Design (E) 314 — Ontwerp (E) 314

Project Definition — Projek Definisie

2024

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This document is NOT the final version. Further information will be added throughout the course.

Version History

Version	**Date**	**Changes**
0.1	13 Feb 2024	- Initial project specification and guide
0.2	28 Feb 2024	Updates for Demo2+: - Section 2.2: Table 1 - Updated UR2, UR3, UR5, UR7 - Section 3.5: Updated sensor and usage information - Section 4.7: Temperature and light sensor information added - Section 4.8: Button command interface expanded and clarified - Section 4.10.1: Updated Table 3, Added Table 4, TX/RX Examples added - Added section 4.10.2 - values reported by UART - Section 5.1: Table 5 - Pin 14 description clarified - Section 5: Updated Demo 2 description, Table 6, Table 7
0.3	12 Mar 2024	- Further updates/clarification for Demo 2, Table 6, Table 7 - Preliminary report task definitions and rubric, section 6
0.4	28 Mar 2024	Updates for Demo 3 - Table 6, Table 7 - User requirement UR6 - Sections 3.4, 3.6, 3.7, 3.8, 4.8, 4.10.2, 4.11, 5.4.
0.5	08 Apr 2024	Updates for Demo 3 - UR2.1, UR2.2, UR2.11, UR2.12 updated and clarified - see Table 1 - Sections 2.5, 3.4, 3.6 - Figure 7, 4.8, 4.10.1 + Table 3, 4.11.
0.6	23 Apr 2024	Updates for Demo 3 - Sections 4.10.1 - Table 3, 4.10.2 Lx_d range, 4.11 - Figure 11. - UR2, table 6
0.7	3 May 2024	Updates for Demo 4, Final report Rubric (section 7) - UR2, UR4, UR5. - Sections 2.5, 3.9, 4.8, 4.10.1, 4.11, 4.12 - Tables 6, 7

1 Purpose of this Document

The purpose of this document is to:

- Provide students with a clear **overview and scope** definition of the project;
- Provide clear **project requirements**, that will be used to test the hardware during demonstrations;
- Provide some assistance in understanding certain **concepts/information** about the components that will used in the project;
- Identify the **critical design choices** that the student should solve.
- Provide **guidance for producing the final report** using an assessment rubric.

For other information about the course ***schedule*** and ***administration***, please see the Module Framework available on SUNLearn.

2 Project Overview

2.1 PV System Efficiency Monitor

Many people in South Africa rely on solar photovoltaic (PV) power as an alternative energy source for their homes and businesses. This is especially becoming an attractive solution, since the return on investment (a performance measure used to evaluate the efficiency or profitability of an investment) has significantly improved over the last five years, given the reduced costs of PV modules, inverters and batteries.

However, dirty/soiled PV modules can seriously affect the PV system power output, which will ultimately result in a financial opportunity cost. Many PV system owners fail to realise the negative impact of dust on PV module power production, which ultimately affects the return on investment.

To their defense, PV system owners are not always sure when to clean their PV system modules, especially if the system is roof mounted, making it more difficult to see the condition (clean vs. dirty) of the PV modules.

As an engineer, your task is to build a device that will help house-hold PV system owners to determine the percentage of reduced PV power output due to dust/soiling. This will help PV system owners to determine when it will be worth going to the effort of cleaning their PV modules to restore maximum power output.

2.2 User Requirements

The project will consist of designing, building and testing a multi-functional device, with the primary objective of reporting on PV module power output given the effects of dirt/soil on the PV module:

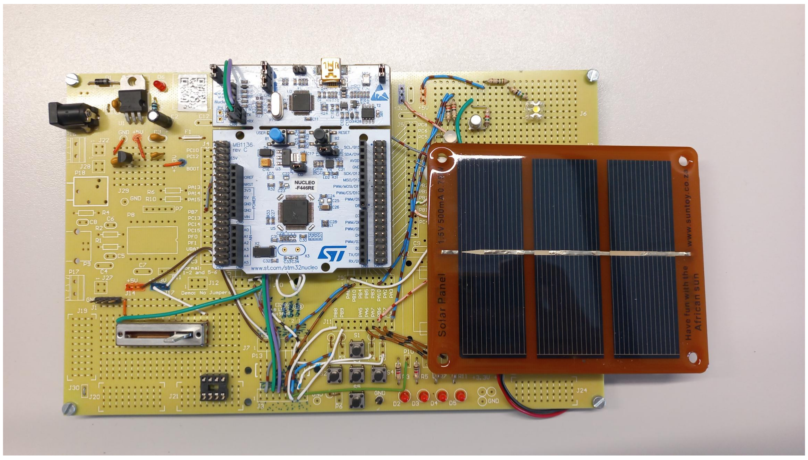


Figure 1: An example of the prototype board.

The requirements that should be fulfilled are listed in Table 1.

Table 1: User requirements for the project.

