Temperature Controller

Easily adjustable general-purpose linear/hysteric temperature controller

Features

Rotary encoder & 7-segment display interface for setting parameters
Controls loads that either heat or cool the sensor
0.1°C display resolution
±0.5°C accuracy in -10°C to +85°C range
±2°C accuracy in -55°C to +125°C range
Adjustable control law allows for linear and/or hysteric load control with adjustable minimum switch period
Complementary OK and ERROR outputs indicate temperature error/alarm.
Robust storage of all parameters in EEPROM

Description

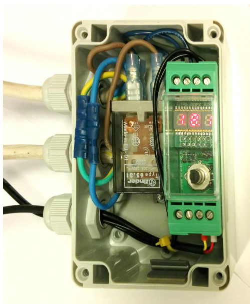
Temperature Controller is a general-purpose temperature controller that can be used for any single-ended load such as a resistive heater, cooling fan, refrigerator/freezer, either directly or through some intermediary (such as a relay).

The control law can be varied from a linear ramp in power between two levels to a purely hysteric output, with an additional minimum duty cycle and minimum switch period.

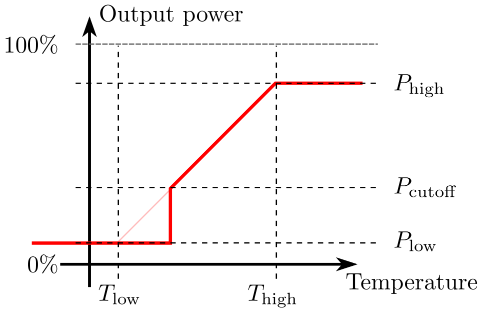
Complementary OK and ERROR outputs indicate a temperature-out-of-range and/or temperature-sensor error condition.

A rotary encoder and three-digit seven-segment display is used to configure parameters and display the current temperature.

Overview



Temperature Controller mounted in an enclosure with a relay, currently measuring 18.1°C.



The output is based on a control law as illustrated here, with an optional hysteresis and minimum switch delay. Note that P_{high} may be lower than P_{low}, which can be useful when used as a heater.

Contents

Copyright Notice

Hardware Revision History

1.1.0 First released version. Minor changes from hardware version 1.0.0.

Software Revision History

1.0.0 Initial version.

1.0.1 Updated seven-segment display to show `8.8.8.` on startup to verify functionality of display.

Documentation Revision History

1.0.0 Initial version, applies to hardware revision 1.1.0.

1.0.1 Updated component C8 to comply with the device's input voltage range.

Absolute Maximum Ratings

PARAMETER	SYMBOL	RATING
Continuous maximum input supply voltage	$V_{in,max}$	+20 V — +30 V[a]
Peak maximum input supply voltage		+40 V
Continuous reverse supply voltage		-40 V
Output short circuit		Continuous
Continuous current sourced through output	$I_{L_{output}}$	2.5 A
Continuous current OK, ERROR output current	$I_{L_{status}}$	1.2 A
Maximum load inductance on output, OK, or ERROR output(s)		66 mH

[a] Maximum supply voltage is limited by the power dissipation in the linear regulator IC4 and the thermal impedance to ambient. In an application with high ambient temperature and/or poor cooling the maximum input voltage must be de-rated to +20 V (or less).

Assembly

Temperature Controller is relatively simply to assemble, and can be soldered either in a re-flow oven or with a fine-pitch soldering iron. **Note that two separate PCBs are used**; a larger board with most components and a smaller board with 7-segment displays and current-limiting resistors. Both have components mounted on both sides. See the section Bill of materials for the components used and figure 5 for their placement. If soldering in a re-flow oven, mount the top side of the larger board (with IC1, C2, and C3) and the bottom side of the smaller board (with RN1 and RN5) first. Neither header J1 (used for one-time programming of the microprocessor) nor header JP1 (optionally used for diagnostic messages) strictly need be soldered to the board.

In low-noise environments the output common-mode choke L1 can be left unmounted. This will reduce noise immunity for the communications bus between Temperature Controller and the temperature sensor. If judged to be not needed, be sure to short the solder jumpers SJ1 and SJ2.

