequency limits to be configured.

`ERRORCHECK` selects which resonance checks are enabled:

0 — Resonance protection disabled
1 — Resonant frequency checking
2 — Resonant duty checking
3 — Frequency and duty checking

Any non-zero setting also detects a failure to establish oscillation during startup or a loss of oscillation while running. `ERRORCHECK` can only be changed while the SM3 is stopped. Setting it to 0 does not disable the voltage, current or temperature protection, but it does disable startup and runtime resonance-loss detection. This setting should normally only be used for controlled diagnostic testing.

Frequency checking compares the measured resonant frequency against `FMIN` and `FMAX`. A persistent measurement outside this range produces fault 5. These limits should be set wide enough to include the normal frequency variation caused by changes in the work coil, tank capacitor and workpiece.

Duty checking monitors the balance of the resonant switching waveform. The expected resonant duty is approximately 50%, with values below 40% or above 60% producing fault 6. This measurement is separate from `PWMDUTY`, which controls power modulation rather than resonant waveform balance.

The onboard temperature sensor measures the internal MCU temperature rather than MOSFET junction temperature. Without a heatsink, it may respond slowly and may not closely follow MOSFET temperature. A heatsink improves thermal spreading and makes the reading more representative, but rapid transistor heating may still occur before a fault is detected.

The protection circuits have limited response time and may not be able to protect from very large fast transients or changes.
The controller cannot block an over-voltage supply. Fast transients are clamped, but a sustained input above the fault threshold is only reported and the output inhibited. The supply must be corrected before operation can resume.

Using the optional OLED display (EXP-THERM1) can delay internal monitoring and fault detection by up to approximately 50 ms. Continuous serial data streaming adds much less latency—typically around 1–2 ms at supported polling rates.

Flashes	Fault	Cause
1	Input Voltage out of range	An input voltage of about 25.5 V or more has been detected. This can be caused by an incorrectly set supply or input power spikes. The output is disabled and a fault is reported, and the fault clears only once the input has remained below 24 V for at least one second. Where an EXP-THERM1 is fitted, a warning is shown on the OLED display and operation is prevented. Note that continuous voltages over 26 V may cause permanent damage to the circuit. -OR- The input voltage has dropped below the minimum required for normal operation. This can happen if the PSU is unable to deliver enough current when switching on or adding a metal workpiece to an active coil.
2	Overload (High Current)	The measured input current has exceeded the `MAXAMPS` limit. This can be due to a short circuit, or the metal workpiece in the work coil being too large.
3	Coil Voltage Too High	Coil voltage can rise in resonant conditions or from power spikes. If it rises above the safe threshold (default 85 V), this fault code will activate. This is more likely to occur with high inductance, low capacitance loads, or when no workpiece is inside the work coil. The measured voltage is averaged over multiple cycles so this does not detect peak coil voltage.
4	PCB High Temperature	Onboard thermistor is detecting a high temperature. Improved cooling is needed to operate if this is occurring.
5	Resonance Frequency Problem	Resonance out of range or not resonating. This can be due to a faulty / incompatible coil or capacitor, too large of a work piece, or operating out of the rated frequency range. This may occasionally occur anyway, but if it happens often, then check for problems with the setup.

6	Resonance Duty Problem	This occurs if the switching transistors are not sharing the load evenly. This can be due to a faulty / incompatible coil or capacitor, or operating out of the rated frequency range.

Table 8: LED flashes and fault codes

Proper system design is essential for long term reliable operation. It is not recommended to operate the circuit continuously when protection modes are activating regularly as more heating in the circuit may occur. The protection circuits should only be considered as backup and diagnostic tools. Failure to operate the circuit within specifications could cause the transistors to fail.

Factory reset

There are a number of ways to perform a factory reset should it be required. A factory reset will erase all user configured data including any calibration before replacing it with the default values. Power should be disconnected from the work coil before performing a reset. When a reset request has been accepted, the MSG and RES LEDs will both light up for one second before the device reboots.

SMD Jumper
Short the pads of SMD jumper “D” on the PCB for around 2 seconds. The MSG and RES LEDs will both flash while this is being shorted.

Digital I/O
Pull the digital I/O pin 11 low, then immediately pull pin 12 low holding both for about 10 seconds. The MSG and RES LEDs will both flash while both pins are held low.

Serial Command (PRO only)
Send `<FDR>` via the serial port.

Web App (PRO only)
The web app can send the `<FDR>` command by using the FACTORY RESET button at the bottom of the settings tab.

Troubleshooting

If the system is not working correctly, try the suggestions in Table 9.

Symptom	Possible Causes	Solutions
MOSFET fails when output stops or during PWM operation	Excessive choke energy and unclamped T1/T2 switch-off voltage; high Vpower; strongly coupled workpiece; excessive choke inductance	Reduce Vpower or maximum current. Use a lower suitable choke inductance. Verify T1 and T2 peak voltage with the intended load. Fit external clamps across the power chokes.
PSU cuts off when the coil is connected, and before pressing the Start/Stop button	Blown T1 / T2 MOSFET	Remove the output connections to the coil, and use a multimeter to test which MOSFET is blown. To do this set the meter to test for a short between the T1 or T2 terminal and GND. Replace any MOSFET that shows a short.
PSU cuts off when, or voltage drops significantly when the Start/Stop button is pressed. Persistent Resonance Fail errors on start-up	PSU not suitably powerful for the setup. Bad output coil configuration or workpiece too large. Insufficient choke rating.	Use a PSU rated for more current, or one of a lower voltage so that less current will be drawn from the PSU. Shorten any connecting wires and make sure the tank capacitor is closer to the PCB Use a choke with a higher saturation current rating. See Choke selection.
Low input voltage error	PSU not suitably powerful for the setup. Or resonance is failing.	As above

Table 9: Troubleshooting

Web application (PRO only)

The CRO-SM3-PRO web application runs in a compatible Chromium-based browser and communicates directly with the controller using the browser's Web Serial API.

Google Chrome and Microsoft Edge are supported for normal desktop use. Firefox and Safari do not currently provide the required Web Serial support.

A compatible 5 V USB-to-TTL serial adaptor is required between the computer and the controller. When connecting, the browser asks the user to select and approve access to the required serial port. No separate desktop application or device-control software is required.

Because Web Serial is a protected browser feature, the application must be opened from a secure HTTPS address or from localhost when self-hosted locally.

Apps and other features are available from the following page
https://www.rmcybernetics.com/product-tools

Figure 11: The SM3 web app dashboard

The application consists of several tabs: The main Dashboard, Graphs, Calibration, Serial Monitor, and Settings which can be selected using the buttons on the left. The top area shows serial port status and controls along with the detected module and version information.

Appearance and layout

The overall appearance can be adjusted by either selecting a predefined theme from the dropdown, or by dragging the “Essential Status” displays over each other. To move them, click and hold on the small dotted areas, then drag them over another status display. When dropped onto another display, they will exchange places.

Figure 12: Alternative themes

Dashboard

The dashboard provides access to the majority of useful functions for the CRO-SM3-PRO. The two sliders will adjust the behaviour of the module based on the currently selected operating mode.

The left slider is generally used for adjusting the modulation duty. This can be as a fixed percentage, or as a fixed current if CC mode is selected below. The PWM duty and input current are reflected in the status named “Current”.

In NORMAL mode, the right control will set how long the output will stay on for once activated. Setting the slider to the maximum will make the output continuous, whilst dragging it lower will set a fixed value in seconds.