UR#	Description
UR1	The system shall generate its own regulated supplies from a nominal 9 V-12 V battery or power supply. 1. 5 V supply voltage 2. 3.3 V supply voltage 3. LED (D6) must turn on to indicate that the 5V regulated voltage is present.
UR2	PV module measurement: Measure the PV module's operating points by changing the value of the adjustable load. Two adjustable loads will be used: a) a manual multi-turn potentiometer, and b) an automated active load. For the manual case, a time of 1 min will be allowed to adjust and measure. For the automated case, a time of 10 s will be allowed to adjust and measure. Specifically, the device must measure from the PV module: 1. The voltage [Volt] delivered by the PV module: V_{PV} 2. The current [Ampere] delivered by the PV module: I_{PV} 3. The MPP voltage [Volt]: V_{MPP} 4. The MPP current [Ampere]: I_{MPP} Using the measured V_{MPP}, I_{MPP} values above to calculate: 5. The MPP power [Watt] of the PV module: P_{MPP} 6. The maximum efficiency, as described in section 2.5, of the PV module: P_{EFF} The above modes (manual or automatic) of operation must be activated by either of the following: 7. UART command input: (a) send SP measurement command to start the measurement sequence, and (b) send SP measurement command again to stop the measurement sequence as per section 4.10. 8. Bottom pushbutton: (a) Press bottom-button for start- measurement command to start the measurement sequence, and (b) press bottom-button again to end the measurement sequence, as per section 4.8. LED 9. LED (D2) must flash rapidly (100 ms on, then 100 ms off) to indicate that the measurement sequence is in progress. 10. LED (D2) must stop flashing (stay on) to indicate that the measurement sequence has ended.
	Continued on next page

	Table 1 – continued from previous page
UR#	**Description**
	Data retrieval/display 11. UART command input: The 2 data points, V_{MPP} and I_{MPP}, and two calculated values, P_{MPP} and P_{EFF}, must be sent via UART to the device requesting information within 100 ms after receiving the stop measurement command, as per section 4.10. The LCD screen must continuously display the V_{PV}, I_{PV}, and P_{PV} during the measurement cycle, as per the format in section 4.11, and update to show the V_{MPP}, I_{MPP}, P_{MPP}, and P_{EFF} values instead of the V_{PV}, I_{PV} after receiving the stop measurement command. 12. Push-button: The 2 data points, V_{MPP} and I_{MPP}, and two calculated values, P_{MPP} and P_{EFF}, must be sent via UART to the device requesting information within 100 ms after the stop measurement button pressed, as per section 4.8, The LCD screen must continuously display the V_{PV}, I_{PV}, and P_{PV} during the measurement cycle, as per the format in section 4.11, and update to show the V_{MPP}, I_{MPP}, P_{MPP}, and P_{EFF} values instead of the V_{PV}, I_{PV} after the stop measurement button pressed.
UR3	Environment Measurement: The device must provide the ambient temperature, solar panel temperature, and light intensity the board is exposed to. Specifically, the device must measure: 1. Using the analogue temperature sensor, the ambient temperature [°C]: T_a 2. Using the digital temperature sensor, the solar panel temperature [°C]: T_{sp} 3. Using the photodiode, the light intensity [Lux]: Lx_d The above mode of operation must be activated by either of the following: 4. UART command input: (a) send EN measurement command to start the measurement sequence, and (b) send EN measurement command again to stop the measurement sequence, as per section 4.10. 5. Top pushbutton: (a) Press top-button to start the measurement sequence, and (b) press top-button again to end the measurement sequence, as per section 4.8. LED 6. LED (D3) must flash rapidly (50 ms on, then 50 ms off) to indicate that the measurement sequence is in progress. 7. LED (D3) must stop flashing (stay on) to indicate that the measurement sequence has ended. Data retrieval/display 8. UART command input: The 3 datapoints listed above must be sent via UART to the device requesting information within 100 ms after receiving the stop measurement command, as per section 4.10. The LCD screen must display the T_a, T_{sp}, and Lx_d, as per section 4.11. 9. Push-button: The 3 datapoints listed above must be sent via UART to the device requesting information within 100 ms after stop measurement button pressed, as per section 4.8. The LCD screen must display the T_a, T_{sp}, and Lx_d, as per section 4.11.
UR4	Cleanness indicator: Device must indicate whether cleaning is necessary when the most recent efficiency, P_{EFF}, has been determined. An indication of “to clean” or “no-cleaning” will be provided ***immediately after a PV module measurement*** was completed (UR2) by:
	Continued on next page

