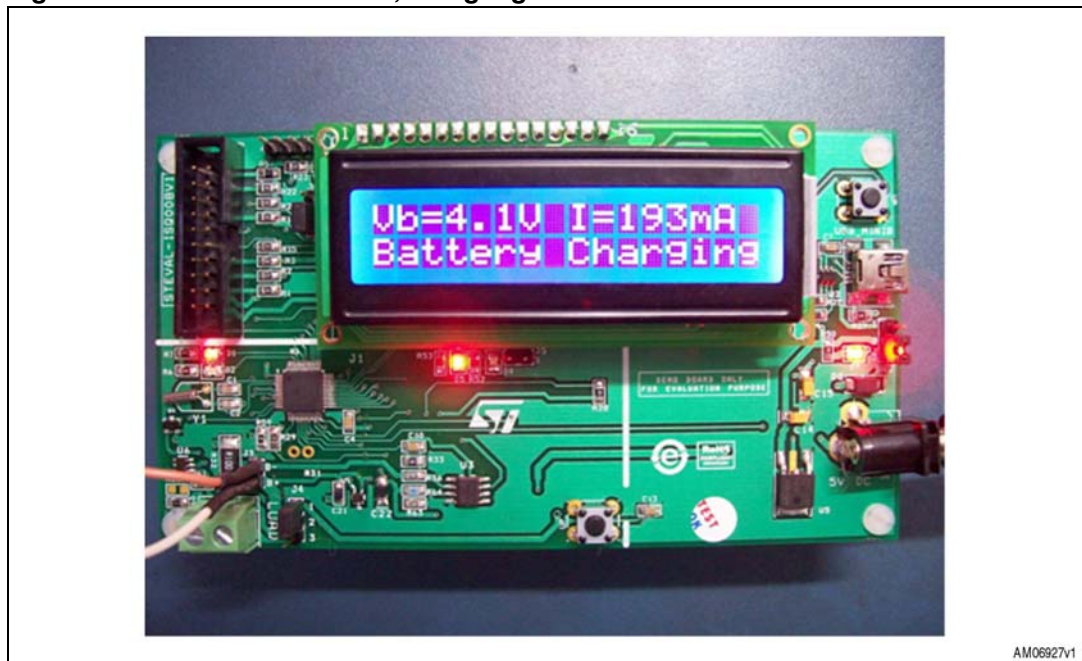STEVAL-ISQ008V1, fuel gauge implementation
based on the STM32F103x

Introduction

This user manual describes the functions of a single cell Li-Ion battery fuel gauge technology using an MCU within the STM32 (ARM Cortex™-M3 core) family. The fuel gauge demonstration board is used to show the capability of an STM32 microcontroller to be used for battery fuel capacity monitoring. The fuel gauge implementation is based on the STM32 microcontroller; the MCU is used for monitoring the capacity of a single cell Li-Ion battery. An on-chip 12-bit ADC from the STM32 family is used for battery capacity calculation.

The fuel gauge technology is a smart system which monitors battery capacity, predicts remaining capacity, and displays its status. The basic ideology used for battery capacity measurements is Coulomb counting, in which the current flowing through the battery is continuously monitored and integrated to calculate the capacity. Current measurement is done when the battery is both discharging and charging. Therefore both the IN and OUT current are taken into account to calculate the remaining capacity of the battery. Battery capacity is measured in mAh.

Figure 1. STEVAL-ISQ008V1, fuel gauge demonstration board

Contents

List of tables

List of figures

1 Getting started

1.1 Package contents

The fuel gauge package comes with hardware and supporting documentation.

● Hardware: one demonstration board (along with onboard battery charger)
● Documentation: user manual for operating the demonstration board

1.2 Hardware description

The fuel gauge demonstration board has onboard charging and discharging capabilities.

Major onboard components are:

● STM32F103C8, 32-bit microcontroller
● TS941B, operational amplifier
● L6924D, battery charger
● LD1086XX33, voltage regulator
● STLQ50XX25, voltage reference
● STT5PF20V, P-channel MOSFET
● 16 x 2 alphanumeric LCD
● Mini USB connector
● External power supply adapter jack
● 100 mΩ sense resistor

1.3 Power supply unit

The power supply unit for the demonstration board is divided into two blocks:

1.3.1 Battery supplied block

This block is powered up using the battery supply.

The battery used for capacity monitoring is also used for supplying the load (if resistance connected at J8).

There is a jumper connection (J3) used for connecting the positive and negative terminal of the battery. Battery connections are shown in *Figure 2*. Therefore during the charging of the battery the current is flowing from the charger to the battery and then through the 100 mΩ sense resistor. During discharge, current is flowing from the battery through the externally connected resistance connected at J8 and through the 100 mΩ sense resistor.

Voltage drop across the 100 mΩ sense resistor is used to evaluate the capacity of the battery.This voltage drop is measured by ADC of the STM32 MCU and from this measured voltage, the battery current is calculated.

Figure 2. Connector for battery
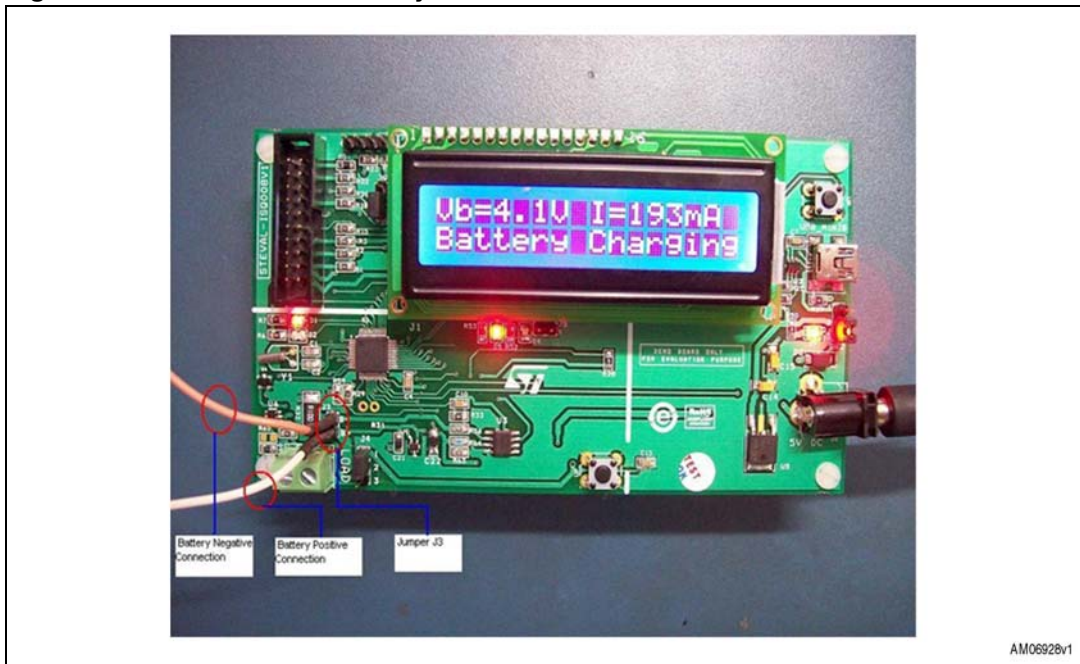
1.3.2 External supplied block

External 5 V of power is used for supplying the following components:

● Battery charger

● Back light of LCD

● LCD display.

