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Getting started with the multifunctional expansion board based on operational amplifiers for STM32 Nucleo
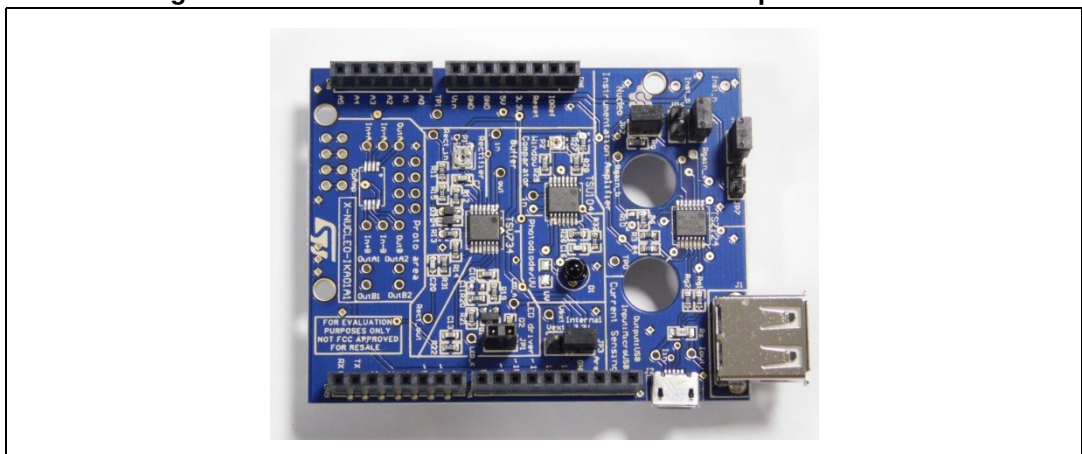
Introduction

The X-NUCLEO-IKA01A1 is a multifunctional expansion board based on operational amplifiers. It provides an easy-to-use and affordable solution for different multifunctional use cases with your STM32 Nucleo board. The X-NUCLEO-IKA01A1 is compatible with the Arduino™ UNO R3 connector, and supports the addition of other boards that can be stacked for enhanced applications with an STM32 Nucleo expansion board. It can be used as a analog front-end by conditioning signals as an actuator to drive LED or coils, or in a comparator architecture. Thanks to its current-sensing configuration, it allows current measurement of any device that has a USB port. For this configuration and the instrumentation amplifier configuration, a highly accurate operational amplifier (TSZ124) is used. The expansion board also contains Nanopower (TSU104) and Micropower (TSV734) operational amplifiers for mobile applications.

This user manual describes how to use the predefined configurations of the X-NUCLEO-IKA01A1 expansion board:

* Instrumentation amplifier structure
* Current sensing with or without USB port
* Photodiode/UV current sensing
* Buffer
* Full wave rectifier
* Constant current LED driver
* Window comparator

The expansion board is also equipped with one prototyping area is powered through the Arduino UNO R3 connectors.

Figure 1. X-NUCLEO-IKA01A1 multifunctional expansion board

Contents

1 Instrumentation amplifier configuration

The instrumentation amplifier configuration allows you to amplify a differential signal without impacting it thanks to the high impedance of operational amplifier input stage. Moreover, with the high accuracy resistors, this configuration features high rejection to common mode voltage.

1.1 Schematic diagram

Figure 2 below depicts the circuit schematic of the instrumentation amplifier configuration.

Figure 2. Instrumentation amplifier configuration circuit schematic
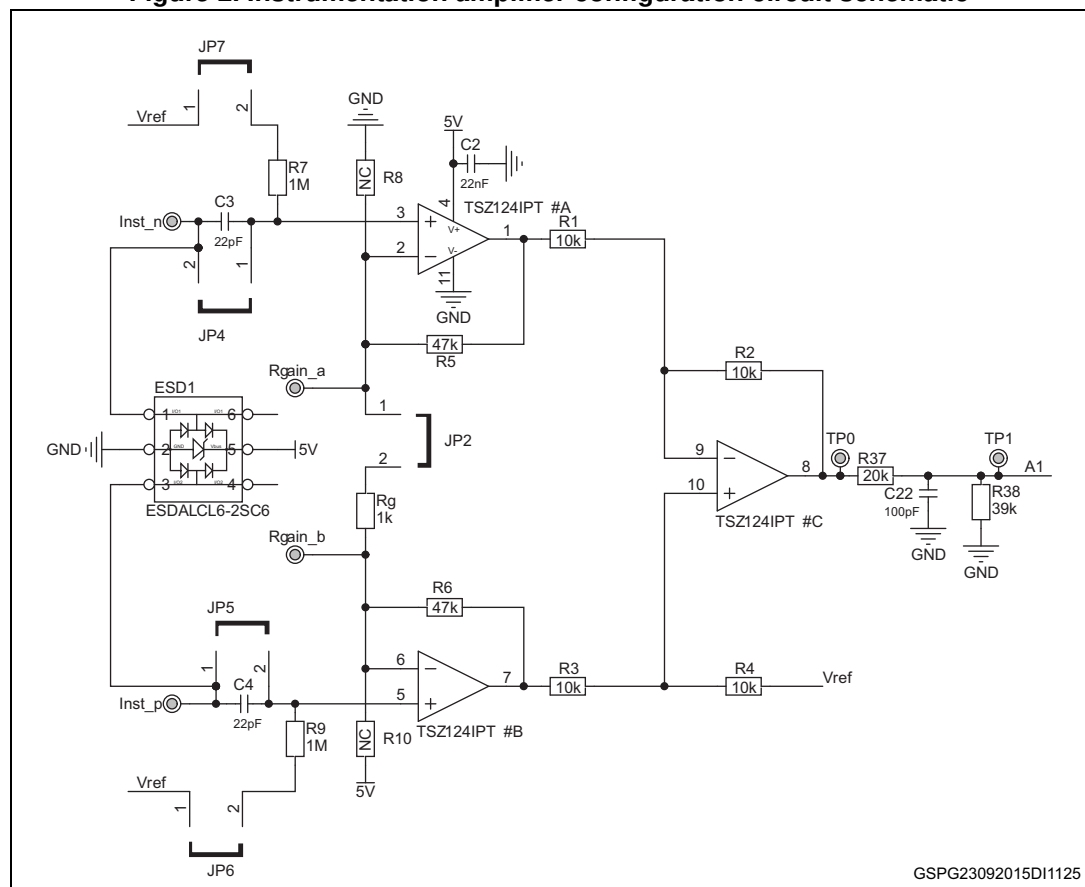
1.2 How to set up the board

The instrumentation amplifier section of the expansion board includes several jumpers for improved versatility. For this configuration, jumpers JP2, JP4 and JP5 must be mounted and JP6 and JP7 should not be mounted. If the input signal is capacitive, a bias voltage needs to be added. This configuration is possible by mounting jumpers JP6 and JP7. Once jumpers have been set in the required configuration, the differential must be connected to pins Inst_n and Inst_p.