	Table 1 – continued from previous page
UR#	**Description**
	LED 1. LED (D5) must flash rapidly (100 ms on, then 100 ms off) to indicate that the PV panel must be cleaned. 2. LED (D5) must be on continuously if the panel is still clean enough.
UR5	Calibration: System owner must be able to calibrate the device. This calibration will only take place when the PV module is clean (without dust/soiling). The calibration procedure must be possible to do using either the manual or automated approaches detailed in UR2. The sequence consists of an Environment Measurement (UR3) followed immediately by an PV module measurement (UR2) resulting in a baseline measurement representing 100% efficiency. The calibration sequence must complete within 10 s. The calibration is activated by: 1. UART command input: Send CA measurement command to start the measurement sequence, which ends automatically when done, as per section 4.10. 2. Right pushbutton: Press right-button to start the measurement sequence, which ends automatically when done, as per section 4.8. LED 4. LED (D4) must flash rapidly (200 ms on, then 200 ms off) to indicate that the calibration measurement sequence is in progress. 5. LED (D4) must stop flashing (stay on) to indicate that the calibration measurement sequence has ended.
UR6	LCD Display Modes: The device will have multiple display modes as defined per section 4.11. The LCD should update immediately - i.e. with no apparent delay or flickering - on receiving commands via button or UART inputs. When automatically cycling through display options in Mode 4 the LCD should dwell in each mode for 2 seconds.
UR7	The device shall use a UART connection, in both transmit and receive modes. The device shall operate in 8 data bits, one odd parity bit and one stop bits configuration, at a data rate of 115200 baud. The UART information, both transmitted and received, shall be formatted as per section 4.10.1. The system shall receive commands as defined in section 4.10.2 and respond accordingly. 1. No sooner than 100 ms after startup, and no later than 500 ms after startup, the device will send the board owner's student number, formatted as per section 4.10.1. 2. The device shall report the following information via UART after receiving the appropriate command: (a) The most recent PV panel parameters, V_{MPP}, I_{MPP}, P_{MPP}, and P_{EFF}. (b) The current ambient temperature, solar panel temperature, and level of the ambient light intensity, T_a, T_{sp}, and Lx_d. (c) The last recorded / calculated MPP power and efficiency of the PV module, P_{MPP} and P_{EFF}.
UR8	Real-Time-Clock (RTC): The device shall keep time using its built-in Real-Time Clock (RTC)

ⓘ *For more detail about how these specifications will be tested, see section 5.*

You will be provided with a ***baseboard*** and an STM32 microcontroller board. The microcontroller board will connect to headers, which have to be soldered onto the baseboard. Some connections to the power supply and UART are already made on the baseboard, but you will have to design certain elements of the system and make decisions about wiring and electrical connections.

You will also have to devise suitable tests to show that your system conforms to the mentioned requirements and specifications. Your design decisions and justification, along with test methods and test results should be documented in a final report, which is due at the end of this module.

Your system will be tested using automated demonstration stations, which will test whether your system meets these system specifications. It is thus important that you devise and perform similar tests to what the demo station will run, ***before*** you present your board for a demonstration.

> ⚠ *The demonstration should not be used to substitute for your own testing since you will be penalised for multiple demonstrations.*

The rest of this document describes the specifications in more detail, the hardware that you will be required to use and interface to (section 3), as well as software considerations (section 4), and finally the test methods that will be used to test your board (section 5).

2.3 UART communication

The system should use the UART port connected to the PC (**and the TIC for Demo purposes** see section 5.3) to report measurements and system statuses and to receive configuration commands. The full details of the communication protocol are given in section 4.10.

2.4 Application command interface

The system should implement an application command interface allowing the user to select the operating mode and modify system parameters. The command input interface shall be via the push buttons, and UART. The output interface shall be via the UART. Selected measurements and calculated values will be displayed on the LCD. The system's current state shall also be indicated using the four debug LEDs.

2.5 Solar panel I/V curve and efficiency

PV panel characteristic I/V curve and the calculated P/V curve are shown in figure 2. The measurement points V_{OC}, I_{SC}, and maximum power point (MPP) with associated MPP voltage and MPP current are also indicated.

To measure a PV panel over the full operational range a variable load must be placed on the panel and varied from low resistance (short circuit condition) to high resistance (open circuit condition). The power is simply calculated as $P = I \times V$ for each measured I/V combination. The highest power value calculated defines the maximum operating power point of the panel - $P_{MPP_{measured}}$.

As the light input on the panel changes, both the V_{OC} and I_{SC} points shift, causing the I/V curve to change. The points also shift as the temperature of the panel changes.

$P_{MPP_{calibrated}}$ is the MPP power of the PV panel at a known Lux value and known PV panel temperature (usually Standard Temperature Conditions (STC)).

Thus, for a fair comparison of $P_{MPP_{measured}}$ to $P_{MPP_{calibrated}}$, we must normalise the measured output of the PV module relative to the conditions of the environment. For example, it would not be a fair comparison to compare PV module efficiency at 30000 LUX, if the original calibration took place at 90000 LUX, since this would automatically result in a lower intensity and therefore also lower calculated efficiency value. Also, a higher PV panel temperature (above STC of 25°C) results in lower PV module output.

> ⓘ *During the final demonstration in this project we cannot guarantee STC and therefore the calibration power must also be normalized w.r.t. temperature (see temperature normalizing equation), and the Lux during calibration saved for future measurements.*

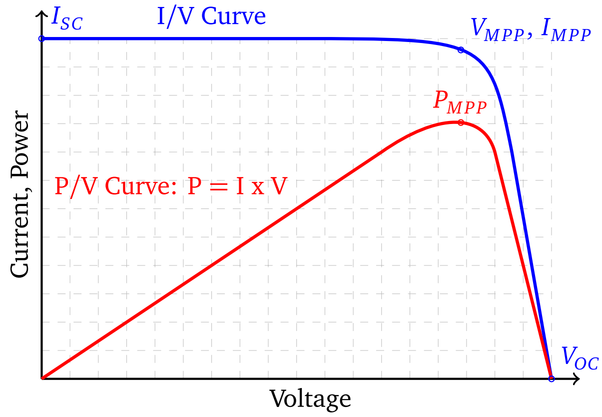


Figure 2: Photovoltaic panel's characteristic I/V and P/V curves.