Note: *1*   *The DC adapter used for external power should be of 5 V*

       2   *The USB Connector is used for external power supply source only.*

Table 1. Power selection jumper positions

Switch jumper SW2	Action
PIN 1 and 2 shorted	USB power supply selected
PIN 2 and 3 shorted	External DC power source selected

Figure 3.   External supply selection
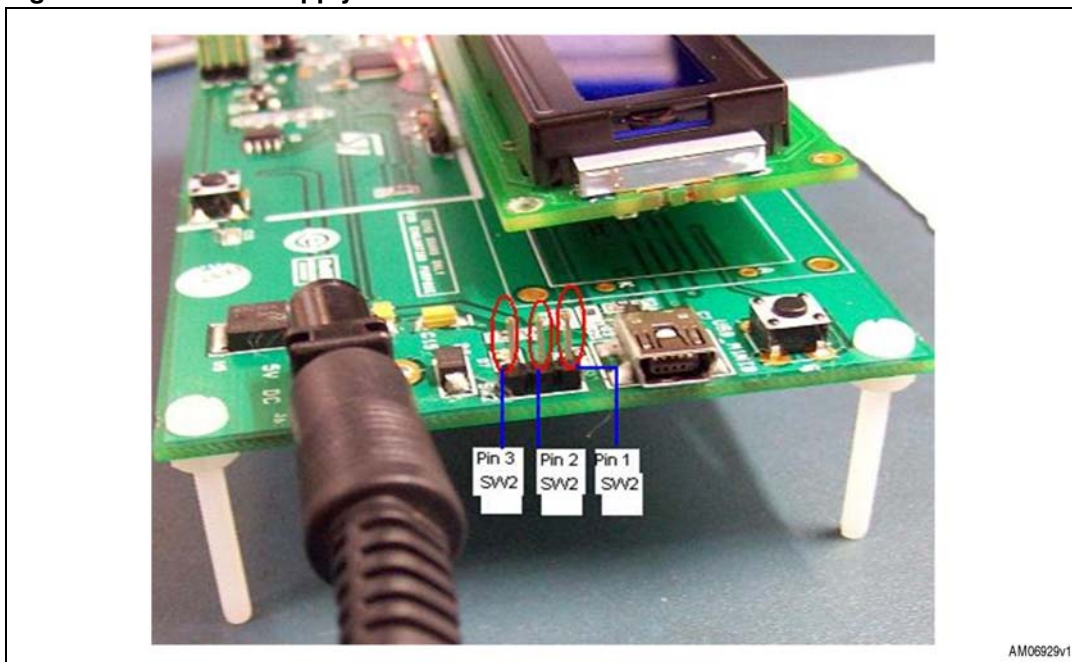
2 Fuel gauge application

This fuel gauge demonstration board is based on the calculation of current flowing through the 100 mΩ sense resistor using the on-chip 12-bit ADC of the STM32 32-bit MCU. The voltage drop across the sense resistor is measured by the on-chip 12-bit ADC at periodic intervals of 1 second and this voltage is used for current calculation from which battery capacity is derived. The current accuracy for this solution is up to +/- 3 mA.

2.1 Demonstration board sections

The fuel gauge demonstration board is split into 4 sections:
● Microcontroller
● Operational amplifier
● Battery charger
● LCD display.

2.1.1 Microcontroller section

The STM32 microcontroller is used for fuel gauge calculations. The features of the STM32 used for this application are:
1. On-chip ADC used for voltage, current, and temperature measurements
2. On-chip RTC used for the time base for fuel gauge computations
3. Input/output ports used for the LCD display

NTC is also connected to one ADC channel of the microcontroller for monitoring battery temperature.

2.1.2 Operational amplifier section

The TS941BIDT operational amplifier is used as an amplifier and for dual polarity detection of current flowing through the battery. Input to the operational amplifier is the voltage drop across the 100 mΩ sense resistor and output of the operational amplifier is connected to the ADC input channel of the microcontroller. Both positive current (in case of battery charging) and negative current (in case of battery discharging) is measured using this operational amplifier.

2.1.3 Battery charger section

The L6924 present on the demonstration board is used for charging the battery. Jumper J4 is used for connecting the battery to the resistive load or to the battery charger, as described in *Table 2*.

Table 2.   **Jumper J4 connections**

Jumper J4	Action
PIN 1 and 2 shorted	Battery connected to battery charger
PIN 2 and 3 shorted	Battery connected to load at jumper J8

The charger supplies current to the microcontroller circuit and also to the battery, maximum charging time is fixed at 4 hours. The charger can be powered up either from an external DC adapter (5 V) or using USB power (shown in *Figure 3*). Jumper J5 is used for the shutdown pin of the charger, it should be shorted using the jumper to enable the charger. There are 2 LED's present on the demonstration board (D4 and D5). When charging, the ongoing D4 is in the OFF state and D5 is in the ON state.

If charging time has lapsed or the battery is not connected to the charger then both D4 and D5 are in the ON state. *Figure 4* shows jumper J4 for selecting the charging and discharging path.

Figure 4.   Charging and discharging path selection
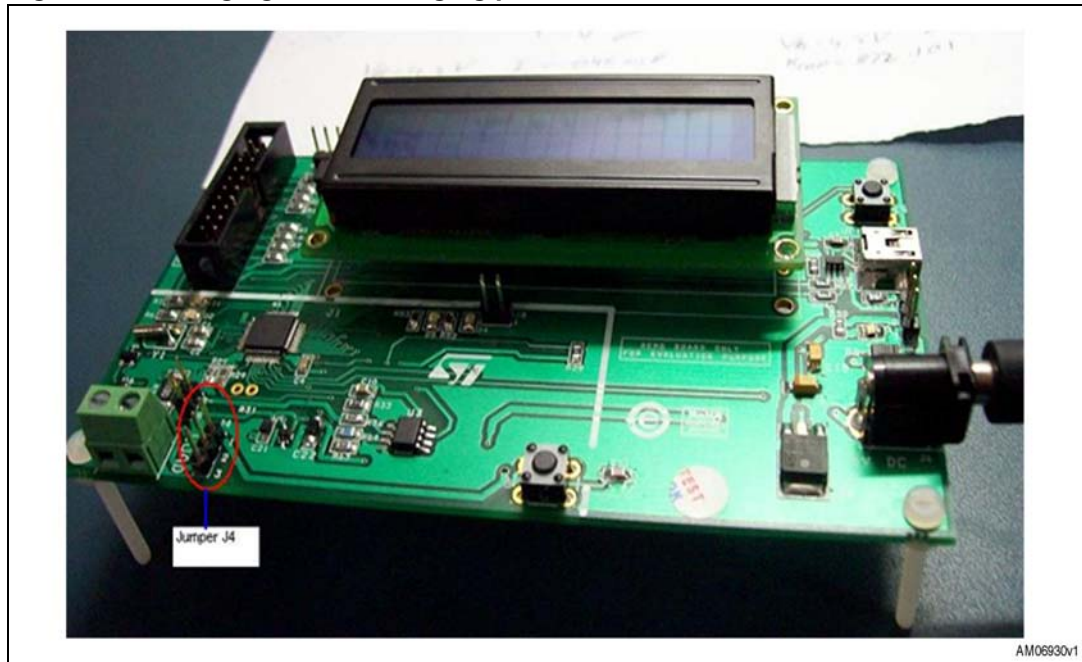
2.1.4   LCD display section