1.3 Theoretical output

The theoretical output voltage is defined by the following formula:

Equation 1

$$\text{Vout} = \left(\text{Inst}_p - \text{Inst}_n\right)\left(1 + 2\frac{R5}{Rg}\right) * \frac{R38}{R37 + R38}$$

The operational amplifiers used for this configuration are used with a 5 V power supply. Thus in order to obtain a range limited to 3.3 V to avoid any damage on the microcontroller side, a divider bridge has been implemented. This additional structure is recognizable by the last term in the above formula (composed of R37 and R38). Thanks to this structure, a DC 5 V output voltage is reduced to 3.2 V.

The gain of this instrumentation amplifier structure is defined by:

Equation 2

$$\text{Gain} = \left(1 + 2\frac{R5}{Rg}\right)\frac{R38}{R37 + R38} = \left(1 + 2 * \frac{47k}{1k}\right)\frac{39k}{20k + 39k} = 62.8$$

Note that it is also possible to increase the gain of the configuration by adding an external resistor on the Rgain_a and Rgain_b pins. When an external resistor is used to change the gain, jumper JP2 must be unmounted.

With this circuitry, the maximum frequency of the input signal is 850 Hz based on the op-amp GBP and the circuit gain.

Equation 3

$$\max frequency = \frac{GBP}{Gain * 10} = \frac{400k}{47 * 10} = 850Hz$$

The factor 10 is taken in order to take margin and to properly amplify the signals at the maximum frequency.

1.4 Software and measurements

The output voltage of the instrumentation amplifier is connected to the pin A1 of the Arduino UNO R3 connector. The X-CUBE-ANALOG1 software available on www.st.com allows users to measure this voltage.

2 Current sensing configuration

The current sensing configuration allows monitoring of the current that is consumed by an application. On this expansion board, the operational amplifier is set to a high-side current sensing structure. This means that the current is measured close to the supply voltage, thus before the application. *Figure 3* illustrates this concept.

Figure 3. High-side current sensing application principle
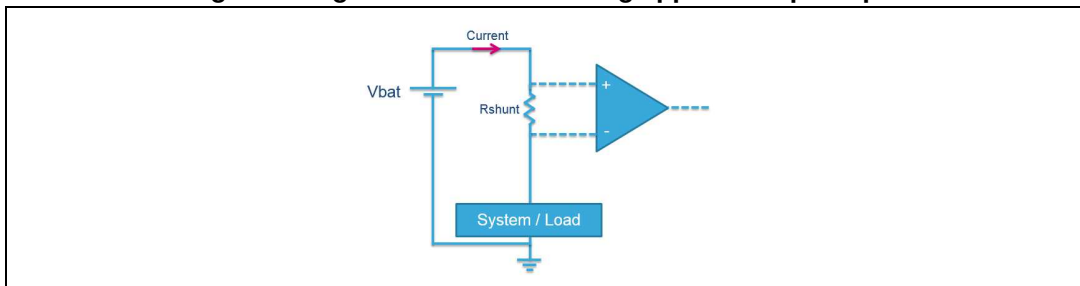
2.1 Schematic diagram

Figure 4, shows the circuit schematic of the current sensing configuration.

Figure 4. Current sensing configuration circuit schematic
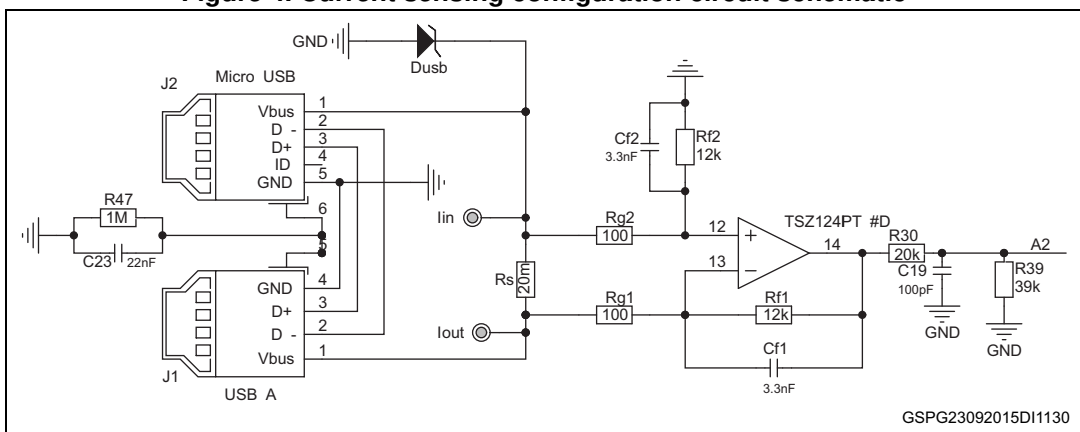
2.2 How to set up the board

With this expansion board, users can measure the current of a USB-powered device or any 5 V application. It is important not to go beyond 5 V in order to avoid operational amplifier damage. To help protect the circuit, an ESDAULC6-1U2 unidirectional ESD protection device has been implemented.

Monitoring USB-powered device current: connect the charger (wall adapter or PC) to the Micro-USB port. Then connect the bottom USB port to the required device.

Monitoring other application current: it is also possible to measure the current of applications that are not USB powered. The power supply voltage should be connected to I_{in}, and I_{out} should be connected to the power supply voltage pin of the application.

2.3 Theoretical output

The output voltage of the operational amplifier is proportional to the measured current, as the following formula illustrates:

Equation 4

$$Vout = Rs * I * \frac{Rf1}{Rg1} * \frac{R39}{R39 + R30}$$

Therefore,

Equation 5

$$I = \frac{Vout}{Rs * \frac{Rf1}{Rg1} * \frac{R39}{R39 + R30}}$$

Similar to the instrumentation amplifier configuration, the operational amplifier for this configuration is used with a 5 V power supply voltage. Thus, in order to obtain a range limited to 3.3 V avoid damage on the microcontroller side, a divider bridge has been added. This additional structure is recognizable by the last term in the above formula (composed by R30 and R39). Thanks to this structure, a DC 5 V output voltage is reduced to a 3.2 V.