Programming the microprocessor

In order to program the microprocessor, supply power to the `V+ raw` and `GND` terminal block pins (5 V – 20 V). Use a programmer that supports programming the XMEGA16E5 (such as, among others, the AVRISP MKII). If J1 is not soldered to the board, connect a 2x3-pin 2.54 mm header to the programmer, insert the header on the board and rotate/apply torque to the header to ensure that all leads make contact with the board. If using Atmel Studio to program the microprocessor, only the internal flash and fuses need to be programmed. Transfer the the `.hex` file to the device and set up the fuses as follows;

Fusebyte 1 0x0A

Fusebyte 2 0xFE

Fusebyte 4 0xF1

Fusebyte 5 0xE8

Fusebyte 6 0xFF

This corresponds to;

- `WDWP = 8CLK`
- `WDP = 8KCLK`
- `BOOTRST = APPLICATION`
- `BODPD = CONTINUOUS`
- `RSTDISBL = [ ]`
- `SUT = 64MS`
- `WDLOCK = [X]`
- `BODACT = CONTINUOUS`
- `EESAVE = [ ]`
- `BODLVL = 3V0`
- `FDACT5 = [ ]`
- `FDACT4 = [ ]`
- `VALUE = 0x3F`

Pin Description

HEADER	PIN	DESCRIPTION
Enclosure terminals	V+ IN	Positive power supply terminal
	GND	Power ground return terminal for incoming power, power load, and the OK and $\overline{\text{OK}}$ signals.
	GND	
	OUT POS	Primary high-power output. Note that load must be connected between here and a GND terminal.
	PROBE GND	Temperature sensor ground
	PROBE SIG	Temperature sensor communications line
	OK	Normally-high OK status indicator. If high, the measured temperature is in the range $ELO < t < EHI$.
	$\overline{\text{OK}}$	Normally-low OK status indicator. If low, the measured temperature is in the range $ELO < t < EHI$.
JP1	TX	Tx output for UART communications
	GND	Ground reference for UART communications
	RX	Rx input for UART communications. Not used at all in the current firmware version.
J1	-	Standard 6-pin debug-wire interface

Usage

Initial set-up

In order to use Temperature Controller, assemble the device and program the microcontroller as per the section Assembly. Connect a DS18B20 (or equivalent) temperature sensor to the `PROBE GND` and `PROBE SIG` terminal block connections (commonly available in TO-92 or SO-8 packages, or in preassembled and often IP68 rated enclosure with a pigtail cable). The DS18B20 temperature sensor is used in the parasite-power mode; in this configuration **connect the `GND` and `VCC` sensor lines to the `PROBE GND` terminal and the `DQ` line to the `PROBE SIG` terminal**. Connect a 5 V – 20 V DC power supply to the `V+ IN` and `GND` connections.

On the first start-up the device will display `CRC` on the display, indicating that the stored settings are corrupt and invalid (this is normal, as the EEPROM has not been programmed with valid settings. Note that it is very unlikely that settings will become corrupt during normal operation, as multiple redundant checksummed copies are stored in EEPROM and verified on startup.). Press and release the encoder button to reset all settings to their default values — `RST` will be briefly displayed.

The idle-state behavior of Temperature Controller is to display the current measured temperature, expressed in degrees Celsius. For temperatures in the range $-0.9 < t < 99.9$, the temperature is displayed to a 0.1° C resolution. Outside this range the temperature is displayed at a 1° C resolution. *Note that regardless of the display resolution, all internal control-law calculations are made at full accuracy.*

By pressing and releasing the encoder button a list of all system parameters is brought up, this can be cycled through by rotating the encoder clockwise or counterclockwise. To change a parameter, press and release the encoder button when the desired parameter is displayed. At this stage, the numerical value of the parameter can be modified by rotating the encoder. When large value adjustments are desired one can hold the encoder button pressed and rotate the encoder, which will change the parameter value by a factor of 10 faster. To confirm the value of a parameter, press and release the encoder button without rotation; the device will save the new parameter setting to EEPROM and return to displaying the current measured temperature. By repeatedly going through all parameters the device can be set up for the desired application.

Ensure that cables with sufficient conductor area are selected for the `V+ IN`, `GND`, `OUT POS`, `OK`, and $\overline{\texttt{OK}}$ terminals. Note that **it is important that the temperature sensor and only the temperature sensor be connected to the `PROBE GND` and `PROBE SIG` terminals**.

The `OUT POS`, `OK`, and $\overline{\texttt{OK}}$ connections can be used to drive a large range of resistive or inductive loads (see section Electrical Characteristics), such as lamps, relays, resistive elements, and so on.