An alphanumeric (16 x 2) LCD is present on the demonstration board. It displays the voltage of the battery and current flowing through (in/out) the battery. Also the capacity of the battery is shown as a percentage of full capacity.

If the battery voltage goes below 3.1 V, the "Battery Low" message is displayed on the LCD and the D2 LED starts blinking.

2.2   Starting the fuel gauge application

The demonstration board has the provision of learning the capacity of a new battery (if not previously known) or if the user is confident that the new battery is fully charged then the capacity learning phase can be skipped, but in this case the battery state is considered as fully charged with a remaining capacity of 900 mAh.
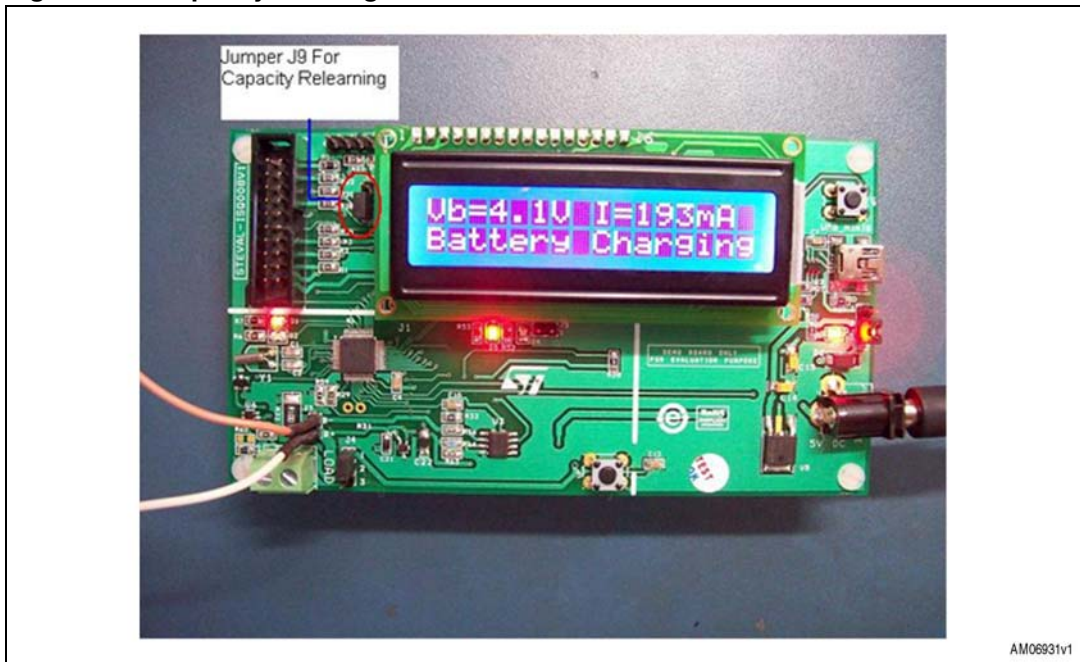
2.2.1 Battery state of health not known

If the battery being plugged into the demonstration board is not fully charged or its full charge capacity is different to 890 - 900 mAh, then the user should allow the system to learn the battery capacity for the fuel gauge application. For this the user should allow one complete cycle before starting the fuel gauge application.

The steps for learning the capacity of a new battery are:

1. Place the jumper J9 to short pin 1 and 2, as shown in *Figure 5*

2. Remove jumper from J4

3. Plug the battery into the demonstration board, as shown in *Figure 2*

4. Plug in the DC power supply

5. Press the reset button present above the USB connector

6. The LCD shows the message "Self Calib ON" for 5 seconds and after shows the messages "Charge The Battery" and "Use Jumper J4"

7. Place the jumper J4 to short pin 1 and 2 (charging mode enabled)

8. The LCD displays "Vb" (battery voltage in volts) and "I" (charging current in mA) in the first line and "Battery Charging" in the second line

9. Allow a complete charge of the battery. At full charge the LCD displays a message "charging complete" in the first line and "discharge battery" in the second line

10. When the battery is fully charged (a 3.7 V, 890 mAh battery takes around 2-3 hours for a complete charge) discharge the battery using the resistance load across connector J8. The resistance connected should be in the range of 20 Ω - 100 Ω. This supports the current measurement up to a maximum of 200 mA

11. Connect jumper J9 to short pin 2 and 3

12. Connect jumper J4 to short pin 2 and 3, as shown in *Figure 4*

13. Now battery discharging starts and the display shows "Vb" and "I" in the first line, showing the battery voltage and discharge current and the "ReLearning phase" in the second line of the LCD.

14. When the battery voltage goes below 2.9 V, the "battery low" message is displayed on the LCD. The user should remove the jumper J4 to avoid the battery going into deep discharge mode

15. The LCD displays "Relearning Done" in the first line and "charge the battery" in the second line (this message is displayed if step 10 is not followed, that is, if pin 2 and 3 of J9 are not shorted. The user should then short pin 2 and 3 of J9)

16. The relearning process is completed and the user should charge the battery by shorting pin 1 and 2 of jumper J4

17. Normal fuel gauge application starts with the display showing "Vb" and "I" in the first line and "RCap" (percentage remaining capacity) in the second line.

Note: *1*   *Pin 1 and 2 shorted for jumper J4 charges the battery and, if pin 2 and 3 are shorted, the battery discharges*

     2   *If no pin is shorted in jumper J4 then only the microcontroller is running on battery power and the system consumption is seen as 25 (+/-3) mA. This is the consumption of the microcontroller, op amp, and voltage regulator*

     3   *When capacity learning is ongoing, allow the battery to charge fully first and then discharge fully, don't interrupt the charging and discharging cycles in this phase*

Figure 5.   Capacity learning for the first time

2.2.2   Battery state of health is known

If the user is sure that the battery plugged into the demonstration board is new and is fully charged with a capacity of 890 - 900 mAh (standard 3.7 V, 890 mAh), then the capacity relearning phase can be skipped and the fuel gauge application can be started directly.