Note that the maximum frequency of this circuit is limited to 330 Hz based on operational amplifier GBP and the circuit gain.

Equation 6

$$\max frequency = \frac{GBP}{Gain * 10} = \frac{400k}{120 * 10} = 330Hz$$

## 2.4 Software and measurements

The output voltage of the instrumentation amplifier is connected to pin A2 of the Arduino UNO R3 connector. The X-CUBE-ANALOG1 software, available on www.st.com, allows users to measure this voltage.

Note that with this predefined configuration, it is possible to measure up to 2.08 A. If a higher current is drawn through the application, the operational amplifier will be saturated and thus its output voltage will not reflect the real current.

The following table shows the correspondence between measured current, output voltage and LSB on ADC.

Table 1. Output parameter values for current sensing configuration

Current (A)	Output voltage of operational amplifier	Voltage after divider bridge (at A4 node)	Number of LSBs with 12-bit ADC
0.1	240 mV	159 mV	197
0.2	480 mV	317 mV	394
0.5	1.20 V	793 mV	985
1.0	2.40 V	1.586 V	1969
1.5	3.60 V	2.380 V	2954
2.0	4.80 V	3.173 V	3938

3 Buffer configuration

The buffer configuration allows users to connect a high output impedance circuit to a low input impedance circuit without disturbing the signal. This function is possible thanks to the high impedance of the operational amplifier input stage and the operational amplifier output capabilities. The operational amplifier used for this configuration is the TSV734, which has a minimum output current of 40 mA.

3.1 How to set up the board

In order to use the buffer configuration on the expansion board, users simply connect their signal to the "in" pin on the buffer section of the board. The output signal can be retrieved on the "out" pin in the same board section. The output voltage of the operational amplifier is not intended to be connected to any microcontroller input on the expansion board since this configuration is most often used before another circuit.

3.2 Theoretical output

The output voltage of the operational amplifier is equal to its input voltage:

$V_{out}=V_{in}$

Note that this equation is correct as long as the input voltage stays between 0 V and 3.3 V (the power supply voltage of the operational amplifier).

4 Full wave rectifier

The full wave rectifier configuration allows rectification of an input signal. This means that by defining a reference voltage with a potentiometer, all signals below it will become positive. When the voltage goes above the reference, the output voltage will not change.

4.1 Schematic diagram

Figure 5 shows the circuit schematic of the full wave rectifier configuration.

Figure 5. Full wave rectifier configuration circuit schematic
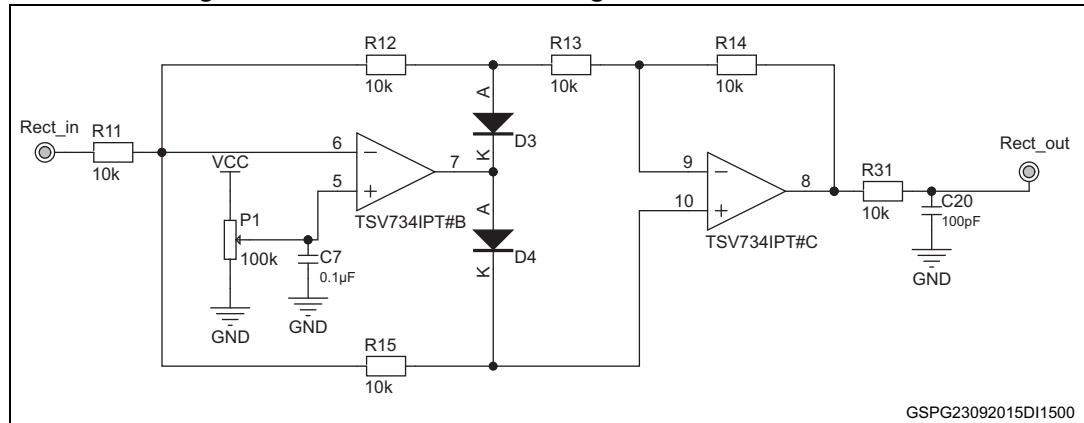
4.2 How to set up the board

The input signal must be connected to the Rect_in pin within the rectifier expansion board section. Similarly, the output signal is available on the Rect_out pin. The output voltage of the rectifier structure is not intended to be connected to any microcontroller input on the board since this configuration is most often connected to another analog block.

4.3 Theoretical output

Thus, we have two formulas to define this configuration:

If $V_{in} < V_{ref}$: $V_{out} = 2V_{ref} - V_{in}$

If $V_{in} \geq V_{ref}$: $V_{out} = V_{in}$

The V_{ref} voltage can be tuned using the P1 potentiometer.