The range of these sliders can be adjusted in the user settings.

The frequency display is marked according to the reliability of the reading. A valid reading is shown with a green check, an estimated reading with an amber “~”, and an invalid reading as “----” with a red X, with the unit and duty indication hidden. An estimated state is marked amber at any confidence value, and a retained fault snapshot is shown as a valid reading because FLT packets carry no confidence field. Frequency measurement confidence explains how the reading is qualified.

Graphs

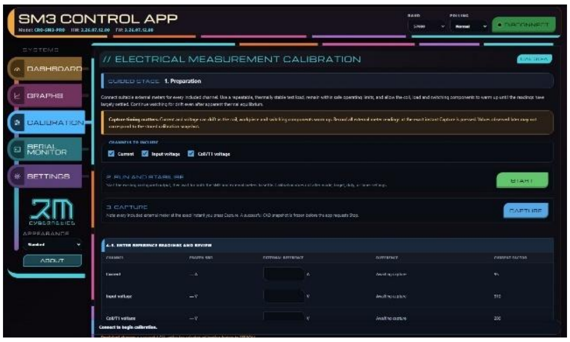
The graph tab allows for plotting and recording of data from the CRO-SM3-PRO. Multiple traces can run at the same time and are selected from the checkboxes to the left of the graph. The power output and data capture can run independently or they can be linked so that capture start at the same time the output is powered on.

Various controls also allow exporting of data to a CSV file and adjusting the graph display to a scrolling or scaling view.

Different display types can also be selected below the graph to help visualise the data.

Calibration

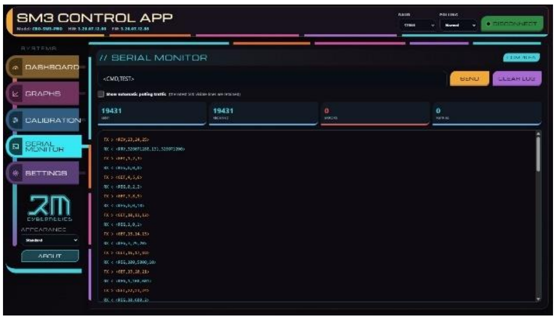
The readouts of internal data such as current and voltage or not precision measurements but they can be calibrated to improve accuracy if desired. This tab provides a procedure in which the output is powered, readings are taken, and the internal calibration factor is then recalculated.



Calibration data should be recorded or exported before running this feature.

Serial monitor

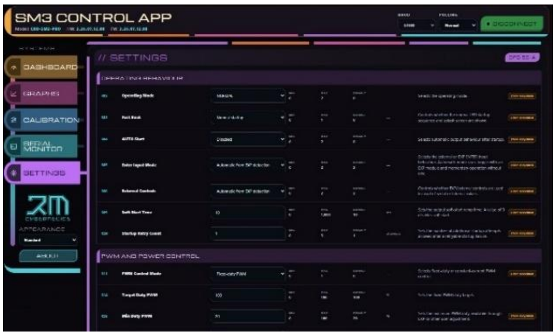
This tab allows for direct command access to the CRO-SM3. It also records the commands sent and received by the running application. Polling data is excluded as not to overwhelm the display.



More details on the serial protocol can be found in the relevant section of this datasheet.

Settings

The settings tab allows direct access to the many internal user register values for configuring the device. Some of these will be written to by varying the dashboard controls, while others will affect the range of control or display on the dashboard too.



Source code and customisation

Customers who purchase a CRO-SM3-PRO through the RMCybernetics website using a registered account can download the complete web application source as a ZIP file for self-hosting and customisation. The package contains the HTML interface, JavaScript application code, style and theme files, images and supporting data files required by the application.

The application uses separate JSON files to describe the CRO-SM3-PRO communications interface:

cro-sm3-pro-serial-protocol.json defines the serial connection, packet format, commands, responses, device identification and protocol behaviour.

Cro-sm3-pro-usrreg.json defines the configurable registers, including their names, ranges, defaults, units, scaling and whether they can be changed while the output is active.

Cro-sm3-pro-rov.json defines the read-only values used for measurements, status information and diagnostics.

Keeping this information in data files rather than embedding it throughout the interface code makes the application easier to maintain and adapt. Updated register or communications definitions can be added without redesigning the complete user interface.
The visual appearance is also kept separate from the controller and serial-communications code. Each supplied theme contains the colours, fonts, backgrounds, borders and other visual settings used by the interface. A new theme can be created by copying an existing theme file, renaming it and changing the required style values. This allows customers to create interfaces that match their own equipment, branding or preferred display style without altering the underlying CRO-SM3-PRO control functions.

Customers may also modify the page layout, add application-specific controls, create simplified operator screens or use the existing serial and data-handling code as the basis for a custom interface. The source is supplied for customer self-hosting and customisation and is not provided as open-source software for unrestricted redistribution.

The source code is supplied for self-hosting and customer-led customisation. No technical support is provided for modifying, extending, deploying or maintaining customised versions of the application, and development questions relating to customer changes cannot be answered.

Customers who require a modified or application-specific interface may commission RMCybernetics to produce the required customisation as a separate paid development service.

Serial communications (PRO only)

The CRO-SM3-PRO uses a simple ASCII command-and-response protocol for configuration, control, calibration, diagnostics, and live-data monitoring. This is the same serial interface used by the web app, but it can also be accessed using a conventional serial terminal or another controller.

Communication is normally initiated by the connected host. The host sends a command, and the unit returns a corresponding response. The firmware does not continuously stream measurements; applications obtain live information by regularly polling the required values. The main exception is fault reporting, which can be transmitted automatically when the unit enters a fault state.

The default configuration of the serial port is shown below. The baud rate is configurable, but a factory reset restores it to 57600 baud.

Baud	Parity	Data Bits	Stop Bits
57600	None	8	1

Table 10: Serial settings

Changing the baud rate can block further serial communication if it is set incorrectly. It should be left at the default value. If the serial connection is lost after changing the baud rate, a factory reset is required to restore it to 57600.

Packet format

Commands and responses are plain ASCII packets enclosed in angle brackets:

```
<COMMAND,value,value,value>
```

Values are separated by commas and are transmitted as unsigned decimal integers. Command names must be uppercase. Depending on the command, zero to three numeric arguments may be supplied.

For example, this command requests the value of registers 1, 2, and 14:

```
<GET,1,2,14>
```

The unit responds with their values in the same order. For example:

```
<REG,0,0,100>
```

The angle brackets identify the beginning and end of each packet. Responses are followed by a serial line ending for readability, but software should use the angle brackets for packet framing.

Command and response behaviour

Most commands produce one response:

```
<SET,14,75>
<ACK,14,75,100>
```

In this example, register 14 was changed to 75; its previous value was 100.

Invalid commands, arguments, or operations produce an `ERR` packet:

```
<ERR,errorCode,detail1,detail2,detail3,reserved1,reserved2>
```

A register value that falls outside its permitted range is not an error. It is clamped, stored and acknowledged, so the acknowledgement may report a different value from the one requested. See Value limits and clamping.

Some commands can take longer than an ordinary register request. Software should wait for the complete response before sending another command.

A fault report is a special case. When the unit enters a fault state, it may transmit an unsolicited `FLT` packet:

```
<FLT,flags,inputVoltage,coilVoltage,current,temperature,frequency,duty>
```

This packet can arrive immediately before the response to an unrelated command. Host software should therefore process `FLT` as an independent event and continue waiting for the expected command response.