The steps for skipping the battery capacity relearning phase are:

1.   Connect jumper J9 to short pin 2 and 3
2.   Connect the battery, as shown in *Figure 2*
3.   Connect load resistance (20 Ω - 100 Ω)
4.   Plug in the power supply
5.   Remove any jumper from J4
6.   Press the reset button onboard (located above the USB connector)
7.   LCD shows "Self Calib ON" for 5 seconds and afterwards shows the battery state
8.   Battery remaining capacity is assumed to be 900 mAh/100 % for the first time
9.   Normal fuel gauge application starts
10.   Either charge or discharge the battery using jumper J4

Note: In this phase it is assumed that the connected battery is fully charged, and if battery charging is enabled, the capacity display is 99.9 %

2.2.3   Alarm condition

When in discharging mode the battery voltage goes below 3.1 V, then the D2 LED onboard starts blinking and the "Battery Low" message flashes on the LCD.

When battery voltage goes below 3.0 V, then the discharging path through the external resistor is automatically disabled using a P-Channel MOSFET and system consumption falls to ~25 mA.

It is recommended to avoid the battery going into deep discharge mode and the user should charge the battery using jumper J4.

2.2.4 LCD messages

Various messages are displayed on the LCD at different stages of the fuel gauge application.

These messages and their respective conditions are listed below:

- "Charge The Battery" and "Use Jumper J4", when the battery is plugged in for the first time and the board is powered for the first time
- "Relearning Phase", this is displayed at the time of discharging the battery during the relearning phase of the battery
- "Vb" and "I" represent the battery voltage in volts and current flowing through the battery in mAmps
- "Charging Complete", when the battery charging current goes below 50 mA
- "RCap" is the notation showing the percentage of remaining capacity left in the battery
- "Battery low" is displayed when the battery voltage goes below 3.0 V
- "Charge the battery", in case of capacity learning and first complete discharge is done.

2.3 Compensations in fuel gauge calculations

Battery capacity is affected by:
- Battery temperature
- Battery self-discharge

So in order to have an accurate fuel gauge system, these factors are to be compensated during calculations. In this implementation all the above mentioned factors are compensated.

2.3.1 Temperature compensation

Battery capacity is dependent on the temperature of the battery. At higher temperatures the battery tends to have more capacity (but battery life is reduced simultaneously). Therefore, in this fuel gauge calculation, whenever the battery is being discharged, battery temperature is monitored and the remaining battery capacity is calibrated according to the battery temperature. To measure the battery temperature, an NTC is used in the system. This NTC should be placed close to the battery surface.

Table 3 shows battery capacity variation with battery temperature.

Table 3.   Battery capacity variation due to temperature

Temperature	% Variation in capacity
< -20 °C	-6
-20 °C to -10 °C	-5
-10 °C to 0 °C	-3
0 °C to 10 °C	-2

Table 3.   Battery capacity variation due to temperature

Temperature	% Variation in capacity
10 °C to 20 °C	-1
20 °C to 30 °C	0
30 °C to 40 °C	+1
40 °C to 50 °C	+3
>50 °C	+4

## 2.3.2   Self-discharge compensation

If the battery is not being used, the battery capacity also reduces due to self-discharge of the battery. This self-discharge rate is minimal but if the battery is not in use for a longer time then this self discharge factor is significant and results in a reduction of battery capacity. Therefore, the remaining capacity of the battery is calculated using this self-discharge rate. In the calculations, the self-discharge rate has been used according to *Table 2*.

Table 4.   Self-discharge rate of Li-Ion battery

Temperature (degree C)	Self-discharge rate
Temp < 10	¼ % per day
10<=temp<20	½ % per day
20<=temp<30	1 % per day
30<=temp<40	2 % per day
40<=temp<50	4 % per day
50<=temp<60	8 % per day
60<=temp<70	16 % per day
70<=temp	32 % per day