4.4 Measurement example

Input voltage = -1 V

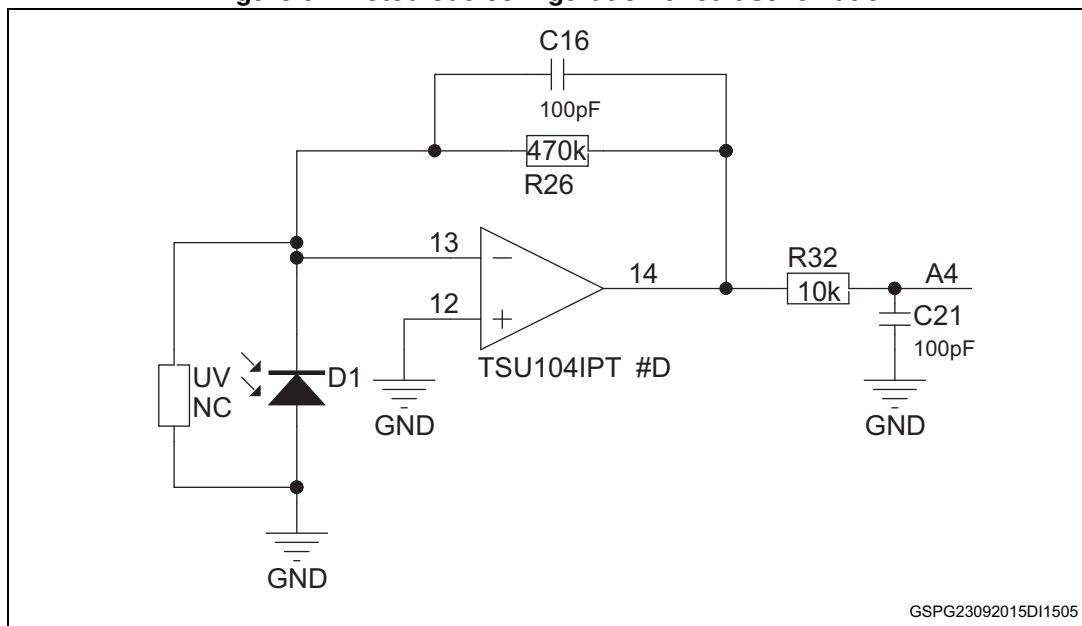V_{ref} = 0.5 V

Thus, V_{out} = 2 V

5 Photodiode/UV sensor

This configuration can be used to monitor the ambient light and, for example, trigger an action when a threshold level is reached.

5.1 Schematic diagram

Figure 6 depicts the circuit schematic of photodiode sensor configuration.

Figure 6. Photodiode configuration circuit schematic

5.2 How to set up the expansion board

This configuration does not require any setup. Only the output voltage is reported. This voltage is available on pin A4 of the Arduino UNO R3 connector and PC1 of the ST morpho connectors (not mounted in the expansion board).

5.3 Measurement example

Here, three examples have been selected.

- Case 1: The board is placed inside a closed box. V_{out} = 33 mV (V_{ol} of the operational amplifier which is saturating)
- Case 2: The board is in ambient light V_{out} = 420 mV
- Case 3: The sensor is below a light source V_{out} = 3.272 V (V_{oh} of the operational amplifier which is saturating)

Depending on the needs of the application, it can be interesting to have current with better sensitivity to darkness. In this case, it is recommended to increase the value of the R26

resistor. When current is flowing through a resistor which has a large value, it is mandatory to use an operational amplifier with a very low input current offset. This is why operational amplifiers with a CMOS input stage, such as the TSU104, are required.

5.4 Additional possible use

With this configuration it is also possible to connect a UV (ultraviolet) sensor in order to derive the UV index instead of ambient light. A free footprint is available on the expansion board to enable this possibility.

Note that if using a UV sensor, R26 should be aligned to the UV sensor datasheet recommendation and the photodiode must be removed.

For additional details on the analog conditioning circuit used for a high impedance sensor and especially on a UV sensor, refer to application note AN4451 "Signal conditioning for a UV sensor", available on www.st.com.

6 LED driver configuration

The LED driver configuration allows users to drive an LED with a constant current. As shown in *Figure 7*, when the forward voltage varies, the current and thus the light intensity is highly variable.

Figure 7. Forward current vs. forward voltage
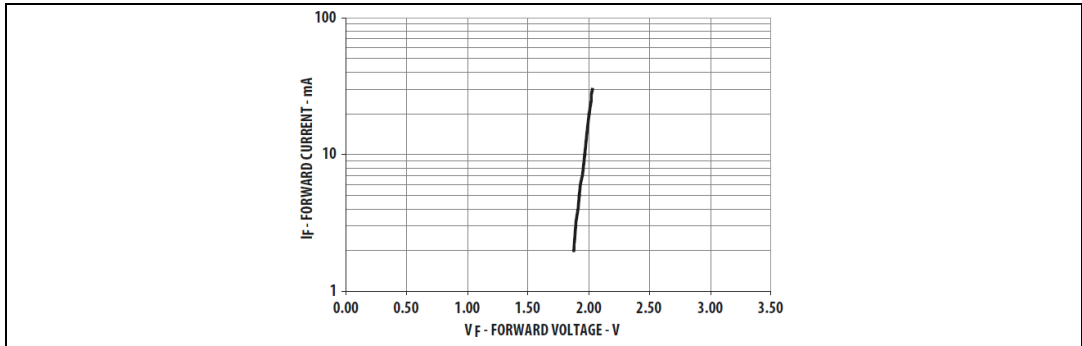
This is why it is recommended to control the LED by current, and thus this architecture is useful.

6.1 Schematic diagram

Figure 8 shows the circuit schematic of the LED driver configuration.

Figure 8. LED driver configuration circuit schematic

6.2 How to set up the board

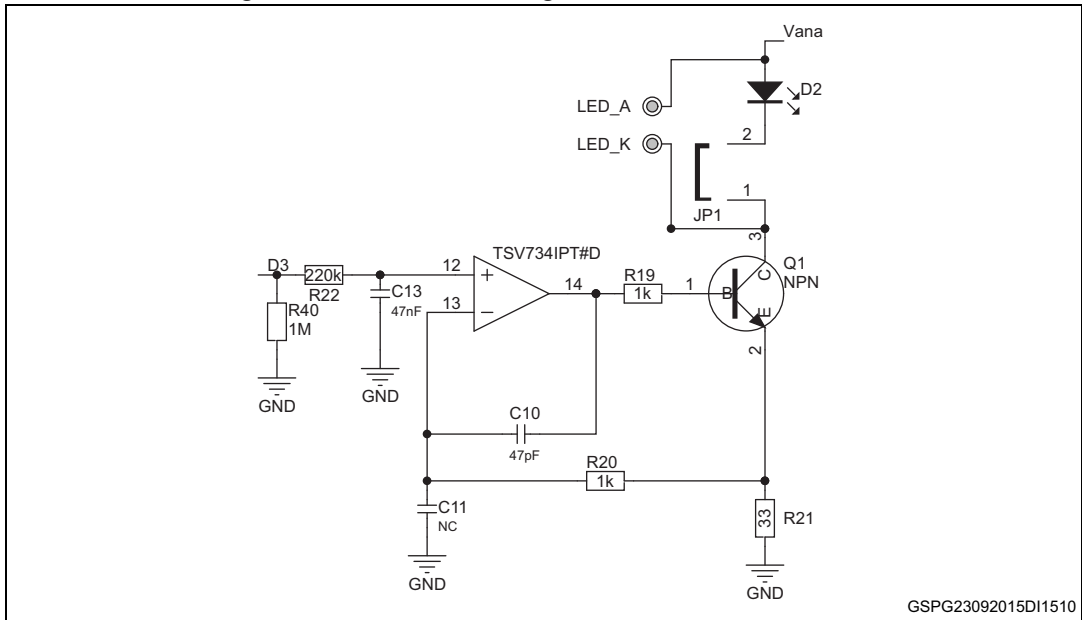There is no specific connection to make the application function, but a PWM input signal is required on pin D3 of the Arduino UNO R3 connector.