Many measurements use scaled integer values to avoid sending decimal numbers. For example, a value marked ×10 represents tenths of a unit.

The command documentation should be consulted for the units, scaling, permitted operating state, and side effects of each command. In particular, commands that start the output, perform calibration, run the tank circuit test, or reset the unit should only be issued when the connected equipment is in a safe condition.

Protocol organisation

The serial protocol provides several groups of commands, each serving a different purpose. General usage is described below, with full detail provided in the appendices.

Configuration and control registers – <GET> and <SET>

The firmware contains a numbered set of internal registers that control its configuration and operating behaviour. These include the operating mode, output power, current targets, timer settings, protection limits, input behaviour, calibration factors, and communications settings.

`GET` reads the current value of one or more registers. `SET` changes a writable register or issues a register-based control request, such as starting or stopping the output. Some registers can be changed while operating, while others can only be changed when the output is stopped. Persistent register changes are saved to EEPROM.

Value limits and clamping

Every writable register has an absolute minimum and maximum, listed in Appendix B. Six registers are adjustment targets that are further constrained by an associated pair of MIN and MAX registers: `PWMDUTY` by `PWMMIN` and `PWMMAX`, `PWMAMPS` by `PWMAMPSMIN` and `PWMAMPSMAX`, `TIMEVAL` by `TIMEMIN` and `TIMEMAX`, `HOLDA` by `HOLDAMIN` and `HOLDAMAX`, `HOLDT` by `HOLDTMIN` and `HOLDTMAX`, and `AUX` by `AUXMIN` and `AUXMAX`. These pair limits apply to every adjustment source, including serial. They are not restricted to external potentiometer or EXP adjustment, and `EXTCTRLS` does not change this behaviour.

A value outside the applicable limits is not rejected. The firmware clamps it to the nearest limit, stores the clamped value, and acknowledges it; if the register is persistent, the clamped value is written to EEPROM. There is no out-of-range error code. Two cases are handled differently: a negative value is rejected as a malformed numeric token and returns `<ERR,1,0,0,0,0,0>`, and an invalid or unavailable `LASTMODE` value is mapped to NORMAL rather than clamped.

Because clamping happens before the response is assembled, the newValue field of an `ACK` reports the value actually stored, not the value requested. Host software should therefore compare the returned value against the value sent rather than assume a write was applied verbatim. For example, with `PWMAMPSMAX` set to 100, `<SET,18,250>` stores 100, acknowledges 100, and a subsequent `<GET,18>` returns 100. The exception is the `ONOFF` command register, where newValue is the normalised 0 or 1 command value rather than a stored register value.

Writing a MIN or MAX register can change its target. If the new window excludes the target's current value, the target is adjusted in the same operation and the adjusted value is saved to EEPROM, even though the acknowledgement reports only the bound that was written. Inverted windows cannot be created over serial: a MIN above the current MAX is silently reduced to that MAX, and a MAX below the current MIN is silently raised to that MIN. `FMIN` and `FMAX` are cross-checked in the same way. Host software that changes both a bound and its target should read back both registers afterwards.

`TIMEVAL` is the one target permitted above its upper bound, because values above `TIMEMAX` select continuous operation. Any requested value above `TIMEMAX` is canonicalised to exactly `TIMEMAX` + 1, and the firmware treats any applied value above `TIMEMAX` as continuous. The lower bound still applies, so `TIMEVAL` remains constrained by `TIMEMIN`. If `TIMEVAL` is already continuous when `TIMEMAX` is changed, the stored value is updated to the new `TIMEMAX` + 1 so that continuous operation is preserved.

Register-number, read-only and stopped-only checks are made before any clamping. An out-of-range write to a stopped-only register while the output is active therefore returns `<ERR,5,regID,requestedValue,currentValue,0,0>`, and nothing is clamped or stored.

The calibration registers `THERMOCAL`, `AMPSCAL`, `VINCAL` and `VCOILCAL` follow the ordinary rules when written directly with `SET`. The `CAL` procedure behaves differently: it covers only `AMPSCAL`, `VINCAL` and `VCOILCAL`, and it rejects a calculated factor outside the register limits instead of clamping it, returning `<ERR,103,channel,measuredValue,rawCapture,0,0>` and leaving all stored factors unchanged. `THERMOCAL` can only be changed through an ordinary register write.

Live and diagnostic values – <ROV>

`ROV` reads numbered, read-only operating values. These values report the unit’s current measurements and internal state but cannot be changed.

They include voltage, current, frequency, duty cycle, temperature, input states, active operating targets, output status, frequency-capture diagnostics, and information about the most recent resonance failure.

Frequency measurement confidence

The resonant frequency is not taken from a single capture. The firmware compares up to ten accepted captures from the preceding 300 ms and groups those agreeing within approximately ±2.5 % into a cluster. Each agreeing sample contributes 10 % to the frequency confidence figure reported by `FREQUENCY CONFIDENCE`. Confidence rises as soon as captures agree and decays more gradually when they do not.

PWM modulation interrupts the oscillation, producing gaps, aliased periods and outliers in the capture stream. Fewer captures then arrive or agree, and confidence falls. The figure measures capture agreement rather than being calculated from PWM duty, so it cannot be predicted from the modulation settings alone.

Confidence determines the state reported by `RESONANT FREQUENCY STATUS`. From a fresh start, below 50 % the frequency is invalid and `RESONANT FREQUENCY` returns 0; 50–79 % gives an estimated reading; 80–100 % gives a valid reading. An estimated reading is not extrapolated. It is either the average of a lower-confidence cluster or the last established frequency held while fresh captures are sparse or rejected, and a held reading can remain estimated after confidence has fallen below 50 %.

The frequency reported in an `FLT` packet is this processed clustered or held value rather than the most recent raw capture, and it is included whenever the firmware still holds an available frequency. `FLT` carries no confidence field. The `FMIN` and `FMAX` resonance checks also use the processed value and accept estimated readings, provided the last qualified update is less than 750 ms old and the out-of-range condition persists for 500 ms. An estimated reading in the 50–79 % band can therefore trip a resonance fault, while an isolated low-confidence capture cannot establish a new faulting frequency.

Host software that logs or acts on the measured frequency should read `RESONANT FREQUENCY STATUS` alongside `RESONANT FREQUENCY` and treat anything other than a valid reading as indicative. The raw capture diagnostics `OSC CAPTURE VALID`, `OSC CAPTURE NEW`, `OSC CAPTURE PERIOD` and `OSC CAPTURE PULSE` are available where the underlying behaviour needs to be examined.

Retained fault information – <FLT>

`FLT` returns the retained fault flags and the measurements captured when the fault occurred. This allows the cause and operating conditions of a fault to be examined after the output has stopped.

The firmware can also transmit an unsolicited `FLT` packet automatically when it enters the fault state.

The fields of the FLT response are listed in Appendix D. The flags field is a packed value that must be decoded before it can be interpreted; the encoding and a worked example are given in Appendix E.

Special procedures – <CAP>, <CAL>, and <CLT>

`CAP` and `CAL` form the electrical calibration procedure. `CAP` records a measurement snapshot while the output is operating, and `CAL` compares it with external reference measurements to calculate and save new calibration factors.

`CLT` performs the tank circuit test. It briefly operates the resonator and reports its frequency, current, and ring-down behaviour for load analysis and comparison.