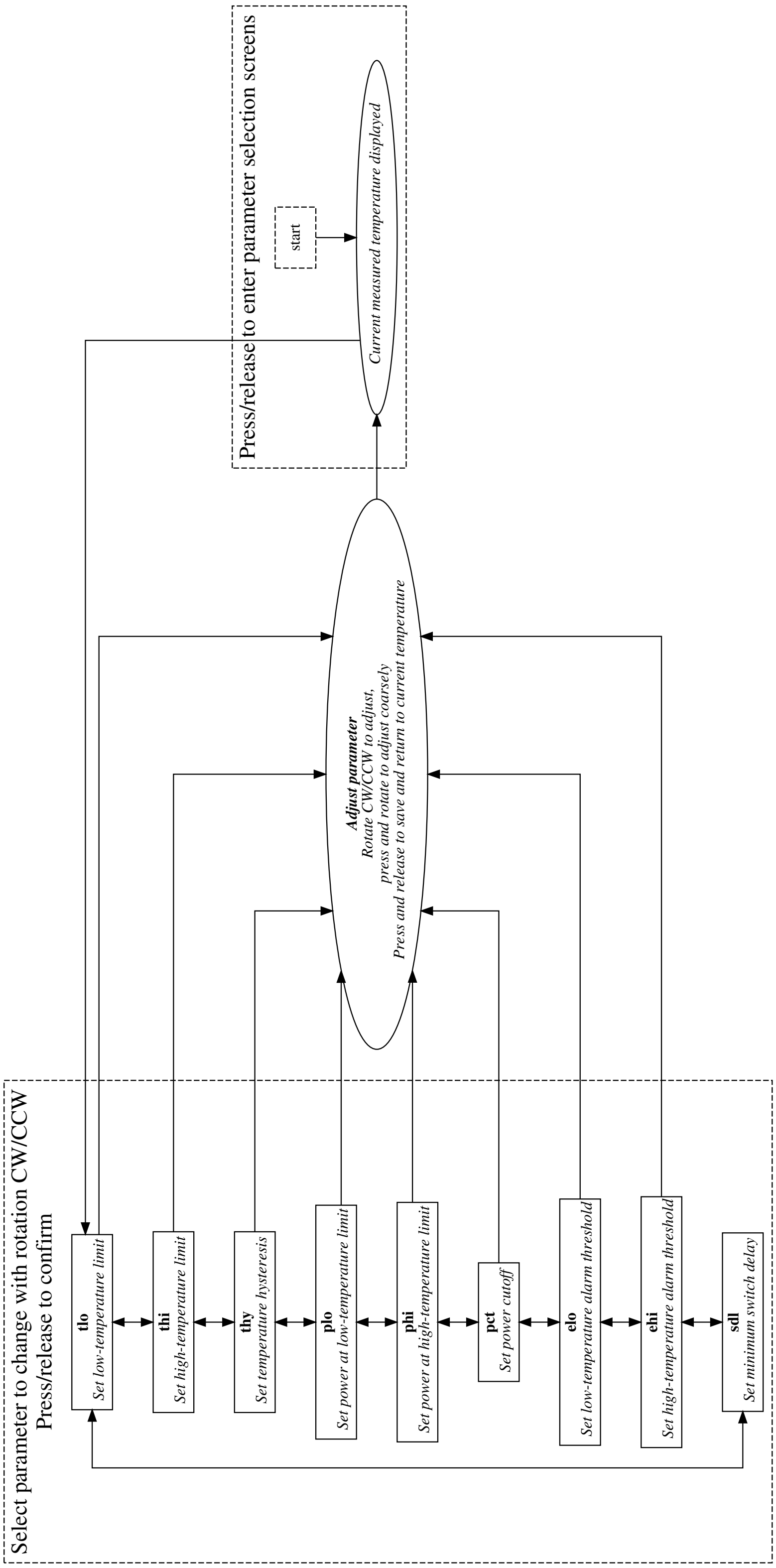


Figure 1: System menu progression.