One or several external LEDs in parallel can be added in order to drive several LEDs at the same time. LEDs can be connected to pin LED_A and LED_K on the expansion board. Moreover, if needed it is possible to disconnect the mounted LED by removing jumper JP1.

Note also that the supply voltage of the LED can be either external or based on the internal 3.3 V. If several LEDs are in parallel or a higher power is needed, it is recommended to place the V_{cc} jumper in the V_{ext} position and use an external power supply.

Depending the PWM duty cycle, the LED intensity will vary. For a duty cycle of 5% (5% of the time at high state), the intensity will be low. On the other hand, for a 70% duty cycle, the light intensity will be high.

7 Window comparator configuration

The window comparator configuration allows the user to compare a signal to two threshold voltages. When the signal is out of the required voltage range, the output of the operational amplifier toggles.

7.1 Schematic diagram

Figure 9 shows the schematic of the window comparator configuration.

Figure 9. Window comparator configuration circuit schematic
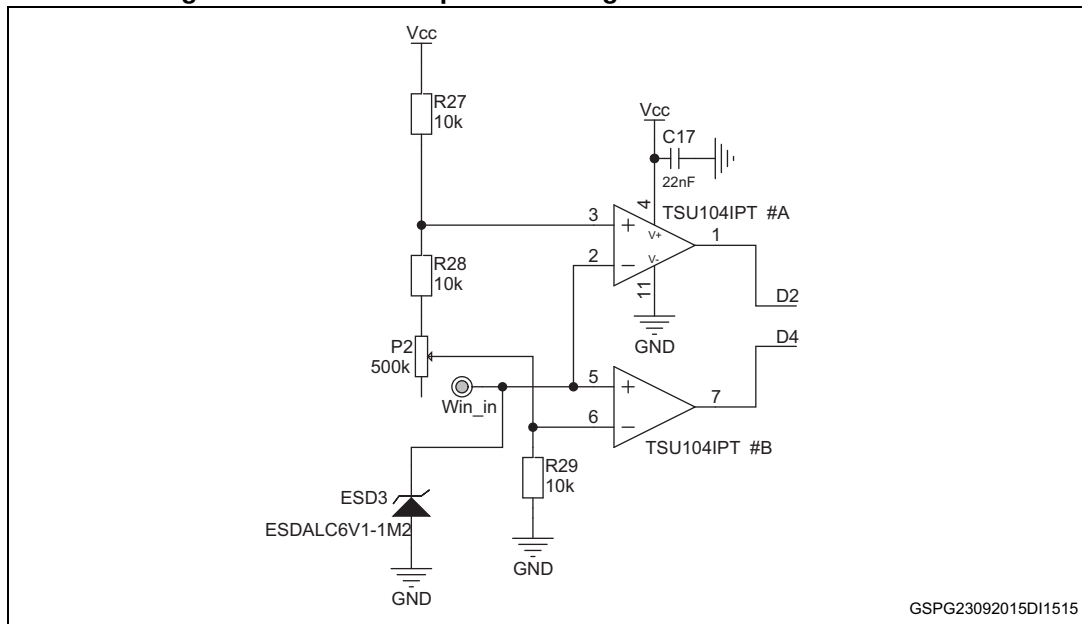
7.2 How to set up the board

To set up the expansion board, connect the signal to the "in" pin within the window comparator section. The high and low threshold voltages then need to be defined by tuning the P2 potentiometer.

Threshold voltages:

Equation 7

$$\text{Vth}_{low} = \frac{R29}{R29 + P2 + R28 + R27} * 3.3V$$

Equation 8

$$Vth_{high} = \frac{R29 + P2 + R28}{R29 + P2 + R28 + R27} * 3.3V$$

- If P2 equals its maximum value (500 k):
  - V_{th_low} = 62 mV
  - V_{th_high} = 3.238 V
- If P2 equals its minimum value (0):
  - V_{th_low} = 1.1 V
  - V_{th_high} = 2.2 V

From a software standpoint, the D2 and D4 pins on the Arduino UNO R3 connectors or PA10 and PB5 on the ST morpho connectors (not mounted in the expansion board) must be monitored.

7.3 Theoretical output

The operational amplifier output toggles when the signal is out of the specified window.

$V_{in} < V_{threshold\_low}$:
　　D2: high state
　　D4: low state

$V_{threshold\_low} < V_{in} < V_{threshold\_high}$:
　　D2: high state
　　D4:high state

$V_{threshold\_high} < V_{in}$:
　　D2: low state
　　D4: high state

Figure 10 depicts the different states:

Figure 10. Window comparator explanation
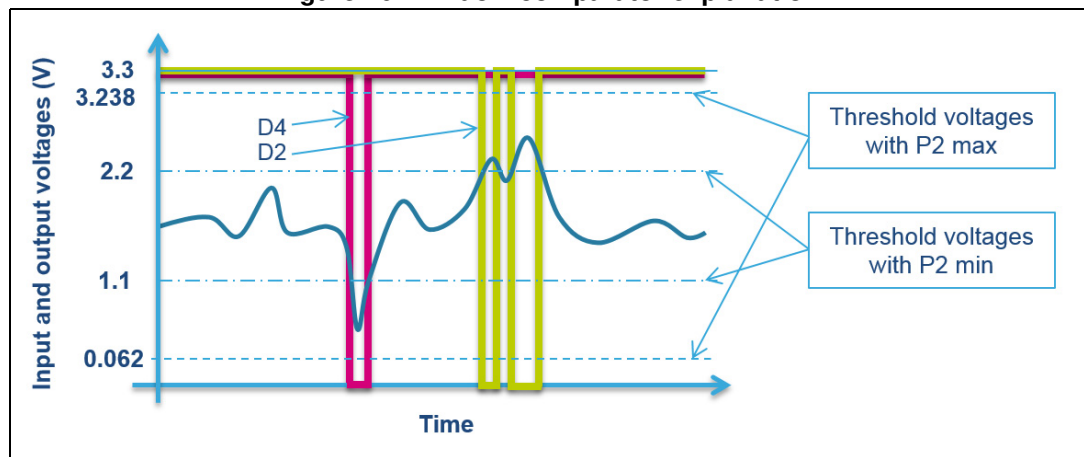
8 Prototyping area

A prototyping area has been implemented in order to perform small additional configurations.