The $P_{MPP_{measured}}$ value should thus be normalised, $P_{MPP_{normalized}}$, with respect to the incoming LUX and the PV panel temperature during measurement, since both these values will affect PV module performance. The *power efficiency* of the panel when measured is therefore defined as:

$$Efficiency = \frac{P_{MPP_{normalized}}}{P_{MPP_{calibrated}}} \times 100\%$$

where: $P_{MPP_{normalized}}$ is $P_{MPP_{measured}}$ normalised with respect to temperature and lux.

To normalise the measured power to PV panel temperature, the effect of temperature on a PV panel is described with the following formula:

$$P_{norm_T} = \frac{P_{measured}}{[1 + \beta(T_{PVpanel} - T_{STC})]}$$

where:

1. $P_{measured}$ = the measured power output [W].
2. P_{norm_T} = Normalised PV power output unaffected by temperature (i.e. Standard Testing Conditions at 25°C), given the amount of irradiance [W]
3. β is the temperature coefficient, which can be assumed as −0.004 for the Seeed manufactured PV module used.
4. $T_{PVpanel}$ is the measured PV panel temperature [°C].
5. T_{STC} is the 25°C Standard Testing Conditions temperature of [°C].

To normalise the measured PV module power w.r.t. the incoming LUX and the original calibrated LUX value, we can use the following formula:

$$P_{normalized} = P_{norm_T} \frac{LUX_{calibration}}{LUX_{measured}}$$

where:

1. $P_{normalized}$ = the measured power output [W].
2. P_{norm_T} = the normalised PV power output w.r.t. the LUX value originally used to calibrate the system [W].
3. $LUX_{calibration}$ = the original LUX value at which the calibration took place [W].
4. $LUX_{measured}$ = the measured LUX value at which the measurement took place [W].

3 Hardware

The STM32 microcontroller board that you will use is the STM32F411RE. It has a NUCLEO-64 form factor which allows it to stack through either the Arduino headers or the Morpho connectors (on top). The STM board will stack on top of the prototyping baseboard that you will use. To simplify the connection choices and possible solder problems, the following pre-determined design choices were made:

- The digital and analogue ground pins of the microcontroller board are hard-wired to the main board ground
- The NUCLEO-STM32F411RE is provided with main board power via the E5V pin (CN7-6) and F1 (fuse or link).
- To assist in building the system, some peripherals have pre-defined layout positions. These include:
  - 5 V power regulation circuit (3.3 V power regulation circuit has a predefined prototyping area where it should be built)
  - Debug / user LEDs
  - Debug / user push button switches
  - Test interface connector (used for Demonstrations)
  - Miscellaneous connectors that might be applicable to this project, eg. power socket, USB, screw terminal, audio jack.

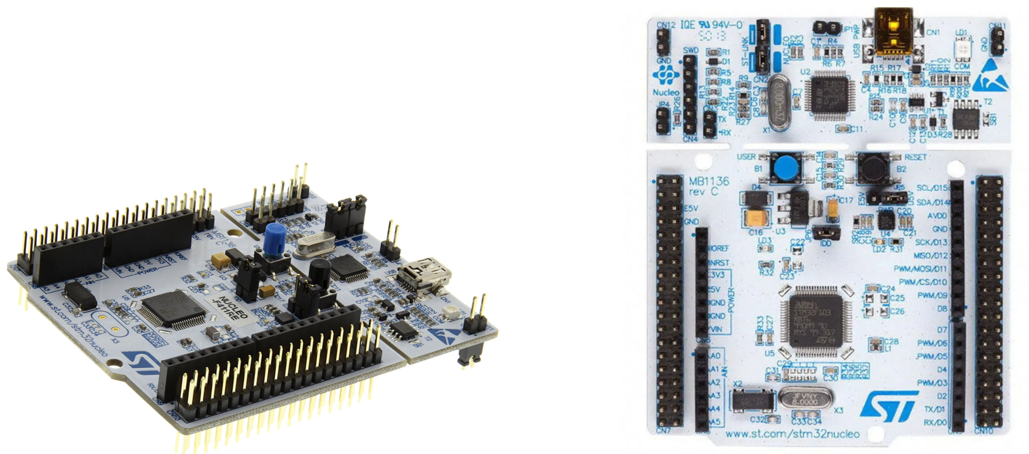


Figure 3: NUCLEO-F411RE development board [2]

3.1 Power Supply

The board must be supplied with a nominal 9 V Battery source (but you can use a bench power supply during development and testing, instead of a real battery). Your project will require you to implement both a 5 V and a 3.3 V power regulated supply. The 5 V circuit is pre-designed and shown in figure 4.

The 5 V power supply circuit on the baseboard uses a standard 7805 regulator (U1) in a TO220 package to regulate the input down to 5 V. The 5 V power is routed to 3 jumpers (J14, J16 and J25, each providing 3 pins for wiring). An LED (D6) circuit is provided to show that a voltage is present on the 5 V line.

> *You will have to determine the minimum supply voltage input required as well as the maximum allowable input voltage. You must also make sure that the regulator (U1) is thermally stable (by calculating the expected heat dissipation and adding thermal heat sinking hardware, if required). You must understand the role of each component in the power supply circuit.*

You will have to design the 3.3 V supply circuit yourself using the MCP1700 regulator, provided in a TO-92 package. Available on the baseboard, there is a 3.3 V power rail routed to 3 jumpers (J17, J18 and J26, each providing 3 pins for wiring).