Full details of how to use these are provided later in the document.

Factory reset – FDR

`FDR` stops the output, invalidates the stored configuration, and restarts the controller. Factory-default register values are restored during the subsequent boot, including the default serial baud rate of 57600.

Basic serial control examples

The following examples demonstrate common control sequences. Commands should be sent one at a time, waiting for the `ACK` response before sending the next command.

An `ACK` response has the format:

```
<ACK,regID,acceptedValue,previousValue>
```

The *previousValue* shown in the examples may differ depending on the unit's existing configuration.

Switching the output on and off

Register 1 (`ONOFF`) controls the run state.

Switch the output on:

```
<SET,1,1>
```

Example response:

```
<ACK,1,1,0>
```

Switch the output off:

```
<SET,1,0>
```

Example response:

```
<ACK,1,0,1>
```

The `ACK` confirms that the request was accepted. The actual run state can be checked by reading register 1:

```
<GET,1,255,255>
```

Example response while running:

```
<REG,1,0,0>
```

Register ID 255 is invalid and is used here as harmless padding for the two unused `GET` positions.

Normal mode: Run for 15 seconds

This example:

- Stops the output.
- Selects NORMAL mode.
- Sets the heating time to 15 seconds.
- Starts the output.

First ensure that the output is stopped:

```
<SET,1,0>
```

Select NORMAL mode:

```
<SET,2,0>
```

The heating-time register uses tenths of a second, so 15 seconds is sent as 150:

```
<SET,21,150>
```

Start the output:

```
<SET,1,1>
```

Typical response sequence:

```
<ACK,1,0,0>
<ACK,2,0,2>
<ACK,21,150,100>
<ACK,1,1,0>
```

The unit operates in NORMAL mode and stops automatically after approximately 15 seconds.

***Timer limits and continuous operation**: `TIMEVAL` is stored in tenths of a second and is persistent. During NORMAL-mode operation, its effective value is constrained by `TIMEMIN` and `TIMEMAX`. Values up to and including `TIMEMAX` select timed operation. Setting `TIMEVAL` to `TIMEMAX` + 1 selects continuous operation. For example, if `TIMEMAX` is 600 (60.0 seconds), setting `TIMEVAL` to 601 selects continuous operation. Because `TIMEMAX` is configurable, software should read register 23 before calculating the continuous value rather than assuming that it is always 600. Values below `TIMEMIN` are raised to the configured minimum; any requested value above `TIMEMAX` is canonicalised to `TIMEMAX` + 1*

THERMO mode: Thermocouple control at 220 °C

This example selects THERMO mode, selects the thermocouple as the regulation source, sets a target of 220 °C, and starts the output.

Ensure the output is stopped:

```
<SET,1,0>
```

Select THERMO mode:

```
<SET,2,2>
```

Select the thermocouple as the regulation source:

```
<SET,8,0>
```

Set the target temperature in °C:

```
<SET,27,220>
```

Start the output:

```
<SET,1,1>
```

Typical response sequence:

```
<ACK,1,0,0>
<ACK,2,2,0>
<ACK,8,0,1>
<ACK,27,220,100>
<ACK,1,1,0>
```

The unit regulates around 220 °C using the thermocouple input and the configured hysteresis.

Machine automation: Normal timed cycle with a post-cycle AUX pulse

The AUX output can generate a short active-high pulse when a timed NORMAL-mode heating cycle finishes. This can be used to trigger an external relay or driver controlling a solenoid, pneumatic valve, or other actuator.

For example, an automated annealing machine could use the pulse to eject or transfer the workpiece after heating is complete.

This example configures:

- NORMAL operating mode
- 15-second heating cycle
- AUX pulse-output mode
- 250 ms AUX pulse

Ensure the output is stopped:

```
<SET,1,0>
```

Select NORMAL mode:

```
<SET,2,0>
```

Set the heating time to 15 seconds. The register uses tenths of a second, so 15 seconds is sent as 150:

```
<SET,21,150>
```

Configure the AUX pin as a pulse output:

```
<SET,7,4>
```

Set the AUX pulse duration to 250 ms:

```
<SET,33,250>
```

Start the heating cycle:

```
<SET,1,1>
```

A typical response sequence would be:

```
<ACK,1,0,0>
<ACK,2,0,0>
<ACK,21,150,100>
<ACK,7,4,0>
<ACK,33,250,1000>
<ACK,1,1,0>
```

The resonator operates for approximately 15 seconds. When the timer expires, the firmware switches off the resonator and drives the AUX output high for approximately 250 ms. The AUX output then returns low automatically.

The post-cycle pulse is generated only when a timed NORMAL-mode cycle reaches its natural end. It is not generated if:

- The output is stopped manually.
- The unit enters a fault state.
- The operating mode is not NORMAL.
- The heating timer is configured for continuous operation.

The requested duration is checked by the main firmware loop, so the actual pulse may be slightly longer than the configured value.

The AUX pin must not be used to power a solenoid or actuator directly. Use an appropriately rated relay, transistor, MOSFET, or other driver circuit. Inductive loads should also have suitable suppression, such as a flyback diode where applicable.

Special commands

There are several commands available that may require user interaction to fulfil their specialist role.

Tank circuit test <CLT>

The built-in tank circuit test provides a repeatable way to analyse the tank circuit and how it behaves within the system. Its measurements can be used to identify changes that may indicate tank circuit degradation, compare the performance of different coils, or assess how different workpieces affect a coil.

The test reports operating frequency, input current, and ring-down behaviour. These results are primarily intended for comparison against previous tests or a known-good setup rather than as a standalone pass/fail assessment.

To begin the test, make sure the resonator is stopped / idle before proceeding or the command will return an error. The command to send is:

```
<CLT>
```

During the test, the firmware briefly energises the resonator, typically for 15–80 ms. It uses the normal output, measurement, and protection paths to:

- Measure the operating frequency.
- Measure input current.

- Stop the output.
- Count the remaining ring-down pulses.
- Estimate the ring-down duration.

Normal fault monitoring remains active throughout the powered portion of the test. The output is left switched off when the test finishes or fails. After the test the return data will be in the following format:

```
<CLT,frequencyHz,currentX10,ringPulseCount,ringTimeUs,status>
```

For Example:

```
<CLT,12345,86,24,1944,0>
```

This represents:

- Frequency: 12,345 Hz
- Current: 8.6 A
- Ring-down: 24 detected cycles
- Estimated ring-down duration: 1,944 µs
- Status: Successful

The ring-down time is estimated from the detected pulse count and measured operating frequency; it is not a direct elapsed-time measurement.

The value for *status* can be interpreted using the information shown in Table F1.

Electrical calibration <CAP> / <CAL>

The `CAP` and `CAL` commands calibrate the unit's input-current, input-voltage, and coil-voltage measurements against known external reference instruments. The web app's guided Calibration page performs this process, although the commands can also be sent manually.

Before beginning:

1. Fit a known, stable coil and workpiece/load. Use a configuration that can be operated consistently for the duration of the calibration.
2. Connect calibrated reference instruments to the channels being calibrated:
    - A suitable current meter, DC-capable current clamp, or shunt connected in series with the DC input supply.
    - A multimeter across the DC input supply.
    - A suitable meter or probe for coil voltage, if this channel is being calibrated.
3. Confirm that every instrument is correctly connected, set to the appropriate range, and suitable for the expected voltage, current, and operating frequency.
4. Start the resonator at a stable, representative operating point.
5. Allow the system and reference readings to settle. Do not change the coil, workpiece, power setting, supply voltage, or meter configuration between capturing the readings and recording the external measurements.