3 Flow chart for fuel gauge demonstration board

Figure 6.   Flow chart
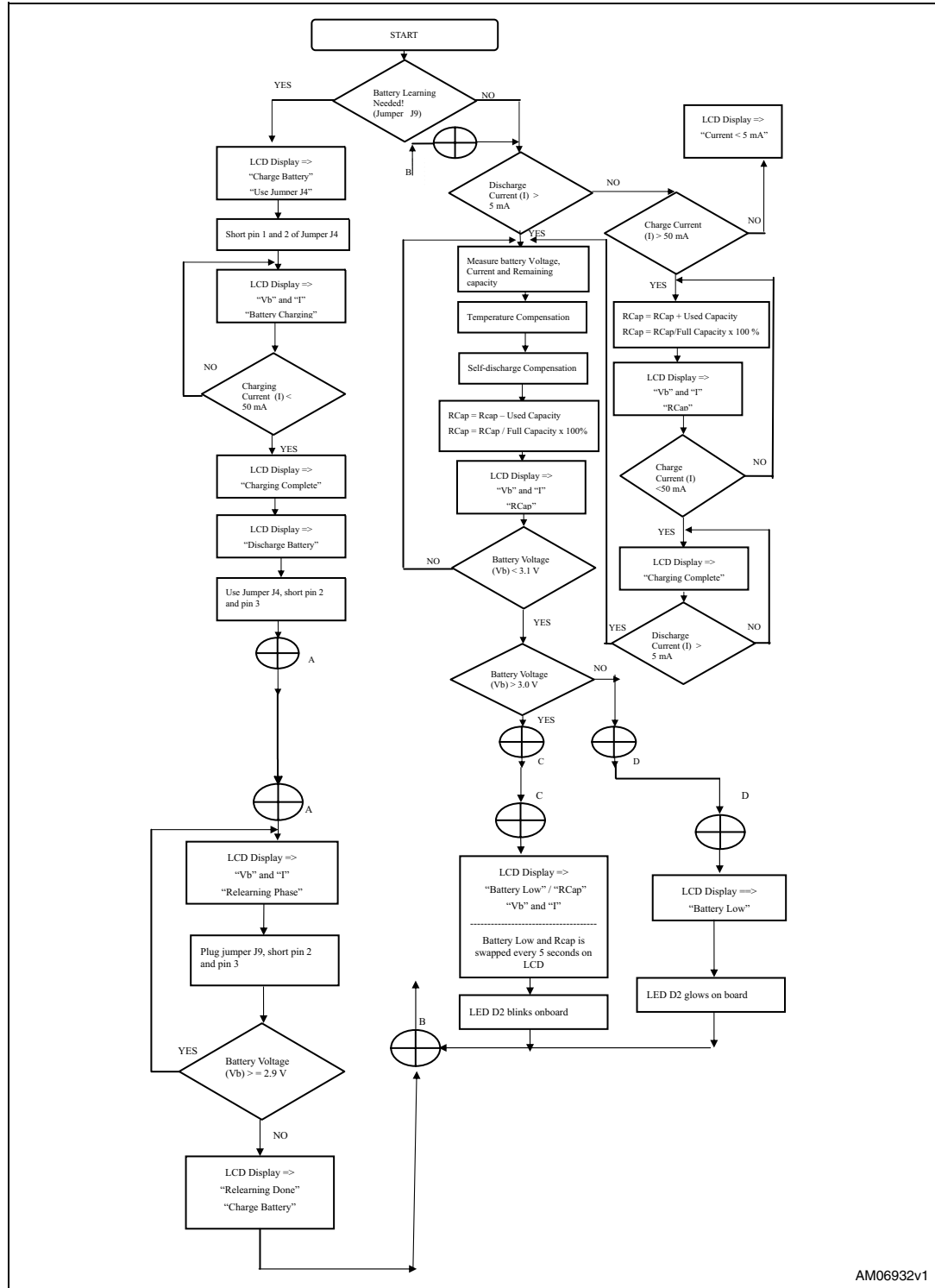
AM06932v1

The D1 LED shows the running status of the fuel gauge system. When the fuel gauge application is running, D1 blinks onboard, and when the fuel gauge is not working, this LED is off.

4 The STM32 as fuel gauge

The STM32 has an on-chip ADC with a 12-bit resolution. In fuel gauge implementation ADC is operated at 2.5 V, and so each LSB accounts for 0.610 mV. This ADC has an inherent error of +/- 2 LSB. Certain considerations to take into account, for minimizing error and achieving the STM32 fuel gauge application, are listed below.

4.1 ADC error minimization

ADC has an error of +/-2 LSB. To account for this error, multiple readings of the same voltage are taken and then these readings are averaged. Therefore, averaging the readings minimizes the error. To get multiple readings of multiple ADC channels, DMA of STM32 is used.

The TS941 is a micropower operational amplifier. This operational amplifier is used to serve the following purpose:

4.1.1 Dual polarity measurement

This operational amplifier is used in default offset mode in inverting configurations, due to which, if the input is zero, a definite output voltage is also available. Therefore, when positive voltage is applied at the input of the operational amplifier, the output goes below the default offset value and if negative voltage is applied, the output goes above the default offset value.

This shifting of the operational amplifier output is used to ascertain whether the current is a charging current or a discharging current. If the output of the operational amplifier is more than the default value, the current is discharging and if the output is lower than the default voltage, the current is charging.

4.1.2 Amplification of low voltage values

The fuel gauge system measures the current ranging from +/- 5 mA to +/- 200 mA. This current is measured from the voltage drop across the 100 mΩ sense resistor. Voltage drop across the 100 mΩ sense resistor is the input to the operational amplifier, and the output of the operational amplifier is connected to the ADC channel of the STM32.

The operational amplifier has a gain of 50. Therefore, the input is amplified by 50 times and is measured by the ADC channel of the microcontroller.

During startup of the application for the first time, the system performs the self calibration for the offset of the operational amplifier and the LCD shows the message "Self Calib ON" for the period this calibration is done.