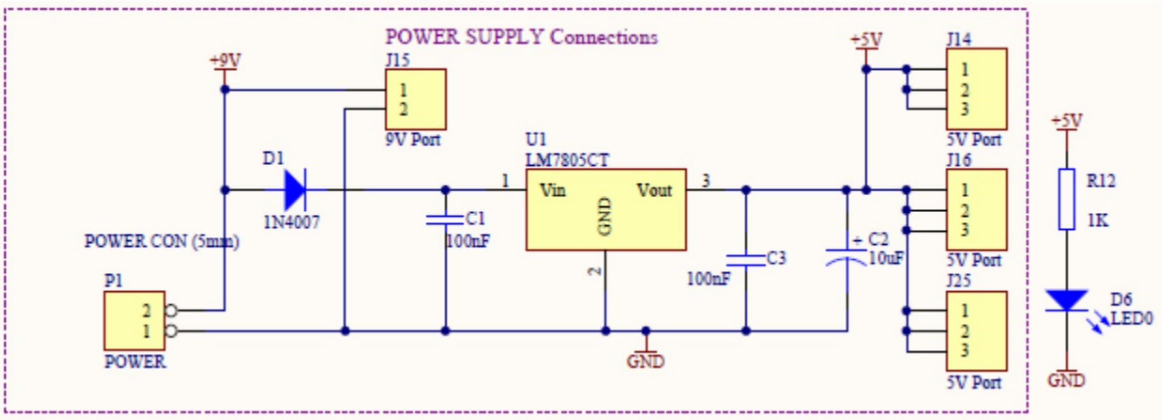
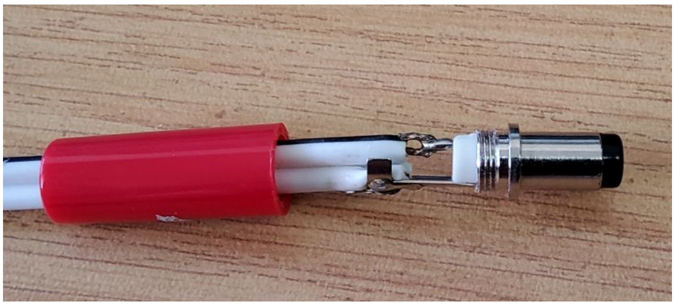


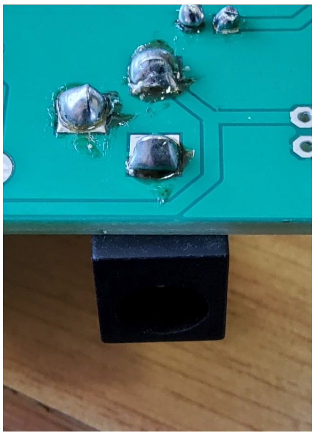
Figure 4: 5 V Power supply circuit diagram

> ⚠ *Note that the 3.3 V supply should NOT be connected to the NUCLEO-STM32F411RE's own 3.3 V regulated voltage!*

On your NUCLEO board, the `VIN` pin should be left floating. To select board power, move the JP5 jumper on the NUCLEO-STM32F411RE to the `E5V` (external power) position, from the `U5V` (USB power) position. Power your board using a bench power supply, set to 9 V, and connect the power to your board using the barrel jack and wire provided.



(a) Barrel jack with wires soldered



(b) Barrel socket soldered on to the PCB

Figure 5: Power connector solder connections.

> ⚠ *Do not power your baseboard and NUCLEO system using the USB power from the PC, as this could damage the USB port. It is safer to keep the jumper in the `E5V` position and use an external 9 V power supply. See more detail on this in "UM1724 User manual" PDF document, section 6.3.2 on page 21 - 22.*

> ⓘ *Jumper J30 must be bridged on student boards to allow the test station to supply the student board with a nominal 9 V during demonstrations. Jumper J31 must be bridged to supply 9 V to the regulator.*

> ⓘ *The fuse, F1, must be bridged on student boards to supply the STM32 board with 5 V.*

3.2 Push button inputs

Space for five push buttons are provided on the board. They are logically arranged to represent up, down, left, right and middle. You need to wire up the buttons to be active low, and read as inputs by the GPIO pins of the Nucleo board. They will also need to be connected to the TIC as per Table 5.

> *These pins are also floating on the baseboard - they are not connected to any other signal. You need to wire them to the pins/signals you wish to use.*

> *Remember to limit the current through the buttons by using a series resistor, otherwise you will damage your regulator circuit!*

3.3 Debug / user LEDs

Space for four LEDs plus series resistors are provided for display and/or debug purposes. You will have to calculate an appropriate value for the series resistors to limit the LED current to an acceptable level. These LEDs must be driven by four GPIO pins of the Nucleo board. The details of the state that is represented by each LED (or LED combination) is given in section 4.9.

> *These pins are also floating on the baseboard - they are not connected to any other signal. You need to wire them to the pins/signals you wish to use.*

> *Remember to limit the current through the LEDs by using a series resistor, otherwise you may damage the processor output pins!*

3.4 LCD Display

Note: Due to supplier stock shortages, there are 4x different LCD screens.