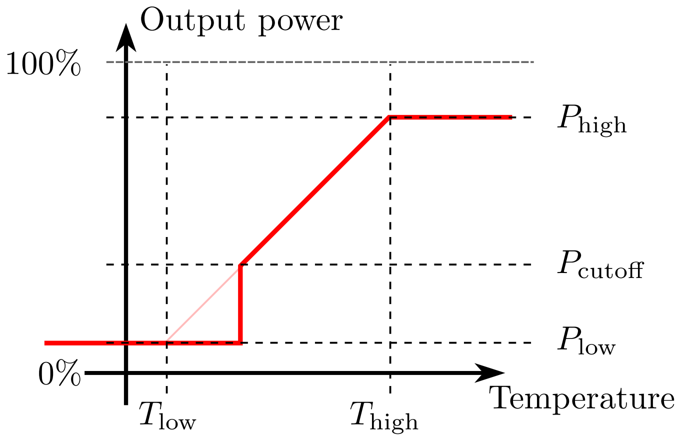


Figure 2: Control law applied by Temperature Controller. This excludes any hysteresis applied, which requires the measured temperature to change by some amount h before changing the output power in the direction opposite to the last change.

Control law

Temperature Controller controls its power output using a linear/hysteric control law defined as

$$P = \begin{cases} P_{low} & t \leq t_{low} \vee P \leq P_{cutoff} \\ P_{high} & t \geq t_{high} \\ \frac{t-t_{low}}{t_{high}-t_{low}} (P_{high} - P_{low}) + P_{min} & otherwise \end{cases} \tag{1}$$

where P is the power to apply to the load, P_{low} is the power to apply at the low temperature threshold, P_{cutoff} is the power cutoff level, P_{high} is the power to apply at the high temperature threshold, t_{low} is the low-temperature threshold, t_{high} is the high-temperature threshold, and t is the temperature after applying hysteresis to the measured temperature such that (assuming some last measured hysteresis-controlled temperature t_k, the current measured temperature t_{meas}, the amount of hysteresis to apply h, and the new hysteresis-controlled temperature t_{k+1})

$$t_{k+1} = \begin{cases} t_{meas} - \frac{h}{2} & t_{meas} > t_k + \frac{h}{2} \\ t_{meas} + \frac{h}{2} & t_{meas} < t_k + \frac{h}{2} \\ t_k & otherwise \end{cases} \tag{2}$$

This may be more easily interpreted graphically, as is shown in figure 2. To reduce power dissipation in the device and allow for a wide range of loads, the output is switched between two levels following a PDM scheme (similar to “standard PWM”, but without a set switching frequency). An additional minimum switch delay parameter allows for setting a minimum time to wait between any two successive changes in the output. See table 2 for a list of all system parameters and their functions and tables 3, 4, and 5 for various application examples.

Table 2: All system parameters and purposes, along with their default, minimum, and maximum values.

NAME	FUNCTION	UNIT	DEFAULT	MINIMUM	MAXIMUM
TLO	Low-temperature threshold	°C	0	-55°C	125°C
THI	High-temperature threshold	°C	0	-55°C	125°C
THY	Temperature hysteresis	°C	0	0	125°C
PLO	Power to apply when at temperature TLO	%	0	0	100
PHI	Power to apply when at temperature THI	%	0	0	100
PCT	When power level is below this value, apply power level PLO	%	0	0	100
ELO	When temperature is below this value, activate the output alarm.	°C	0	-55°C	125°C
EHI	When temperature is above this value, activate the output alarm.	°C	0	-55°C	125°C
SDL	Minimum time to wait between any two successive output transitions.	s	1.0	0.01 s	60 s

Table 3: Setting example for a brushless DC (EG. standard PC) cooling fan directly connected to the `OUT POS` and `GND` terminals.

PARAMETER	VALUE	COMMENT
`TLO`	40	At temperatures below 40° C the fan will be completely off.
`THI`	60	At temperatures above 60° C the fan will be fully on.
`THY`	4	A four-degree hysteresis ensures that minor temperature variations doesn't result in a changing fan speed.
`PLO`	0	At temperatures below 40° C the fan will be completely off.
`PHI`	100	At temperatures above 60° C the fan will be fully on.
`PCT`	25	At calculated output power levels below 25%, clamp to 0% output. This ensures the fan will reliably start at the minimum nonzero power level.
`ELO`	-55	Effectively disable the low-temperature alarm threshold.
`EHI`	65	Generate an alarm signal when the measured temperature exceeds 65° C.
`SDL`	0.01	Switch the output between ON and OFF as quickly as possible. This will generate a PDM output signal that (at most) switches at 50 Hz.

Table 4: Setting example for a resistive heater (such as an immersion heater keeping a pot of soup at a constant temperature) connected driven by a (normally open) relay controlled by the output.