Only calibrate channels for which a reliable external reference measurement is available. Unmeasured channels can be skipped during `CAL`. Once the output is stable, send the command:

```
<CAP>
```

The firmware captures the raw ADC readings at that moment and replies:

```
<CAD,currentX10,inputVoltageX10,coilVoltageX10>
```

For Example:

```
<CAD,85,241,178>
```

represents:

- Input current: 8.5 A
- Input voltage: 24.1 V
- Coil voltage: 17.8 V

Record the readings shown by the external instruments at the time of capture. The returned CAD values are for reference; the firmware retains the underlying raw ADC snapshot for the following CAL command.
Next, send the measured values back to the device with the following command:

```
<CAL,measuredCurrentX10,measuredInputVoltageX10,measuredCoilVoltageX10>
```

For example, if the external instruments read:

- Input current: 8.8 A
- Input voltage: 24.3 V
- Coil voltage: 18.2 V

Send:

```
<CAL,88,243,182>
```

The firmware stops the output, calculates the new calibration factors, saves them to EEPROM, and replies:

```
<CAL,newCurrentCalibration,newInputVoltageCalibration,newCoilVoltageCalibration>
```

For example:

```
<CAL,98,917,205>
```

These returned numbers are the new calibration factors, not measurement readings.
Use 0 to skip any channel that was not measured.

For example, to calibrate only current and input voltage:

```
<CAL,88,243,0>
```

A successful CAL consumes the captured snapshot. Run CAP again before verifying the result or performing another calibration.

Calibration requires measurements around an energised resonant circuit. Use appropriately rated instruments and probes, observe safe working practices, and do not use an ordinary multimeter for high-frequency measurements unless its specifications explicitly support the signal being measured.

Appendices

Appendix A: Command reference

This section defines the request and success-response format for every command. The register and ROV tables in the appendices that follow list identifiers and value ranges only; they do not repeat these formats.

In each entry below, the first monospaced line is the request and the second is the success response.

Scaling: values identified as x10 are transmitted in tenths; for example, 12 represents 1.2 A and 243 represents 24.3 V.

<GET>

Reads up to three configuration or control registers in a single packet. Values are returned in the order the IDs were requested. Always send three IDs, padding unused positions with 255: invalid IDs return 0, so `<GET,1,255,255>` gives `<REG,1,0,0>` and the padding is unmistakable. Omitting a position instead is read as ID 0 (`HASDATA`), which always returns 88 — harmless to read, but easily mistaken for a measurement. Any invalid ID works; 255 is the convention used throughout this document.

```
<GET,regID1,regID2,regID3>
<REG,value1,value2,value3>
```

<SET>

Writes a single register, or issues the ON/OFF command through register 1. Values outside the permitted range are clipped to the nearest limit rather than rejected, so check the `acceptedValue` field to see what was actually stored. An `ACK` confirms only that the controller accepted the value; for an ON request, it does not confirm that the output has physically energised.

```
<SET,regID,newValue>
<ACK,regID,acceptedValue,previousValue>
```

<ROV>

Reads up to three live or internal diagnostic values. Values are returned in the order the IDs were requested. Pad any unused position with ID 0 and ignore the zero returned for it. Note that this is the reverse of `<GET>`: here 0 is not a valid ID and 255 is not used as padding.

```
<ROV,rovID1,rovID2,rovID3>
<RRV,value1,value2,value3>
```

<FLT>

Returns the retained fault flags and the measurement snapshot captured at the moment of the fault. A zero-filled response means no retained fault exists.

```
<FLT>
<FLT,flags,vinX10,vcoilX10,ampsX10,temp,freqKHz,dutyPct>
```

<CAP>

Captures a raw ADC snapshot for calibration. Requires the unit to be in the ACTIVE state with the resonator output ON.

```
<CAP>
<CAD,ampsX10,vinX10,vcoilX10>
```

<CAL>

Calculates and saves the calibration factors from the most recent `CAP` snapshot. A zero skips that channel. On success the output is stopped and the snapshot is consumed.

```
<CAL,measuredAmpsX10,measuredVinX10,measuredVcoilX10>
<CAL,newAmpsCal,newVinCal,newVcoilCal>
```

<CLT>

Runs the coil/load test while the output is stopped and returns the operating and ring-down measurements.

```
<CLT>
<CLT,freqHz,ampsX10,pulses,ringUs,status>
```

<FDR>

Stops the output, invalidates the stored settings, acknowledges, and reboots into factory defaults. The baud rate returns to 57600.

```
<FDR>
<FDR,1,0,0>
```

Appendix B: Configuration and control registers

Type: RO = read-only; CMD = command register; RW = writable; RW-L = writable while running; RW-S = writable only while stopped.
All registers are saved to EEPROM immediately after a successful `SET`, except `ONOFF` (register 1) and RESERVED (register 12), which are not retained.

The Min and Max columns give each register's absolute limits. For the adjustment targets `PWMDUTY`, `PWMAMPS`, `TIMEVAL`, `HOLDA`, `HOLDT` and `AUX`, the associated MIN and MAX registers impose a second, narrower limit that applies to serial writes as well as to external and EXP adjustment. Values outside either limit are clamped rather than rejected. See Value limits and clamping. Note that a unit restored from an older or corrupted EEPROM image may hold an inverted MIN/MAX pair, as stored values are validated only against their own absolute limits on load.

ID	Serial name	Type	Min	Max	Default	Description
0	HASDATA	RO	88	88	88	RESERVED

ID	Serial name	Type	Min	Max	Default	Description
1	ONOFF	CMD	0	1	0	Commands the output off or on. Reading the register returns the actual run status. Values: 0=OFF; 1=ON.
2	LASTMODE	RW-S	0	2	0	Selects the operating mode. Values: 0=NORMAL; 1=AUTO; 2=THERMO / regulation.
3	FASTBOOT	RW-S	0	1	0	Controls whether the normal LED startup sequence and splash screen are shown. Values: 0=Normal startup; 1=Skip LED flashes and splash screen.
4	AUTOSTART	RW-S	0	2	0	Selects automatic start behaviour. Values: 0 = disabled; 1 = issue one start request after each power-up; 2 = start after power-up and request another start whenever operation stops.
5	TOGGLEMODE	RW-S	0	2	2	Selects the external pin 12 or BUTTON_ENTER input behaviour. Automatic mode uses toggle with an EXP module and momentary operation without one. Values: 0=Momentary; 1=Toggle; 2=Automatic from EXP detection.
6	EXTCTRLS	RW-S	0	2	2	Controls whether EXP/external controls are used instead of serial or internal values. Values: 0=Disabled; 1=Enabled; 2=Automatic from EXP detection.
7	AUXMODE	RW-S	0	4	0	Selects the function assigned to the AUX pin. Values: 0=ANALOG 1=INTERLOCK_HI (HIGH BLOCKS OP) 2=INTERLOCK_LO (LOW BLOCKS OP) 3=FAN 4=PULSE
8	REGSRC	RW-S	0	1	0	Selects the feedback source used for THERMO/regulation mode. Values: 0=Thermocouple (pin 6); 1=AUX ADC (pin 3).
9	SOFTSTART	RW-S	0	1000	10	Sets the output soft-start ramp time. A value of 0 disables soft start. Units: milliseconds.
10	STARTRETRY	RW-S	0	5	1	Sets the number of additional attempts allowed after a retriable startup or runtime resonance failure.
11	PWMMODE	RW-S	0	1	0	Selects fixed-duty or constant-current PWM control. Values: 0=Fixed-duty PWM; 1=Constant-current PWM.
12	RESERVED	RO	1	1	1	Reserved. No function.
13	ERRORCHECK	RW-S	0	3	3	Selects which resonance measurements are checked for faults. Values: 0=Disabled; 1=Frequency only; 2=Duty only; 3=Frequency and duty.
14	PWMDUTY	RW-L	20	100	100	Sets the fixed PWM duty (%) target. Output OFF is controlled separately.
15	PWMMIN	RW-S	20	100	20	Sets the minimum PWM duty (%) available through EXP or other user adjustment.
16	PWMMAX	RW-S	20	100	100	Sets the maximum PWM duty (%) available through EXP or other user adjustment.
17	PWMFRQ	RW-S	1000	100000	5000	Sets the fast PWM modulation frequency. Units: hertz.