- LCD: Micro Robotics: LCD1602-YB-5V
  - For these LCDs, the 5V power supply connection can be utilised and no PCB changes are required.
  - The contrast control resistors are already integrated on the LCD module. Leave Pin 3 as not-connected (NC).
- LCD: Micro Robotics: LCD1602-WB-33V
  - For these LCDs, the 5V power supply connection can be utilised and no PCB changes are required.
  - You have to design and populate the contrast controlling resistors on the mainboard.
- LCD: TOPWAY: LMB162A, Micro Robotics: LCD1602-YB-33V
  - For these LCDs, the PCB must be altered so that a 3.3V supply is provided and not a 5V supply. Read further to see PCB changes required.
  - The contrast control resistors are already integrated on the LCD module. Leave Pin 3 as not-connected (NC).

These screens are very similar from a hardware perspective, with some minor differences to take note of. From a software perspective, the screens operate in the same manner, since the screens all have the Hitachi HD44780 controller/driver or a compatible one.

Each screen has a 16x2 character LCD display. You can use a male header strip to solder the LCD to your base board. The LCD connections on the PCB are pre-connected to the required VCC (5 V) and GND. Note that both LCDs are 3.3 V compatible, but the baseboard is powering it from 5 V.

LCD Power supply:

The 5 V supply is suited for the Micro Robotics LCD screen, as the 3.3 V changes are only to provide enough voltage drop (it generates a negative voltage for the LCD panel).

However: for the TOPWAY LCD screen, it is necessary to supply LCD pin 2 (VDD) with 3.3 V. This can be accomplished in several ways, but the following is recommended as a safe way to provide a 3.3 V supply:

1. Cut/Separate the PCB 5V track as illustrated in Figure 6. Use a sharp blade to do this.
2. Connect the separated track, which supplies the LCD screen's pin 2 (VDD), to the 3.3 V track.
3. Be careful and ensure that the GND, primary 3.3 V and primary 5 V lines are not connected by doing a continuity test. (Otherwise all the components on the 3.3 V line will now receive a 5 V value.)
4. Power the board after confirming the connections are fine.

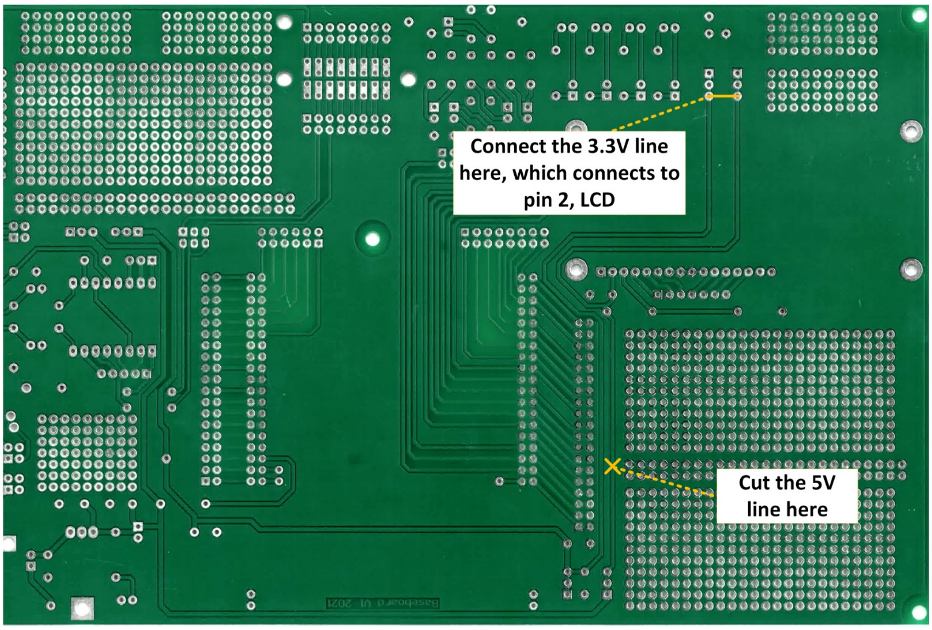


Figure 6: PCB change required to accommodate the TOPWAY and YB-33V LCD screen's preferred 3.3V supply. (Not required for the Micro Robotics 5V and WB-33V LCD screens.)

Remaining pin connections

You will need to connect the interface LCD pins electrically to your NUCLEO pins, using wires, from P19.

> *You should only require 7 GPIO pins. You can have all LCD GPIOs in Output mode as you will not be reading data from the LCD.*

You will have to use the LCD in 4-bit (nibble) interface mode, since the LCD's data lines D0 - D3 are hard wired to ground.

The LCD further has a contrast adjustment pin, for which you should design the two resistors R8 and R9 required to provide a good contrast on the display. Note: This is only necessary for the Micro Robotics WB-33V LCD screen, since the other three types already have internal/local resistors that take care of the contrast setting.

> ⚠ *Do not connect the backlight A and K terminals directly between VCC (5 V) and ground! It is still an LED and it requires a current limiting resistor in series (keep the current below 10 mA). The typical voltage drop across the backlight can be as high as 4.1 V, but be safe and measure it in your circuit.*

If desired, you can connect the LCD backlight for increased visibility. However, there is no specific allowance for connecting the backlight (LED) to the PCB, you will have to connect wires to the A and K solder terminals (Pin 15 and 16). Do not connect the backlight A and K terminals directly between VCC (5 V) and ground! It is still an LED and it requires a current limiting resistor in series (keep the current below 10 mA).