PARAMETER	VALUE	COMMENT
TLO	70	At temperatures below 70° C the heater will be fully on.
THI	75	At temperatures above 75° C the heater will be fully off.
THY	0.5	A 0.5° C hysteresis ensures that very small temperature variations don't result in a changing duty cycle (primarily useful when the measured temperature is near 70 or 75° C).
PLO	100	At temperatures below 70° C the heater will be completely on.
PHI	0	At temperatures above 75° C the heater will be completely off.
PCT	0	Do not limit the minimum power level.
ELO	67	Generate an alarm signal when the measured temperature is below 67° C.
EHI	78	Generate an alarm signal when the measured temperature exceeds 78° C.
SDL	10	Limit the output switch frequency to be no more than 0.05 Hz. (IE. after an off→on or on→off transition, wait at least 10 seconds before changing again).

Table 5: Setting example for a cooler (such as a household freezer) driven by a (normally open) relay controlled by the output.

PARAMETER	VALUE	COMMENT
TLO	-18	Set both temperature thresholds to the same value — this generates a purely hysteric control; without any hysteresis temperatures below -18° C will force the freezer to be fully off, while when above -18° C the freezer will be fully on.
THI	-18	
THY	3	A 3° C hysteresis requires that the measured temperature rise to $-18 + 1.5 = -16.5$° C before turning on and fall below $-18 - 1.5 = -19.5$° C before turning off.
PLO	0	At temperatures below -19.5° C the freezer will be completely turned off.
PHI	100	At temperatures above -16.5° C the freezer will be completely turned on.
PCT	0	Do not limit the minimum power level.
ELO	-55	Effectively disable the low-temperature alarm threshold.
EHI	-10	Generate an alarm signal when the measured temperature exceeds -10° C.
SDL	60	Limit the freezer to turn on/off at most once per minute. (Allowing for all the refrigerant to equalize between power cycles).

UART interface

An optional UART interface is available that can be used to view diagnostic/debug data during operation. The default firmware version displays limited output, by defining the `DEBUG_PRINT` symbol in `config.h` significantly more data can be printed. The UART interface is only configured to use the Tx pin (IE. only data transmission from Temperature Controller to some form of display). To use this interface, connect any 3.3V-compatible UART receiver to the Tx and GND pins of JP1 and configure it for 8 data bits, 1 start bit, 1 stop bit, no parity, no flow control, and a baud rate of 115200 bps.

Bill of materials

Note; A value of 4n7 corresponds to a value of 4.7n, and in the case of a capacitor corresponds to 4.7 nF. The suggested part number is only that — a suggestion — and may be replaced with any other equivalent matching the specifications listed under value, rating, and type.

Component name	Value	Rating	Type	Suggested Part No.
C1, C2, C3	470n	20%, 16 V	X7R ceramic, SMD 0805	MC0805B474K500CT
C8	100n	20% 50 V	X7R ceramic, SMD 0805	MCSH21B104K101CT
C4, C5, C6, C7	2u2	20%, 50 V	X7R ceramic, SMD 1206	GRM31CR71H225KA88L
D1, D3	-	3.3 V	Quad ESD suppression diode in SOT-353	PESD3V3L4UG
D4, D5	-	3 A, 40 V	Generic SMB Schottky diode	STPS340U
DISP1, DISP2, DISP3	-	-	KCSC02-105	KCSC02-105
IC1	-	-	ATXMEGA16E5-AU	ATXMEGA16E5-AU
IC2	-	-	ITS711L1	ITS711L1
IC4	-	-	LT3082EST#PBF	LT3082EST#PBF
J1	-	-	2-row, 6-way 2.54 mm pitch header	2213S-06G
JP1	-	-	1-row, 3-way 2.54 mm pitch header	825433-3
JP2/JP3	-	-	2-row, 12-way 2.54 mm pitch header	2213S-12G
L1	2k2 @ 100 MHz	50 mA	SMD common-mode choke	744232222
R1	4k7	5%, 63 mW	Thick film, SMD 0603	CRCW06034K70FKEA
R2	360k	1%, 63 mW	Thick film, SMD 0603	CRCW0603360KFKEA
RN1, RN5	1k	5%, 63 mW	Thick film quad resistor array, SMD 1206	CAY16-102J4LF
RN2, RN3	330R	5%, 63 mW	Thick film quad resistor array, SMD 1206	CAY16-331J4LF
RN4	10k	5%, 63 mW	Thick film quad resistor array, SMD 1206	CAY16-103J4LF
SJ1, SJ2	-	-	Normally open solder jumper	-
SW1	-	-	EC12D1524406	EC12D1524406
X1	-	-	DIN rail housing; EMG 25-LG/SET and EMG 25-H 7,5MM KLAR	EMG 25-LG/SET, 2943000; EMG 25-H 7,5MM KLAR, 2947132

Mechanical Description

Temperature Controller consists of a PCB and associated components, with a finished size of 71.8 mm by 21.6 mm, with a build height of 22 mm, limited by the rotary encoder SW1. There are no mounting holes integrated into Temperature Controller— a generic electronics enclosure (part X1) is instead used that allows mounting onto a standard "Top hat" 35 mm/7.5 mm DIN rail (EN 50022). PCB manufacturing requirements are shown in table 7 and should be generally achievable at any PCB house.