5 Demonstration board schematics
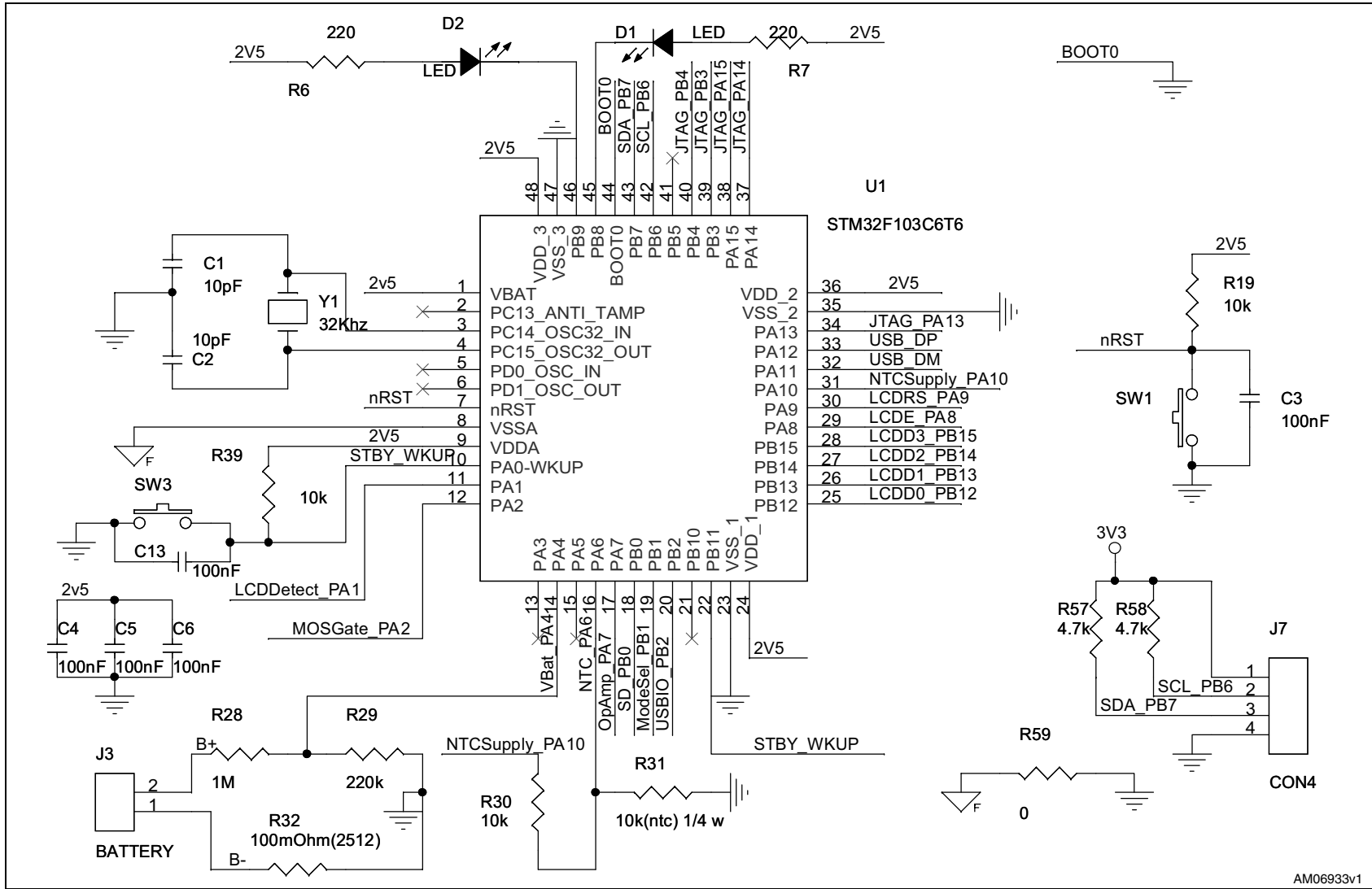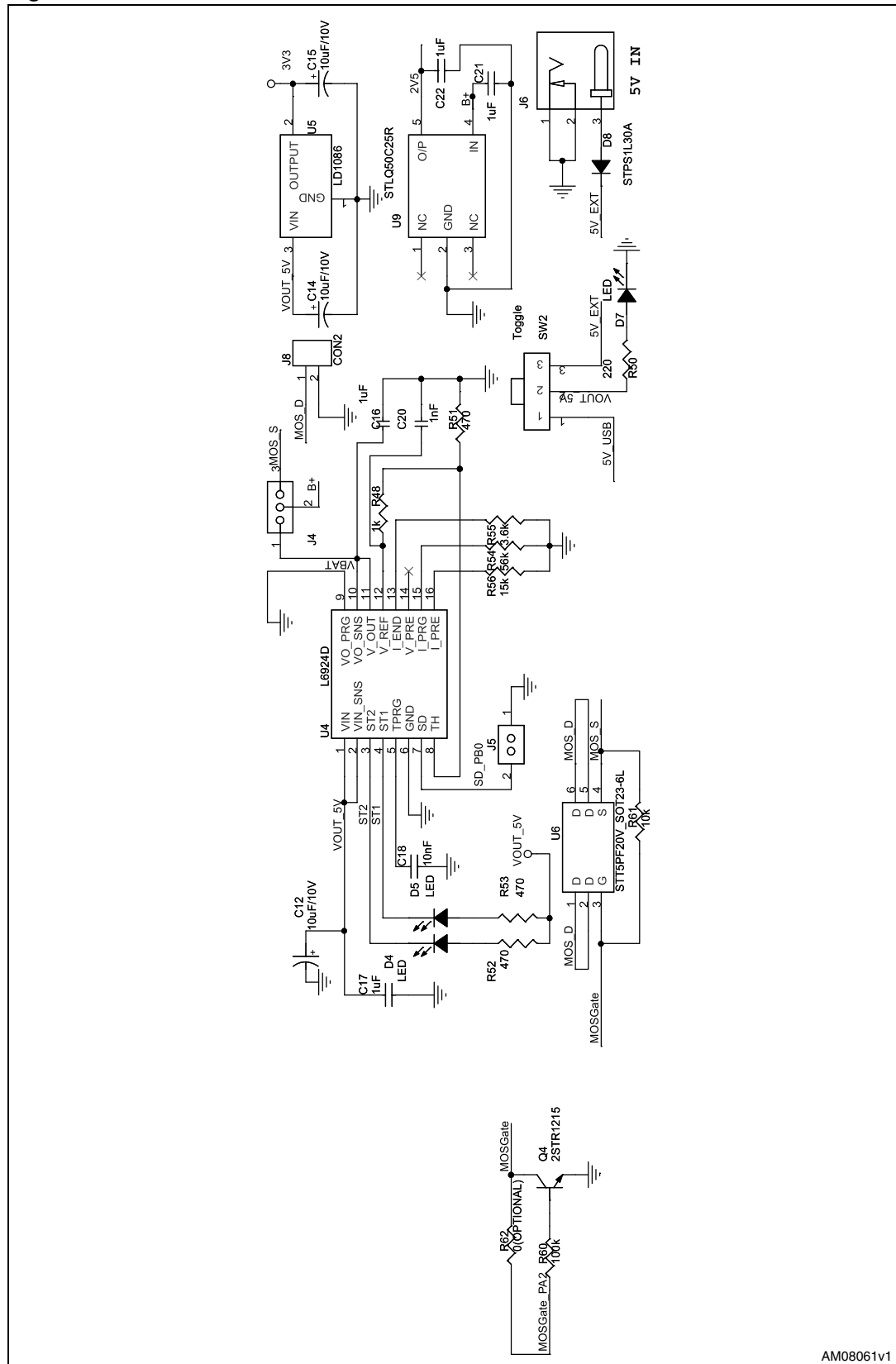
Figure 7. Microcontroller section