3.5 Temperature sensing

The system will measure the ambient and PV panel temperatures using an analogue and digital temperature sensor respectively.

> ⚠ *Both these temperature sensors are sensitive devices, please handle them with care and do not expose them to harsh conditions or over voltages.*

For the ambient temperature, the analogue sensor (LM235) together with the built-in ADC of the microcontroller should be used. The sensor needs power and ground and provides an analogue output. Please see the LM235 datasheet uploaded on SUNLearn for more information about using the device. The analogue output of the sensor must also be connected to the TIC (see section 5.1). THis sensor must be mounted so that the ambient (room) temperature is measure by it.

For the solar panel temperature the digital sensor (LMT01) connected to two GPIO pins. This sensor has a two wire interface that you connect using two GPIO pins and a resistor, please see the device datasheet on SUNLearn for more information. This sensor uses a digital pulse train to communicate the measured temperature within a timing window. You will have to count the pulses using one of the GPIO pins. By using the GPIO pin as a "clock" input, through configuring one of the STM32F411 timers, the pulse counting can be accomplished. Alternatively configuring the GPIO pin with an external interrupt and counting in software is also possible. In both cases you will probably need a second timer to handle the window timing. When the solar panel is available, this sensor will b mounted to the panel to measure the solap panel temperature.

> ⓘ *For Demo 2 the digital temperature sensor will also measure the ambient temperature since the solar panels are not available yet.*

3.6 Light sensing

The system will measure the light intensity the PV panel is exposed to a photo sensitive diode-based sensor. Measurements are to be made with an Osram SFH 203 PIN photodiode and an operational amplifier by creating a photo-current-to-voltage converter circuit. The output voltage should be wired to an ADC pin of the STM32. The output should also be wired to TIC J13 pin 12 as detailed in Table 5. The diagram shown in figure 7 illustrates the recommended design for the photo-current-to-voltage converter circuit. The only design choice you have to make is choosing an appropriate feedback resistor R_f. The MCP602 has two op-amps built in. For this circuit you will only need to use one of them.

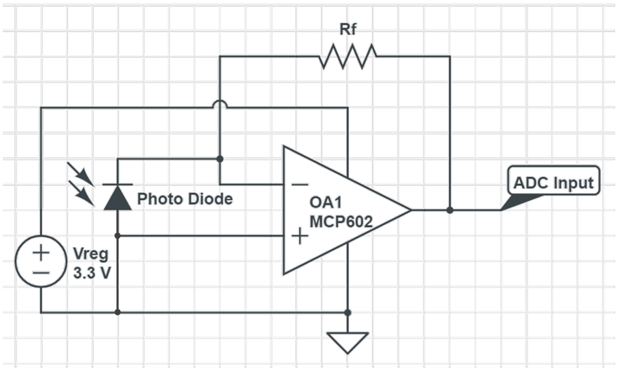


Figure 7: Photo diode with Op-Amp circuit diagram - in Photovoltaic mode.

3.7 PV panel voltage and current measurement

> ⚠ *The PV panel has a open-circuit voltage, V_{OC}, that is above 3.3V - it can be up to 8V. Due to the variability in manufacturing you need to check what your panel's V_{OC} is and design your voltage divider circuits accordingly.*

The system will use a representative PV panel that will be used as a reference PV source for the system. When exposed to light, the PV module will have power available to be delivered. It will be necessary to construct a circuit that will measure the output voltage V_{PV} and current I_{PV} of the PV module. The current will have to be obtained as a voltage measurement, so that both the panel voltage and current values can be provided as an analogue voltage input to the STM32 ADC pins. The suggested circuit for voltage and current measurement is shown in figure 8.

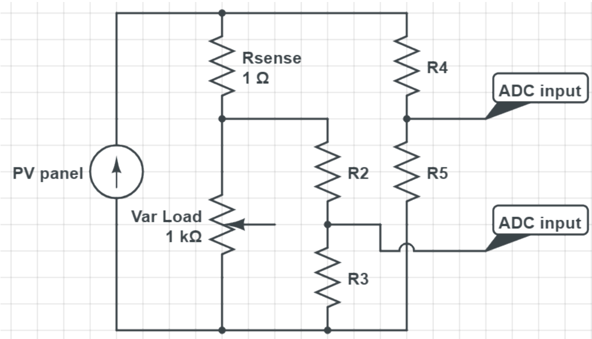


Figure 8: PV panel voltage and current measurement using voltage dividers to lower the voltages for ADC input to below 3.3V.

3.8 Multi-turn potentiometer

The PV panel will have to be connected to a load. Initially the load element will be a variable resistor, more specifically a multi-turn potentiometer. This will be used to measure the I-V curve of the PV panel using a manual sequence. It is recommended that the variable resistor is connected, in series with the 1 Ω current sense resistor, between the positive and negative terminals of the PV module (see figure 8). With a change in the resistor value, there will also be a change in the operating point of the PV module, which will be evident from the measured V_{PV} and I_{PV} voltage values. When the variable resistor value is close to or at 0 Ω, then the short-circuit current I_{SC} can be obtained. When the variable resistor is at a maximum of 1 kΩ, then the open-circuit voltage V_{OC} can be obtained. By manually changing the variable resistor value, it will be possible to achieve impedance matching, so that the maximum power point P_{MPP} (where maximum power is delivered by the PV module) can be obtained.