Table 7: PCB manufacturing requirements.

PARAMETER	REQUIREMENT	UNIT
PCB thickness	Any (nominal 1.6)	mm
PCB layers	2	-
Copper fill thickness/density (tested)	35/1	µm / oz/ft^2
Trace isolation (minimum)	0.2032/8	mm/mil
Trace width (minimum)	0.254/10	mm/mil
Trace to board edge (minimum)	0.25	mm
Drill to board edge (minimum)	0.4532	mm
Drill diameter (minimum)	0.3	mm
Via annular ring (minimum)	0.2032/8	mm/mil

Electrical Characteristics

Output characteristics largely limited/controlled by IC2, ITS711L1. Thermal accuracy is entirely determined by the chosen sensor (nominally a Maxim DS18B20). See the relevant datasheet(s) for more information.

PARAMETER	SYMBOL	TEST CONDITIONS/COMMENTS	MIN	TYP	MAX	UNIT
Input Characteristics						
Power Input voltage	V_{in}	Maximum input voltage dependent on cooling/ambient temperature	5.5		20-30	V
Quiescent supply current	I_Q	Excluding any current through output load. Virtually independant of supply voltage.		35		mA
Output Characteristics						
Output current, active	$I_{L_{output}}$	Load dependent			2.5	A
Output impedance, active				83		mΩ
Load inductance					66	mH
Output leakage current					24	μA
Status output currents	$I_{L_{status}}$	Load dependent			1.2	A
Status leakage current					12	μA
Thermal Characteristics						
Absolute temperature accuracy		-10°C to +85°C			±0.5	°C
		-55°C to +125°C			±2	°C
Internal temperature resolution				0.0625		°C
Sample Rates/Timing						
Temperature sample rate	f_{samp}			1.25		Hz
UART baud rate	f_{baud}			115200		bps
Encoder sample period				1000		μs
Display refresh period		Time for a full seven-segment refresh over all displays		300		μs
UART Logic Levels						
Logic high level		$I_{source} = 20\mu A$		3.1		V
Logic low level		$I_{sink} = 20\mu A$		0.3		V

Operation

The following sections will describe the internal operation of Temperature Controller, both from an electronic as well as software perspective.

Electronic structure

The electronic structure of Temperature Controller is relatively simple, without much in the way of odd or unusual design choices. See figure 3 for a complete schematic of the electronic parts used. Incoming power is brought in through X1. D4 and D5 act as protection in the event of reverse input polarity. This relatively unfiltered input is fed directly into the power distribution switch IC2, which handles all high-power switching. The linear regulator IC4 generates a 3.3 V supply for the remainder of the electronics. This particular regulator was chosen as it has a relatively low drop-out voltage, is stable with ceramic capacitors, and can withstand input voltages up to 40 V. The regulated 3.3 V supply is used to drive the microcontroller IC1, the external temperature sensor, and all user control/displays. RN2, RN3, and D1 form a robust ESD-protection network.

A common mode choke L1 is used to filter the communications bus used for the temperature sensor. This helps to reduce common-mode disturbances that couple to the communications conductor of the probe. As per the recommendations in the DS18B20 datasheet a 5 kΩ pullup resistor biases the probes communications bus. (During a temperature conversion the microcontroller will switch the `PROBE_SIG` net to a hard-driven output to power the sensor.)

The seven-segment LED displays are driven in an entirely ordinary common-cathode scheme, where one display is active at a time and switched sequentially.

Software structure

Temperature Controller's software structure is relatively basic, after some peripheral/hardware initialization an infinite loop is entered which handles low-speed tasks (triggering a temperature conversion, acting on input from the rotary encoder, generating raw output to the display, saving parameters to EEPROM, and so on) in a cooperative multitasking manner. Two interrupt contexts are used, one of which periodically switches the active 7-segment display, the other which handles an internal timekeeping function, samples the rotary encoder state, and generates the software PDM output based on the current target power level.