It allows the user to connect an expansion board, components on input and output, and a divider bridge for a 5 V to 3.3 V conversion, as shown on the following figure.

Figure 11. Prototyping area
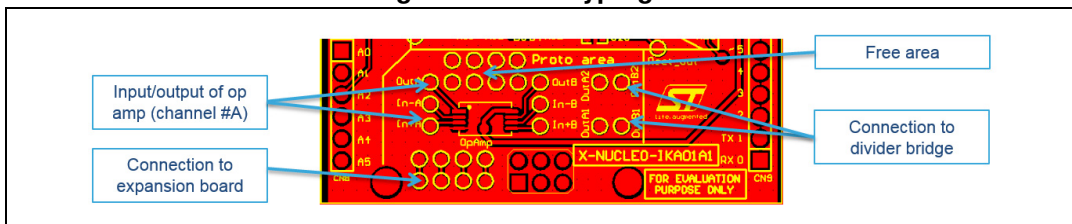
Note also that the supply voltage of the operational amplifier can be either external or based on the internal 3.3 V. If a high output voltage and thus a higher power supply voltage is required, it is recommended to place jumper JP3 in the V_{ext} position.

9 Scenario examples

9.1 Current sensing: motor outside of standard operation

To avoid damage to an application, it can be useful to know how much current is going through the motor. With the high-side current sensing or instrumentation amplifier configuration, the current can be monitored. The motor can be in different configurations: stopped, in standard operating condition or in overload. By sensing the current, it is easy to detect the configuration of the motor. Thus we can set some flag to alert the user or the microcontroller. If the current is too low or too high, the output of the window comparator will toggle. Then, for example, when the motor is in a standard operating range, the LED can illuminate with a low intensity, but if the current is out of range, the LED can blink with a high intensity. The threshold current can be adjusted thanks to potentiometer P2 with the window comparator configuration. Of course, an LED is used here as an example in order to obtain a visual response, but it can also be useful to capture the interruption at the output of the window comparator. By doing this, it would be possible to stop the motor or to perform another action in order to prevent damage to the application.

This scenario uses the following configuration available on the expansion board:

- Current sensing or instrumentation amplifier structure
- Window comparator
- LED driver

Note that with the instrumentation amplifier configuration, an external shunt resistor is required. But it will allow you to sense the current in both clockwise and counter-clockwise directions.

9.2 Strain gauge

Having some strain gauge composing a Wheatstone bridge, the instrumentation amplifier can help you to detect deformation. These deformations can be, for example, for structure monitoring, for torque monitoring or even to develop your own scale for weight measurement.

9.3 Electromyogram

An electromyogram (EMG) application can help users monitor muscle electrical activity. It can be used to trigger an action by contracting your arm, for example.

The signal generated by the muscle is a very small AC signal. This is why it is mandatory to amplify it. Then its envelop must be detected. Envelop detection should be performed with an accurate rectifier in order to avoid losing diode voltage. Thus is why an active configuration with operational amplifiers is used. Once the signal is rectified, we just need to filter the signal. It can be done on the microcontroller side, by software or with its integrated operational amplifier. *Figure 12* shows the signal conditioning for an EMG application.

Figure 12. Electromyogram signal conditioning
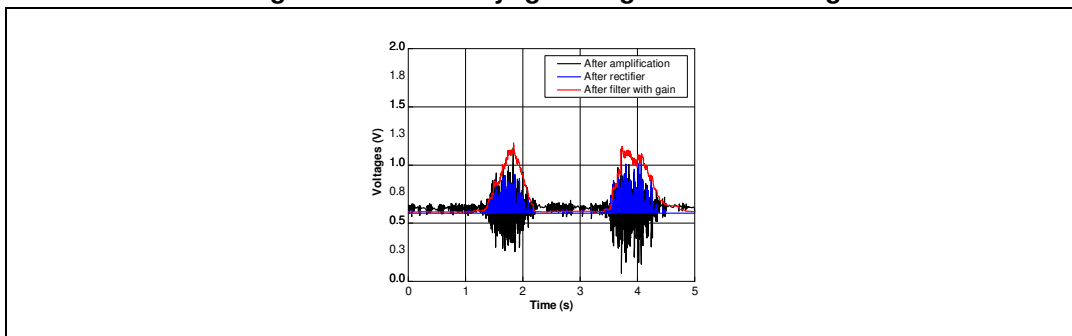
This scenario uses the following configuration available on the expansion board:

- Instrumentation amplifier structure
- Full wave rectifier
- Window comparator to perform an action depending on muscle activity level

9.4 Body detection

With the use of an external passive infrared (PIR) sensor, it is possible to light a room with the different configurations available on the expansion board. The signal generated by the PIR sensor will be amplified. Then this analog signal can be converted to a digital signal thanks to the window comparator. When the sensor detects motion, based on an emissivity difference the output of the comparator will toggle. The comparator output can be coupled to the photodiode sensor which indicates whether it is day or night. This functionality allows lighting a room only at night.

Note that the LED driver configuration contains a slot for plugging in additional LEDs in parallel if. for example, you wish to provide light in several directions at the same time.

This scenario uses the following configuration available on the expansion board:

- Instrumentation amplifier structure (used in standard gain configuration)
- Photodiode sensor
- Window comparator
- LED driver

High-pass and low-pass filtering can be performed by software or with microcontroller-integrated operational amplifiers or even with external components on the expansion board prototyping area.

For more details on PIR signal conditioning, please refer to application note AN4368 "Signal conditioning for pyroelectric passive infrared (PIR) sensors", available on www.st.com

10 Operational amplifiers on the expansion board

Table 2 summarizes the main parameters of the operational amplifiers used on this analog expansion board.