ID	Serial name	Type	Min	Max	Default	Description
18	PWMAMPS	RW-L	0	300	10	Sets the constant-current target used when PWMMODE is constant current. Units: 0.1 A.
19	PWMAMPSMIN	RW-S	0	300	1	Sets the minimum constant-current target available through EXP or other user adjustment. Units: 0.1 A.
20	PWMAMPSMAX	RW-S	1	300	100	Sets the maximum constant-current target available through EXP or other user adjustment. Units: 0.1 A.
21	TIMEVAL	RW-L	0	60002	TIMEMAX+ 1	Sets the heating timer. Values above TIMEMAX select continuous/INF operation. Units: 0.1 s.
22	TIMEMIN	RW-S	1	600	10	Sets the minimum heating time available through EXP or other user adjustment. Units: 0.1 s.
23	TIMEMAX	RW-S	1	60000	600	Sets the maximum timed heating value available through EXP or other user adjustment. Units: 0.1 s.
24	HOLDA	RW-L	1	300	2	Sets the AUTO mode holding-current target. Units: 0.1 A.
25	HOLDAMIN	RW-S	1	300	1	Sets the minimum AUTO holding-current target available through EXP or other user adjustment. Units: 0.1 A.
26	HOLDAMAX	RW-S	1	300	200	Sets the maximum AUTO holding-current target available through EXP or other user adjustment. Units: 0.1 A.
27	HOLDT	RW-L	0	1000	100	Sets the THERMO mode temperature target. Units: °C.
28	HOLDTMIN	RW-S	0	1000	1	Sets the minimum THERMO target available through EXP or other user adjustment. Units: °C.
29	HOLDTMAX	RW-S	0	1000	1000	Sets the maximum THERMO target available through EXP or other user adjustment. Units: °C.
30	AUX	RW-L	0	1023	100	Sets the AUX ADC regulation target. Units: ADC counts.
31	AUXMIN	RW-S	0	1023	0	Sets the minimum AUX target available through EXP or other user adjustment. Units: ADC counts.
32	AUXMAX	RW-S	0	1023	1023	Sets the maximum AUX target available through EXP or other user adjustment. Units: ADC counts.
33	AUXPULSEMS	RW-S	1	10000	1000	Sets the AUX output pulse duration when AUXMODE is PULSE. Units: milliseconds.
34	HYSTERESIS	RW-L	0	100	3	Sets regulation hysteresis. Units depend on the active mode and feedback source.
35	FMIN	RW	1000	1500000	1000	Triggers a resonance fault when the measured frequency falls below this limit. Units: hertz.
36	FMAX	RW	10000	1500000	300000	Triggers a resonance fault when the measured frequency rises above this limit. Units: hertz.
37	MAXAMPS	RW	1	300	200	Sets the maximum measured input-current safety limit. Units: 0.1 A.

ID	Serial name	Type	Min	Max	Default	Description
38	THERMOCAL	RW-S	500	1500	1000	Thermocouple calibration multiplier. A value of 1000 is nominal. Units: multiplier.
39	AMPSCAL	RW-S	10	3000	95	Calibration factor applied to input-current measurement.
40	VINCAL	RW-S	100	30000	910	Calibration factor applied to input-voltage measurement.
41	VCOILCAL	RW-S	50	60000	200	Calibration factor applied to coil/T1-voltage measurement.
42	BAUD	RW-S	1200	250000	57600	Sets the serial communication baud rate

Table B1: Configuration and control registers

Appendix C: Read-only operating values (ROV)

ID	Value	Units / encoding	Purpose
1	RESONANT FREQUENCY	Hz	Measured resonant frequency in hertz. This is the processed clustered or held value, not the most recent raw capture. Returns 0 when the reading is invalid. Read with IDs 11 and 21.
2	RESONANT DUTY	%	Measured resonant switching duty in percent. Returns 0 when the reading is invalid.
3	MEASURED AMPS	x10 (0.1 A)	Live measured DC input current in 0.1 A units. In AUTO mode while active and unlatched, returns the AUTO ping current.
4	INPUT VOLTAGE	x10 (0.1 V)	Measured input voltage returned by firmware in 0.1 V units (volts x10).
5	COIL VOLTAGE	x10 (0.1 V)	Measured coil/T1 voltage returned by firmware in 0.1 V units (volts x10).
6	AUX INPUT	ADC counts	Live AUX analogue-to-digital converter reading.
7	THERMOCOUPLE TEMPERATURE	°C	Live thermocouple temperature/value from the external thermocouple input.
8	HEATSINK TEMPERATURE	°C	Live CPU/heatsink temperature value.
9	POT A INPUT	ADC counts	Raw or smoothed Pot A analogue-to-digital converter reading.
10	POT B INPUT	ADC counts	Raw or smoothed Pot B analogue-to-digital converter reading.
11	RESONANT FREQUENCY STATUS	0 - 2	Frequency reading state: 0 = invalid, 1 = valid, 2 = estimated. Derived from ID 21: from a fresh start, below 50 % is invalid, 50–79 % estimated, and 80–100 % valid. A held reading can remain estimated below 50 %.
12	TCA PWM ACTIVE	0/1	Output drive source: 0 = direct GPIO output, 1 = TCA PWM output.
13	RESONATOR OUTPUT	0/1	Normal resonator drive state: 0 = off, 1 = on. In unlatched AUTO mode, the short synchronous probe pulses do not change this value; use `RUN STATE` with `AUTO LATCHED` to determine whether the AUTO run is active and pinging.
14	HEAT REQUEST	0/1	Current heat request state: 0 = off, 1 = on.
15	SELECTED PWM DUTY TARGET	%	Selected PWM duty target after choosing serial/internal or external controls. This is not the final duty applied after constant-current control or soft start.
16	OSC MONITOR ENABLED	0/1	Oscillation monitor enable state: 0 = disabled, 1 = enabled.