AM06933v1

Figure 8. Power section

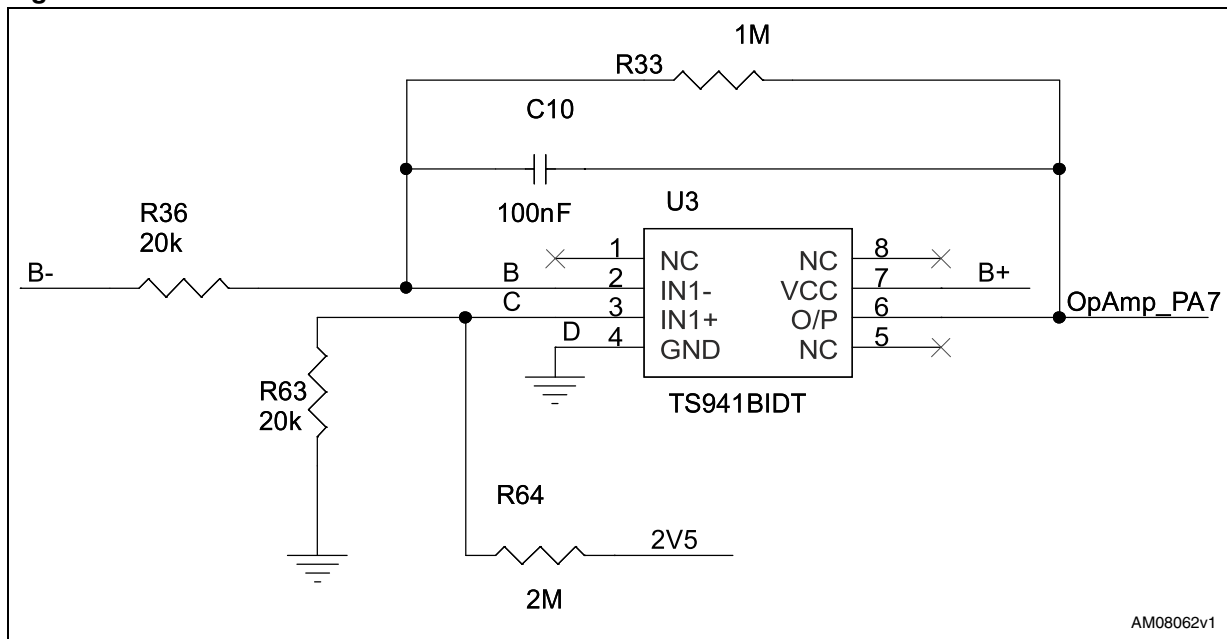AM08061v1

Figure 9. OP-AMP-section
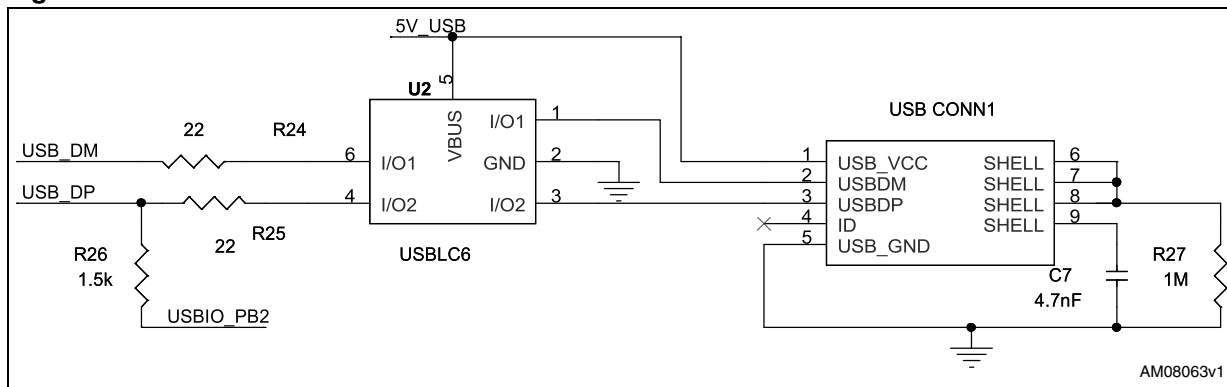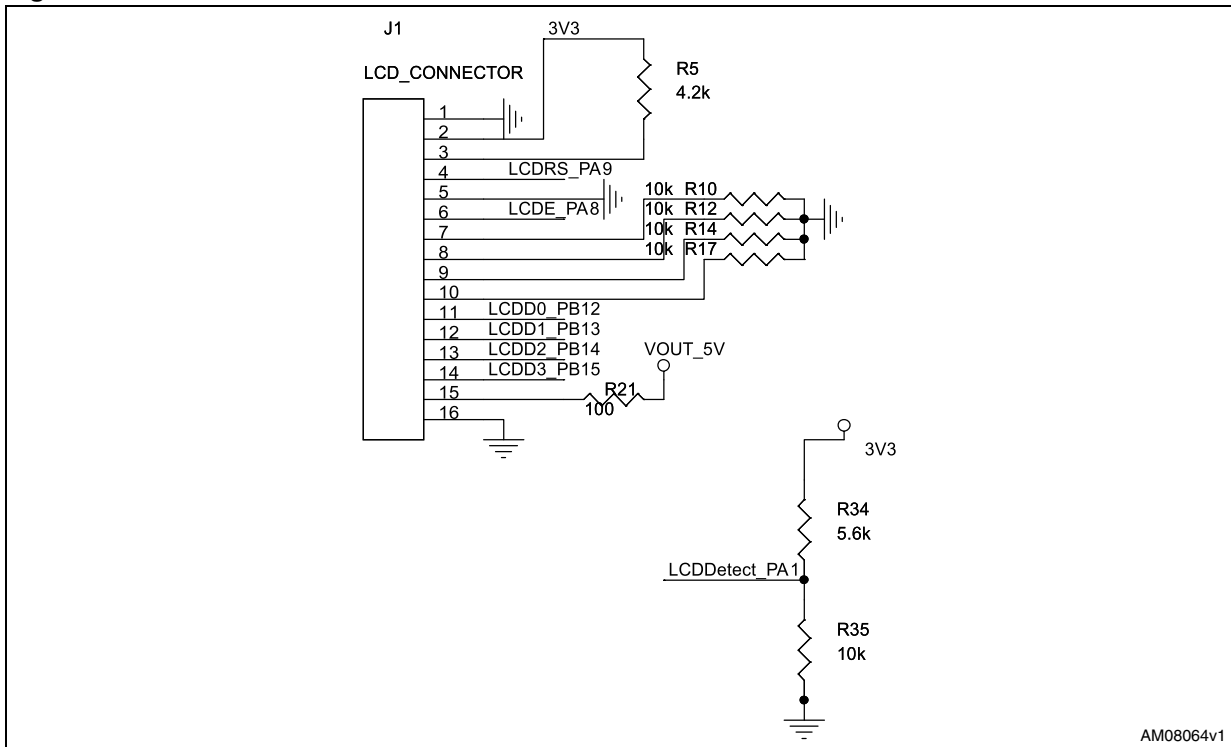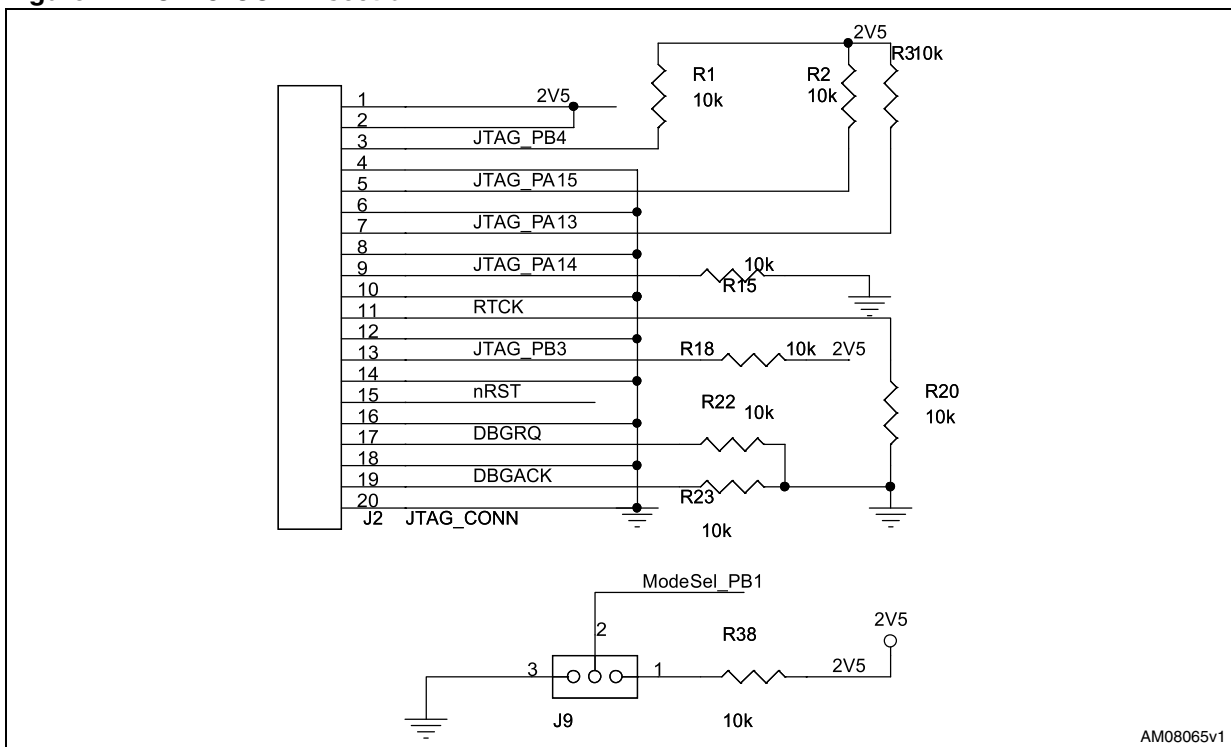