Table 2. Operational amplifier main parameters

	Configuration on the expansion board	I_{cc} per amplifier (µA)	GBP (kHz)	V_{io} max (µV)	Comments
TSZ124	Instrumentation amplifier, current sensing	31	400	5	5 V operational amplifier Very high accuracy Available in QFN package
TSV734	Buffer, rectifier, LED driver	59	850	200	5 V operational amplifier High accuracy Available in QFN package
TSU104	Photodiode structure, window comparator	0.6	8	3000	5 V operational amplifier Nanopower Available in QFN package

Note: *Current consumption is mentioned per amplifier. The TSZ124, TSV734 and TSU104 contain four operational amplifiers in the same package.*

Figure 13. X-NUCLEO-IKA01A1 circuit schematic (1 of 2)
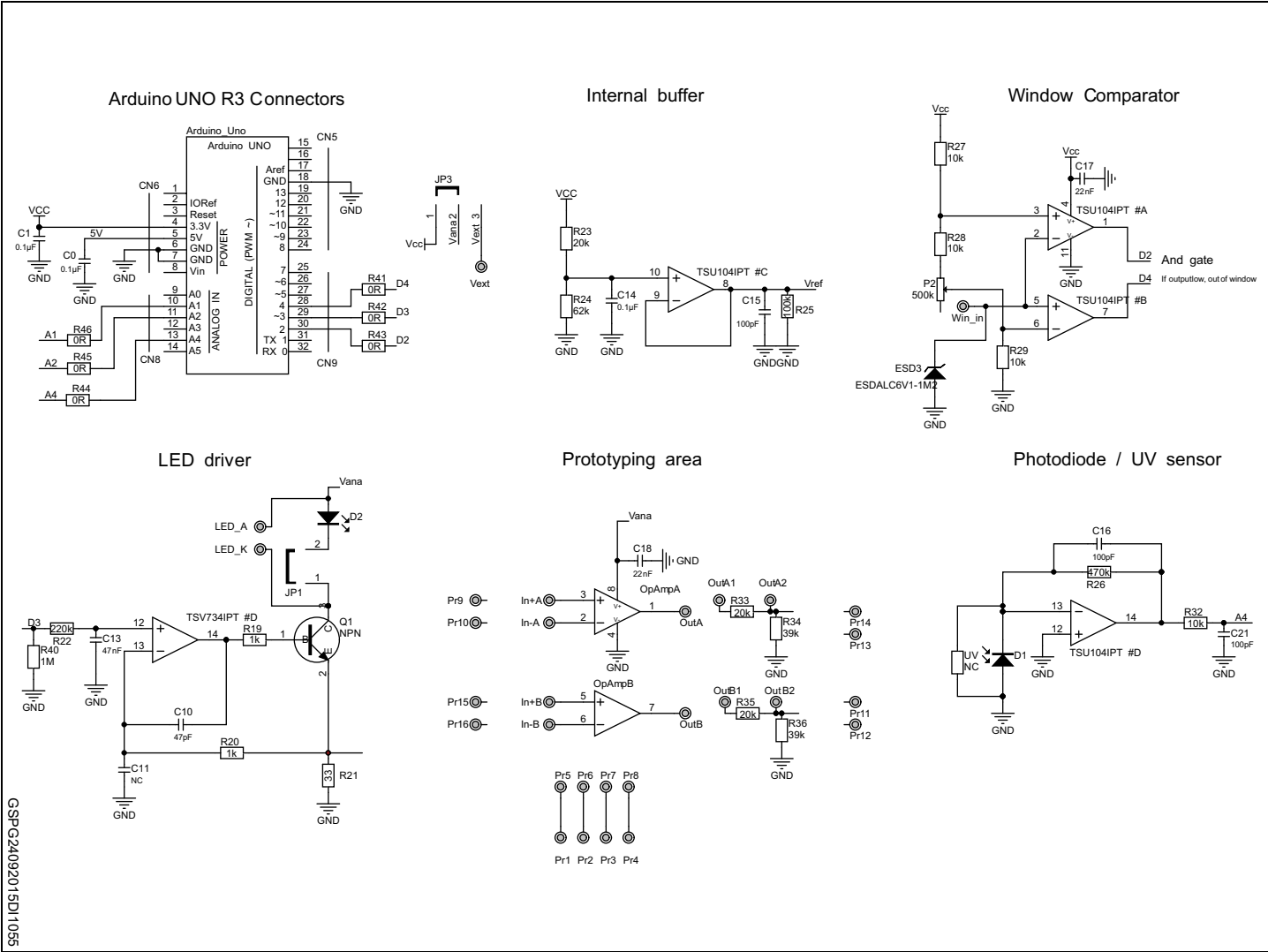
GSPG24092015D11055

Figure 14. X-NUCLEO-IKA01A1 circuit schematic (2 of 2)

Instrumentation amplifier

High side current sensing configuration

Buffer

Full wave Rectifier

12 Bill of material (BOM)

Table 3. Bill of material (part 1)