ID	Value	Units / encoding	Purpose
17	`OSC CAPTURE VALID`	0/1	Indicates whether the last oscillation capture was accepted: 0 = no, 1 = yes.
18	`OSC CAPTURE NEW`	0/1	Indicates whether a new oscillation capture was seen on the last update: 0 = no, 1 = yes.
19	`OSC CAPTURE PERIOD`	timer counts	Raw TCB oscillation period count from the most recent capture.
20	`OSC CAPTURE PULSE`	timer counts	Raw TCB pulse count from the most recent capture.
21	`FREQUENCY CONFIDENCE`	%	Frequency measurement confidence from 0 to 100 percent. Measures agreement among up to ten accepted captures from the preceding 300 ms, each sample within approximately ±2.5 % of the cluster contributing 10 %. Falls during PWM operation. See Frequency measurement confidence.
22	`AUTO LATCHED`	0/1	AUTO mode latch status: 0 = unlatched, 1 = latched.
23	`FIRMWARE VERSION`	numeric ID	Numeric firmware version identifier.
24	`HARDWARE ID`	numeric ID	Numeric hardware family/model identifier.
25	`HARDWARE VERSION`	numeric ID	Numeric hardware revision/version identifier.
26	`OPERATING MODE`	0 - 2	Current operating mode identifier. Same as `LASTMODE`
27	`RUN STATE`	0 - 2	Current run state identifier: 0=OFF, 1=ACTIVE or 2=FAULT.
28	`EXTERNAL CONTROLS ACTIVE`	0/1	Control source state: 0 = serial/internal values, 1 = EXP/external controls active.
29	`TARGET AMPS CC`	x10 (0.1 A)	Live effective constant-current target, referenced to input current, in 0.1 A units.
30	`DUTY CC`	%	Live constant-current PWM duty in percent.
31	`HEATING TIME`	x10 (0.1 s)	Live effective heating time in 0.1 second units.
32	`HEATING TIME CONTINUOUS`	0/1	Heating timer mode: 0 = timed, 1 = continuous/INF.
33	`HOLD AMPS AUTO`	x10 (0.1 A)	Live effective AUTO hold current, referenced to input current, in 0.1 A units.
34	`TARGET TEMP THERMO`	temperature	Live effective THERMO temperature target.
35	`TARGET AUX`	ADC target	Live effective AUX regulation target.
36	`AUX PULSE ACTIVE`	0/1	Indicates whether the AUX pulse output is currently active: 0 = inactive, 1 = active.
37	`HEATING TIME REMAINING`	x10 (0.1 s)	Authoritative remaining time for an active timed NORMAL-mode run, in 0.1 second units. Returns 0 when stopped, faulted, in another mode, or operating continuously/INF.
38	`APPLIED PWM DUTY`	%	Final PWM duty currently applied to the resonator drive after fixed/constant-current selection and soft-start processing. Returns 0 whenever the resonator drive is off.
39	`EXPANSION BOARD DETECTED`	0/1	Physical EXP board presence detected during firmware startup: 0 = absent, 1 = detected.
40	`LAST RESONANCE FAILURE REASON`	0 - 6	Reason recorded for the most recent resonance failure. The value persists until another resonance failure occurs. Values: 0=None; 1=Missing capture; 2=Frequency low; 3=Frequency high; 4=Duty low; 5=Duty high; 6=Startup proof failed.
41	`LAST RESONANCE FAILURE RAW FREQUENCY`	Hz	Raw frequency calculated from the last accepted TCB capture at the most recent resonance failure. Returns 0 if no capture had occurred.

ID	Value	Units / encoding	Purpose
42	LAST RESONANCE FAILURE RAW CAPTURE AGE	ms	Age of the last accepted raw TCB capture when the most recent resonance failure occurred. Returns 0xFFFFFFFF if no capture had occurred.

Table C1: Read-only operating values (ROV)

Appendix D: Fault response values

The FLT response contains two types of information: a fault summary in the flags field, followed by measurements captured when the fault occurred.

The flags value is not a single fault number. It is the decimal representation of a packed 16-bit value containing seven separate fault groups. Each group uses two bits to report one of four states: 0 = no fault, 1 = low, missing or unsatisfied, 2 = high, and 3 = invalid or reserved. Packing the groups into one value keeps the serial packet short while allowing more than one fault condition to be reported at the same time.

A flags value of 0 means that no fault is retained. Any non-zero value must be decoded using Table E1 to determine which fault groups are active. The remaining FLT fields provide the voltage, current, temperature, frequency and duty measurements captured when the controller entered the fault state.

Position	Field	Units / encoding	Meaning
1	flags	packed uint16	Seven two-bit fault groups; decode using Table E1.
2	inputVoltageX10	0.1 V	Input voltage captured at the fault.
3	coilVoltageX10	0.1 V	Coil/T1 voltage captured at the fault.
4	currentX10	0.1 A	Measured current captured at the fault.
5	heatsinkTemperature	degC	Heatsink/CPU temperature captured at the fault.
6	frequencyKHz	kHz integer	Resonant frequency captured as integer freqHz/1000.
7	resonantDutyPercent	%	Resonant duty captured at the fault.

Table D1: Fault response values

Appendix E: Fault flag encoding

Each group is decoded as (flags >> shift) & 0x03.

For example, if flags = 264. As a 16-bit value this is 0000 0001 0000 1000. Applying the formula to each group in turn gives:

Input voltage	`(264 >> 0) & 0x03 = 0`	No fault
Current	`(264 >> 2) & 0x03 = 2`	High
Coil voltage	`(264 >> 4) & 0x03 = 0`	No fault
Temperature	`(264 >> 6) & 0x03 = 0`	No fault
Frequency	`(264 >> 8) & 0x03 = 1`	Low or missing
Duty balance	`(264 >> 10) & 0x03 = 0`	No fault
AUX interlock	`(264 >> 12) & 0x03 = 0`	No fault

A flags value of 264 therefore reports two conditions at the same time: high current, and a low or missing frequency reading.

Bits	Shift	Fault group	Decoded value
0-1	0	Input voltage	0=None; 1=Low; 2=High; 3=Invalid

Bits	Shift	Fault group	Decoded value
2-3	2	Current	0=None; 1=Low/missing; 2=High; 3=Invalid
4-5	4	Coil voltage	0=None; 1=Low; 2=High; 3=Invalid
6-7	6	Temperature	0=None; 1=Low; 2=High; 3=Invalid
8-9	8	Frequency	0=None; 1=Low/missing; 2=High; 3=Invalid
10-11	10	Duty balance	0=None; 1=Low; 2=High; 3=Invalid
12-13	12	AUX interlock	0=None; 1=Unsatisfied; 2=High/invalid; 3=Invalid
14-15	-	Reserved	Ignore

Table E1: Fault flag encoding

The following C function returns the state of one fault group. The group index runs from 0 for input voltage to 6 for AUX interlock, so the shift is twice the group index. Bits 14 and 15 are reserved and are not decoded.

```
/* Decode one fault group from the FLT flags field.
   group: 0 = input voltage, 1 = current, 2 = coil voltage,
          3 = temperature, 4 = frequency, 5 = duty balance,
          6 = AUX interlock
   Returns 0 = none, 1 = low/missing, 2 = high, 3 = invalid. */

uint8_t faultGroupState(uint16_t flags, uint8_t group)
{
    return (flags >> (group * 2)) & 0x03;
}
```

Appendix F: Tank circuit test response status

Status values 2, 4, and 8 are flags and may be added together.

Status	Meaning
0	OK
1	Refused because output is already active
2	Frequency invalid
4	Ring-down capture failed
8	Captured current was zero
20	Normal protection fault occurred during the test
21	Refused because the unit was already faulted
30	Test did not finish within the firmware 250 ms timeout
101	A tank circuit test is already active or requested

Table F1: Tank circuit test response status

Appendix G: Error packets

Code	Packet	Meaning
1	`<ERR,1,0,0,0,0,0>`	Malformed or non-numeric argument.
2	`<ERR,2,0,0,0,0,0>`	Unknown command.