The majority of the complexity in Temperature Controller lies in the user interface — decoding the encoder state, switching between different menu screens, altering parameters, saving parameters to EEPROM, and displaying data on the 7-segment displays. Some noteworthy aspects that may be useful to explicitly state are;

- The rotary encoder angular state is sampled and filtered in software, which ensures that mild jitter between any two positions does not result in a changing parameter value (see the `enc_divisor` parameter in `struct rotary_enc_t`).

- The rotary encoder button state is debounced in software using a rudimentary saturating-integrator scheme, with callbacks that are generated on detection of a press or release event.
- The entire menu structure is defined in `globals.c/.h`, with all references to other menus, text strings, and so on. This allows for a relatively flexible set-up, making it fairly easy to alter or add new parameters.
- `enc_callbacks.c` contains all the connections between the selected menu parameter and which actual parameter to modify.
- `seven_seg.c/.h` creates a printf-compatible interface for generating output to the display. This makes conversion from a numerical value (integer or floating point) to displayed characters simple.
- The `flex_settings` subsystem gives a general interface for reading/writing parameters in a thread-safe manner, as well as storing parameters in nonvolatile memory with adjustable levels of redundancy.
- During startup the software will check if the device started due to a watchdog timeout; if this is the case the device will alternatingly display `SYS` / `ERR` until restarted. Should this occur this indicates a serious software bug or (less likely) faulty hardware.

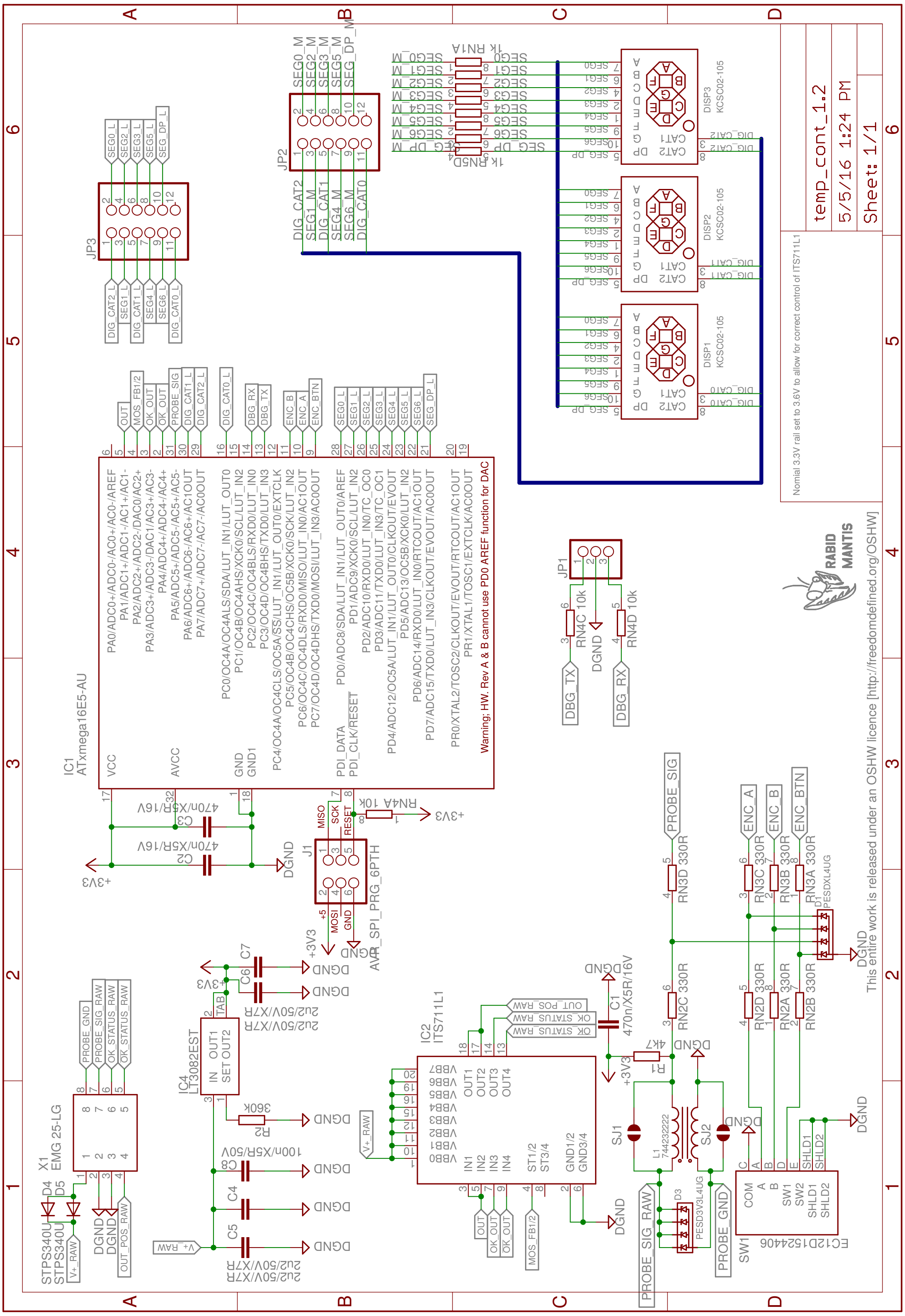
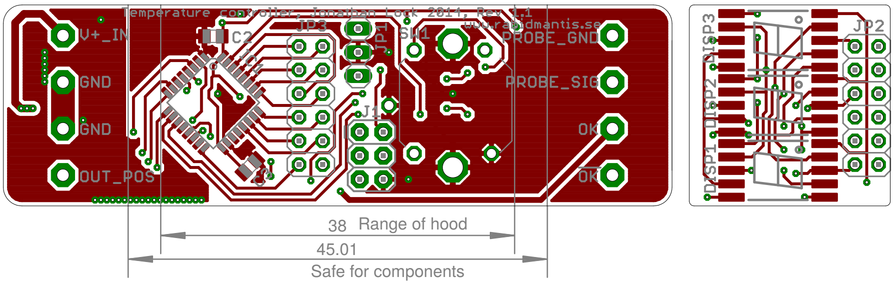
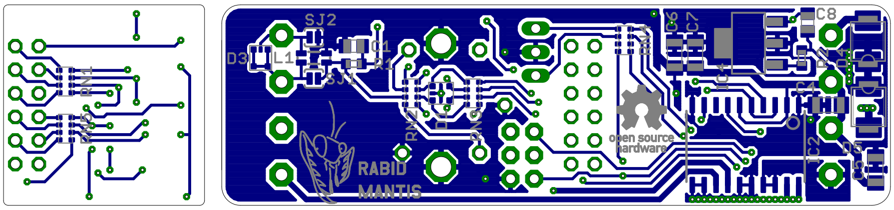