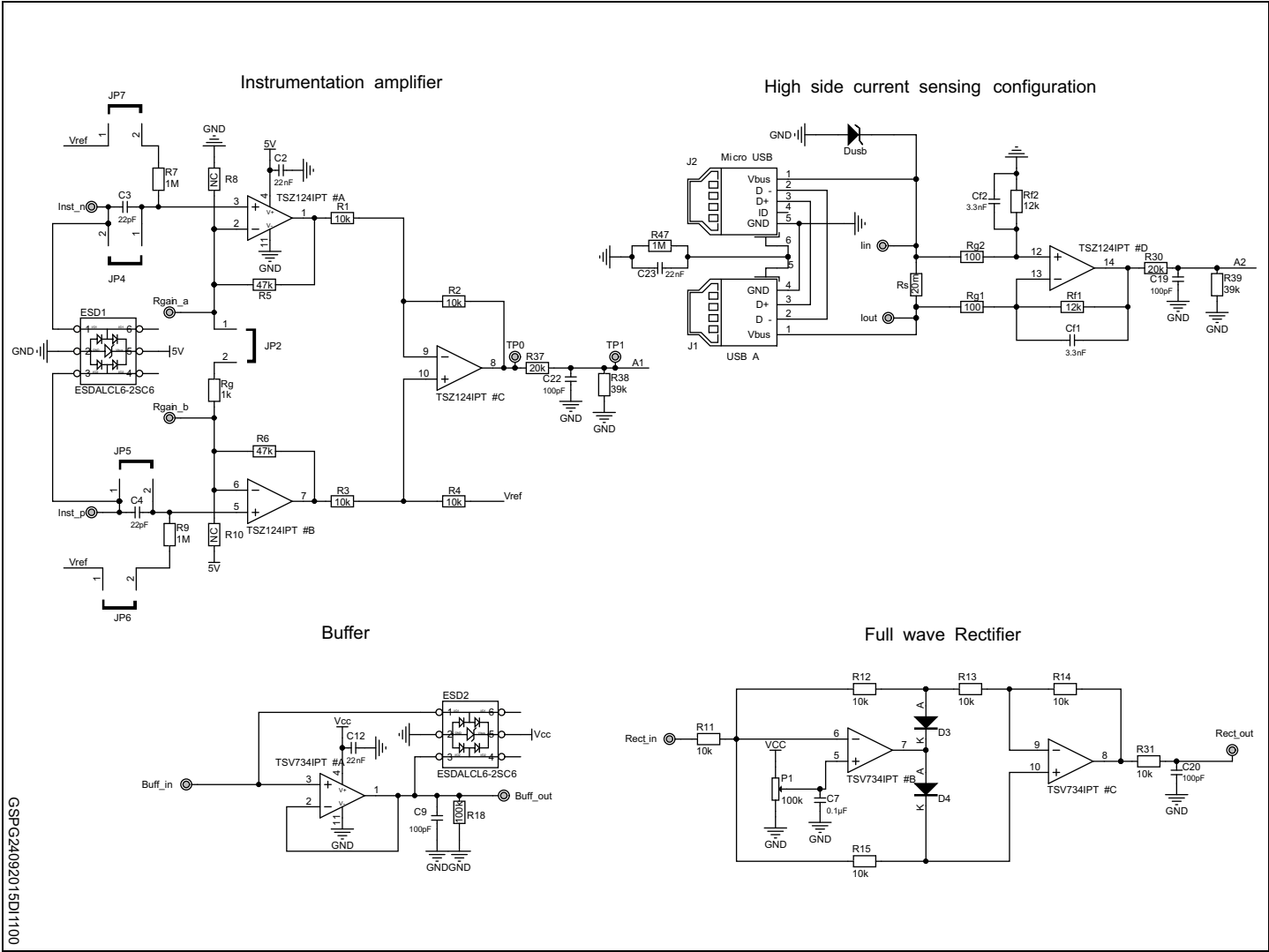| Item	Qty	Ref.	Part / value	Voltage Watt Ampere	Package
1	4	C0, C1, C7, C14	0.1 µF		SMD0603
2	5	C2, C12, C17, C18, C23	22 nF		SMD0603
3	2	C3, C4	22 pF		SMD0603
4	7	C9, C15, C16, C19, C20, C21, C22	100 pF		SMD0603
5	1	C10	47 pF		SMD0603
6	1	C11	Not mounted		SMD0603
7	2	R8, R10	Not mounted		SMD0603
8	1	UV	Not mounted		SMD0805
9	1	C13	47 nF		SMD0603
10	2	Cf1, Cf2	3.3 nF		SMD0603
11	1	D1	Photodiode		Through hole
12	1	D2	LED	Orange / Red	SMD0603
13	2	D3, D4	Diode	BAT48JFILM	SOD-323
14	1	Dusb	USB protection	ESDA7P60-1U1M	1610
15	2	ESD1, ESD2	ESD protection dual	ESDALCL6-2SC6	SOT23-6L
16	1	ESD3	ESD protection	ESDALC6V1-1M2	SOD882
17	1	J1	USB A connector		
18	1	J2	micro USB B connector		
19	6	JP1, JP2, JP4, JP5, JP6, JP7	TSH 2.54 mm		TSH 2,54
20	1	JP3	TSH 2.54 mm		TSH 2,54
21	5	JP1, JP2, JP3, JP4, JP5	Jumper		
22	1	P1	Potentiometer 100 k		
23	1	P2	Potentiometer 500 k		
24	4	Pr1, Pr2, Pr3, Pr4	connector		
25	10	LED_A, LED_K, OutA1, OutA2, OutB1, OutB2, Rgain_a, Rgain_b, TP0, TP1,	connector		
26	10	Buff_in, Buff_out, Iin,Iout, Inst_n, Inst_p, Rect_in, Rect_out, Vext, Win_in	connector		

Table 3. Bill of material (part 1) (continued)

Item	Qty	Ref.	Part / value	Voltage Watt Ampere	Package
27	1	Q1	NPN transistor	3STR1630	
28	4	R1, R2, R3, R4	Resistor	10 k	SMD0603
29	2	R5, R6	Resistor	47 k	SMD0603
30	4	R7, R9, R40,R47	Resistor	1 M	SMD0603
31	10	R11, R12, R13, R14, R15, R27, R28, R29, R31, R32	Resistor	10 k	SMD0603
32	2	R18, R25	Resistor	100 k	SMD0603
33	3	R19, R20, Rg	Resistor	1 k	SMD0603
34	1	R21	Resistor	33	SMD0603
35	1	R22	Resistor	220 k	SMD0603
36	5	R23, R30, R33, R35, R37	Resistor	20 k	SMD0603
37	1	R24	Resistor	62 k	SMD0603
38	1	R26	Resistor	470 k	SMD0603
39	4	R34, R36, R38, R39	Resistor	39 k	SMD0603
40	2	Rf1, Rf2	Resistor	12 k	SMD0603
41	2	Rg1, Rg2	Resistor	100	SMD0603
42	1	Rs	Resistor	20 M	SMD0805
43	1	TSU104IPT	Operational amplifier	TSU104IPT	TSSOP14
44	1	TSV734IPT	Operational amplifier	TSV734IPT	TSSOP14
45	1	TSZ124IPT	Operational amplifier	TSZ124IPT	TSSOP14
46	1	CN5	2.54 mm pitch (10 pins)		
47	2	CN6, CN9	2.54 mm pitch (8 pins)		
48	1	CN8	2.54 mm pitch (6 pins)		

Table 4. Bill of material (part 2)

Item	Manufacturer	Orderable part number	Additional notes
1			
2			
3			
4			
5			
6			Not mounted
7			Not mounted
8			Not mounted
9			
10			
11	Vishay	TEFD4300F	
12			
13	ST	BAT48JFILM	
14	ST	ESDA7P60-1U1M	
15	ST	ESDALCL6-2SC6	
16	ST	ESDALC6V1-1M2	
17			
18			
19			
20			
21			JP3 jumper must be set on "Internal 3.3V" position
22			
23			
24			CAN BE REMOVED / NOT MOUNTED
25			CAN BE REMOVED / NOT MOUNTED
26			
27	ST		
28			
29			
30			
31			
32			