Figure 10. USB section

Figure 11. LCD section

AM08064v1

Figure 12. JTAG-CONN section

AM08065v1

6 Bill of material

Table 5.   BOM

Reference designator	Component description	Package	Manufacturer	Manufacturer's ordering code / orderable part number	Supplier	Supplier ordering code
U1	STM32F103C6T6/ Microcontroller	LQFP	STMicroelectronics	STM32F103C6T6		
U2	USBLC6-2SC6/USB protection device	SOT-23-6L	STMicroelectronics	USBLC6-2SC6		
U3	TS941/OpAmp	Mini SO-8	STMicroelectronics	TS941BIDT		
U4	L6924D/battery charger	VFQFPN16	STMicroelectronics	L6924D/L6924D013TR		
U5	LD1086/voltage regulator	DPAK	STMicroelectronics	LD1086DT33TR		
U6	STT5PF20V / P-channel MOSFET	SOT23-6L	STMicroelectronics	STT5PF20V		
U9	STLQ50C25R/ voltage regulator	SOT323-5L	STMicroelectronics	STLQ50C25R		
D8	STPSIL30A/ Schottky diode	SMA	STMicroelectronics	STPS1L30A		
Q4	2STR1215 / NPN transistor	SOT23	STMicroelectronics	2STR1215		
Y1	32.768 kHz	XTAL-3	ECS	ECS-327-18-9X	Mouser	520-ECS-3276-18-9X
USB CONN1	USB-B type mini connector	SMD	Molex or equivalent	67503-1020	Mouser	538-67503-1020
J1	LCD connector and 16 x 2 alphanumeric LCD	16 x 1 Bergstrip	Oriole or equivalent	ODM16216-9SL3/AX	Oriole	
J2,J5	Jtag connector	10 x 2 header	3M electronic solutions division	30320-6002HB	Mouser	517-30320-6002
J3	2-pin Bergstrip	2 pin	Any		Samtec	TSW-102-23-G-S
J4,J9,SW2	3-pin Bergstrip	3 x1-pin Bergstrip	Any		Samtec	TSW-103-23-G-S

Table 5.   BOM (continued)

Reference designator	Component description	Package	Manufacturer	Manufacturer's ordering code / orderable part number	Supplier	Supplier ordering code
J6	DC power jack	3-pin through hole	Kobiconn	163-180PH-EX	Mouser	163-180PH-EX
J7	4-pin Bergstrip	4x1-pin Bergstrip	Any		Samtec	TSW-104-23-G-S
J8	Screw type connector	Through hole	Phoneix Contact or equivalent	1729131	Mouser	651-1729131
SW1,SW3	Pushbutton Switch	Through hole	E-Switch or equivalent	TL1105F250Q	Mouser	612-TL1105-250
D1,D2,D4,D5, D7	LED-Red	LED-3mm	Any			
C1,C2	10 pF	SMD0805	Panasonic - ECG or equivalent	ECJ-2VC1H100D	Digi-Key	PCC100CNTR-ND
C3,C4,C5,C6, C10,C13	100 nF	SMD0805	Panasonic - ECG or equivalent	ECJ-2VB1E104K or equivalent	Digi-Key	PCC1828CT-ND
C7	4.7 nF	SMD0805	Panasonic - ECG or equivalent	ECJ-2VB1H472K	Digi-Key	PCC472BNTR-ND
C12,C14,C15	10 µF	Case A	Vishay/Sprague or equivalent	293D106X96R3A2TE3 or equivalent	Mouser	74-293D106X96R3A2TE3
C20	1 nF	SMD0805	AVX	08051A102J4T2A	Farnell	1301711
C16,C17,C21, C22	1 µF	SMD0805	Vishay/Sprague	298D105X0050P2T	Digi-Key	718-1720-1-ND
C18	10 nF	SMD0805	Panasonic - ECG or equivalent	ECJ-2VB1H103K		PCC103BNTR-ND
R1,R2,R3,R10, R12,R14,R15, R17,R18,R19, R20,R22,R23, R30,R35, R38,R39,R61	10 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ103V	Digi-Key	P10KACT-ND

Table 5. BOM (continued)

Reference designator	Component description	Package	Manufacturer	Manufacturer's ordering code / orderable part number	Supplier	Supplier ordering code
R5	4.2 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6ENF4221V	Digi-Key	P4.22KCTR-ND
R6,R7,R50	220 Ω	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ221V	Digi-Key	P220ACT-ND
R21	100 Ω	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ101V	Digi-Key	P100ATR-ND
R24,R25	22 Ω	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ220V	Digi-Key	P22ATR-ND
R26	1.5 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ152V	Digi-Key	P1.5KATR-ND
R27,R28,R33	1 MΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ105V	Digi-Key	P1.0MATR-ND
R29	220 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ224V	Digi-Key	P220KACT-ND
R31	10 kΩ(ntc) 1/4 W	Through hole	Vishay	2381640	Farnell	1187031
R34	5.6 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6ENF5601V	Digi-Key	P5.60KCCT-ND
R36,R63	20 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ203V	Digi-Key	P20KACT-ND
R48	1 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ102V	Digi-Key	P1.0KATR-ND
R51,R52,R53	470 Ω	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ471V	Digi-Key	P470ATR-ND
R54	56 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ563V	Digi-Key	P56KACT-ND
R55	3.6 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ362V	Digi-Key	P3.6KACT-ND

Table 5.   BOM (continued)

Reference designator	Component description	Package	Manufacturer	Manufacturer's ordering code / orderable part number	Supplier	Supplier ordering code
R56	15 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6ENF1502V	Digi-Key	P15.0KCCT-ND
R57,R58	4.7 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ472V	Digi-Key	P4.7KATR-ND
R32	100 mΩ (2512)	2512	BOURNS	CRA2512-FZR100ELF	Farnell	1435952
R59,R62(OPTI OAL)	0	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEY0R00V	Digi-Key	P0.0ATR-ND
R60	100 kΩ	SMD0805	Panasonic - ECG or equivalent	ERJ-6GEYJ104V	Digi-Key	P100KACT-ND
R64	2 MΩ	SMD0805	RMCF 1/10 2M 1% R	RMCF 1/10 2 M 1 % R	Digi-Key	RMCF1/102MFRCT-ND

7 Abbreviations

Table 6. **Abbreviations**

Word	Abbreviation
LCD	Liquid crystal display
USB	Universal serial bus
RTC	Real time clock

8 Revision history

Table 7.   Document revision history

Date	Revision	Changes
06-Sep-2010	1	Initial release

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