Figure 3: Temperature Controller schematic.

Note; Generate gerber files by selection; either base board or 7-seg board



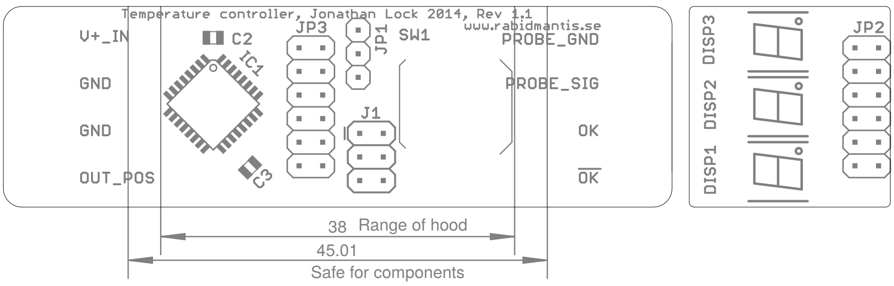
(a) Complete top layer as seen from above.



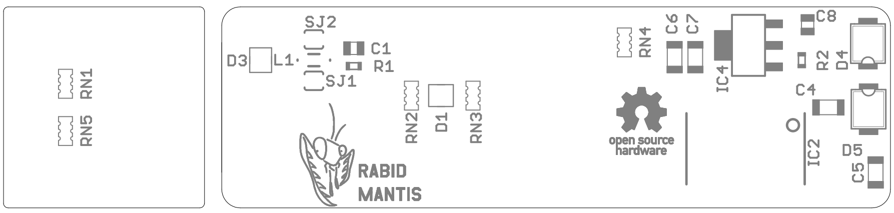
(b) Complete bottom layer as seen from below.

Figure 4: PCB details.

Note; Generate gerber files by selection; either base board or 7-seg board



(a) Top layer component outline as seen from above.



(b) Bottom layer component outline as seen from below.

Figure 5: Component placement details.