Code	Packet	Meaning
3	`<ERR,3,regID,attemptedValue,0,0,0>`	SET used an invalid register ID.
4	`<ERR,4,regID,attemptedValue,currentValue,0,0>`	SET attempted to write a read-only register.
5	`<ERR,5,regID,attemptedValue,currentValue,0,0>`	Register may only be changed while stopped.
6	`<ERR,6,1,attemptedValue,7,0,0>`	Output start was blocked by the AUX interlock; this does not latch FAULT.
100	`<ERR,100,currentX10,inputVoltageX10,coilVoltageX10,0,0>`	CAP was requested while the output was inactive.
101	`<ERR,101,0,0,0,0,0>`	CAL was requested without a valid retained CAP snapshot.
103	`<ERR,103,channel,measuredValue,rawCapture,0,0>`	Calibration failed or the calculated factor was outside its register limits. Channel: 1=current, 2=input voltage, 3=coil voltage.
104	`<ERR,104,0,0,0,0,0>`	CAL contained no non-zero measured values.

Table G1: Error packets

Appendix H: Variant feature comparison

The table below lists the major differences between the CRO-SM3 variants. Individual features that depend on the serial interface or configurable registers are covered by the corresponding entries rather than listed separately. Features marked for both apply to the CRO-SM3-ST and CRO-SM3-PRO alike.

Feature	CRO-SM3-ST	CRO-SM3-PRO
Push button on/off operation	✓	✓
Output power set by onboard button (25 %, 50 %, 75 %, 100 %)	✓	✓
Fault detection & protection	✓	✓
Digital I/O (5 V) for on/off/error	✓	✓
EXP-THERM1 & OLED support	On / Off and Display only	Display, modes and control
Soft start	Fixed	Adjustable
Factory reset	Hardware only	Hardware or serial
5 V TTL serial interface	✗	✓
Configurable registers	✗	✓
Output power adjustable in 1 % steps, 20 % to 100 % (serial, EXP-THERM1 or external potentiometer)	✗	✓
Selectable constant current or PWM mode	✗	✓
Adjustable PWM frequency (1 kHz to 100 kHz)	Fixed 5 kHz	✓
Timed mode	✗	✓
Workpiece detection mode	✗	✓
Temperature regulation mode	✗	✓
Configurable protection limits	✗	✓
Live monitoring and diagnostic values	✗	✓
Retained fault information	✗	✓
Browser-based web application	✗	✓
Electrical calibration and tank circuit test	✗	✓
FMAX protection setting	Fixed; 300 kHz maximum	Configurable to 1.5 MHz (300 kHz default)

Table H1: Variant feature comparison

Purchasing and OEM Supply

The CRO-SM3 (and related modules) is available both as an individual module for development and as a production component for incorporation into commercial equipment. Customers can develop and validate an application using standard production units before moving to quantity supply.

Quantity pricing is available for production orders. Larger quantities can be manufactured to order, with scheduled or repeat supply available where ongoing production is required. Contact RMCybernetics with the expected quantity, application and anticipated purchasing schedule for current pricing and lead times.

Purchased CRO-SM3 modules may be incorporated into equipment manufactured and sold by the customer without an additional per-unit licence or royalty. This permission applies to the use of genuine supplied modules and does not grant rights to reproduce the CRO-SM3 hardware design, firmware or other proprietary material.

For production applications, units can also be supplied with agreed configuration settings or other application-specific preparation. Custom firmware, hardware modifications, control interfaces, work coils and integration engineering can be provided as separately quoted development services.

Where an application requires substantial quantities, a modified product or other specific supply arrangements, contact RMCybernetics to discuss the requirements before committing the CRO-SM3 to a production design.

Revision and legal information

In this document, CRO-SM3 and SM3 refer collectively to both the ST and PRO variants. Where ST or PRO is omitted from an entry in the revision histories, that entry applies to both variants.

Hardware, firmware, web application and document revisions are maintained independently. Detailed serial commands, registers and web-application behaviour in this document apply to the versions listed in the revision histories below. Earlier ST firmware does not provide the PRO-only configuration and communication functions.

Product identification

The CRO-SM3-ST and CRO-SM3-PRO currently use the same PCB, components and hardware revision. The product variant is defined by the firmware supplied and licensed at manufacture, rather than by differences in the underlying hardware though this is subject to change.

CRO-SM3-ST units cannot be upgraded to PRO by the user, and no firmware-upgrade service is offered. Select the PRO variant where its additional functions are required.

Production CRO-SM3-PRO units carry a PRO identification label fitted to the microcontroller. Units supplied without this marking are CRO-SM3-ST unless identified otherwise in the original sales documentation.

When connected through the serial interface, PRO firmware also reports its product and firmware identity in the `RRV` response returned by a `ROV` request. The relevant values are `FIRMWARE VERSION`, `HARDWARE ID` and `HARDWARE VERSION`, listed in Appendix C. Earlier ST firmware does not provide the PRO serial interface.

Document revision history

Revision	Date	Changes
Legacy	24/05/2023	Initial Release. ST Only
1.0.0	20/08/2026	Combined datasheet
1.0.1	12/09/2026	Additional connection info

Table 11: Document revision history

Hardware revision history

Version	Date Released	Model	Changes
Original hardware (unversioned)	14/02/2023	CRO-SM3-ST	Initial Release
3.23.02.14.00	12/06/2024	CRO-SM3	Diode model change

Table 12: Hardware revision history

Firmware revision history

Version	Date Released	Model	Changes
Original ST firmware (unversioned)	14/02/2023	CRO-SM3-ST	Initial Release
3.26.08.10.00	20/08/2026	CRO-SM3	• Unified ST and PRO firmware source • Improved frequency monitoring • Changed to fast PWM • Added soft-start function • Font Changes • Introduced PRO firmware variant and advanced features • Minor bug fixes

Table 13: Firmware revision history

Web application revision history

Version	Date Released	Supported Models	Changes
1.0.0	20/08/2026	CRO-SM3-PRO	Initial Release

Table 14: Web application revision history

Disclaimer

The information in this document is provided as-is and is not guaranteed to be free of errors. Specifications and firmware behaviour are subject to change without notice as the product is developed.

The CRO-SM3 is supplied as a component for incorporation into a complete system. RMCybernetics Ltd accepts no liability for damage, injury or loss arising from the design, construction, installation or use of any system built around it. Suitability for a particular application must be verified by the system designer.

Intellectual property and software licence

The firmware is supplied in the product and is not distributed separately. The web application source code is provided for customisation as described in the Web Application section, subject to the licence terms accompanying it. Custom firmware and design services are available on request.

Compliance

The CRO-SM3 is manufactured to RoHS requirements. As a component intended for incorporation, it does not carry independent CE or UKCA marking. Conformity assessment of the finished machine or apparatus, including EMC and electrical safety, remains the responsibility of the integrator.

Warranty, returns and contact

Warranty and returns are covered by the terms of sale published on our website. Damage caused by operation outside the specified electrical or thermal limits is not covered.

RM Cybernetics Ltd, 31 Lawton Road, Alsager, Cheshire, ST7 2AA, United Kingdom
Tel: 01270 747 008 (+44 1270 747 008)
Email: info@rmcybernetics.com
www.rmcybernetics.com