Yes it is OK to short the PV panel output. The only limitation is that all components, in this case R_{sense} and Var Load, that will need to carry the short circuit current can do so without overheating.

3.9 Active load

The PV panel will have to be connected to a load. For the system to automatically measure the I-V curve an active load will be used that can be automatically controlled by the STM32F411RE controller.

One way to achieve this functionality is to use a Bi-polar Junction Transistor (BJT) as an active load. By controlling the voltage on the base, and therefore the current I_{base}, we can control how much the transistor is switched on. When fully off, this is a high-resistance load, when fully on, this approximates a low-resistance load. For the BJT we will use a TIP31C in this project.

Since the STM32F411 does not have a Digital-to-Analog Converter (DAC), you will use a Pulse-width-modulated (PWM) signal, that is low-pass filtered, to provide a drive voltage for the TIP31C's base. By changing the duty-cycle of the PWM signal, we are controlling the average amplitude of the signal. If followed by a low-pass filter, the switching signal is filtered to approximate a DC signal. The low-pass filter cut-off should be well below the PWM frequency.

We recommend PWM frequencies above 10 kHz, and a -3dB cut-off frequency for the 1st-order RC filter to be 100 Hz to 200 Hz. Aim to use capacitor values of 6,8μF to 15μF.

We recommend that you connect the active load in parallel with the variable 1 kΩ resistor. This way, if you fail to drive the TIP31C you can still use the variable resistor as a backup.

3.10 NUCLEO-STM32F411RE Connections

Table 2 gives some suggested pinouts, not all are required. The connections **that are not listed should be chosen by you** as part of your design solution. Many pins are restricted to a limited set of functionalities so consider all the pin requirements for the project when making your decision.

The NUCLEO-STM32F411RE plugs into the baseboard through two separate 38-pin double row connectors, CN7 (left) and CN10 (right). These connections correspond to the NUCLEO Morpho connectors. The outer row connections are linked to solder connections J4 (for the odd numbered CN7 pins) and J5 (for the even numbered CN10 pins). The majority of the inner row CN7 (even numbered) pins that correspond to Arduino connections are brought out through J10, and the odd-numbered CN10 pins are brought out through J9 and J11.

It is good practice to trace the PCB connections on your board and familiarise yourself with the connections made via the PCB and therefore the interfaces available to you.

Table 2 provides a cross-reference to the signals available on the Arduino, Morfo and baseboard connectors. This table also contains some proposed and pre-determined signals to enable the use of UART and I2C communications. More detail on this will follow later in the course.

The 5 V compatible pins are also listed — the rest of the pins are only 3.3 V compatible and need protection if connected to a 5 V source.

CPU Pin	Port	5V	Connector-Pin			Proposed Function
			Morpho	Arduino	Baseboard Solder Pad	
PA0	A	n	CN7-28	CN8-1	J10-1/2	
PA1	A	n	CN7-30	CN8-2	J10-3/4	
PA2	A	n	CN10-35	CN9-2	J9-13/14	UART2 TXD
PA3	A	n	CN10-37	CN9-1	J9-15/16	UART2 RXD
PA4	A	n	CN7-32	CN8-3	J10-5/6	
PA5	A	n	CN10-11	CN5-6	J11-9/10	LED2 on Nucleo
PA6	A	n	CN10-13	CN5-5	J11-11/12	
PA7	A	n	CN10-15	CN5-4	J11-13/14	
PA8	A	Y	CN10-23	CN9-8	J9-1/2	
PA9	A	Y	CN10-21	CN5-1	J11-19/20	
PA10	A	Y	CN10-33	CN9-3	J9-11/12	
PA11	A	Y	CN10-14		J5-13/14	
PA12	A	Y	CN10-12		J5-11/12	
PA13	A	Y	CN7-13		J4-13/14	
PA14	A	Y	CN7-15		J4-15/16	
PA15	A	Y	CN7-17		J4-17/18	
PB0	B	n	CN7-34	CN8-4	J10-7/8	
PB1	B	n	CN10-24		J5-23/24	
PB2	B	n	CN10-22		J5-21/22	
PB3	B	Y	CN10-31	CN9-4	J9-9/10	SWO (PC Debug)
PB4	B	Y	CN10-27	CN9-6	J9-5/6	
PB5	B	Y	CN10-29	CN9-5	J9-7/8	
PB6	B	Y	CN10-17	CN5-3	J11-15/16	
PB7	B	Y	CN7-21		J4-21/22	
PB8	B	Y	CN10-3	CN5-10	J11-1/2	
PB9	B	Y	CN10-5	CN5-9	J11-3/4	
PB10	B	n	CN10-25	CN9-7	J9-3/4	
PB11	B	n	CN10-18		J5-17/18	
PB12	B	n	CN10-16		J5-15/16	
PB13	B	n	CN10-30		J5-29/30	
PB14	B	n	CN10-28		J5-27/28	
PB15	B	n	CN10-26		J5-25/26	
PC0	C	n	CN7-38	CN8-6	J10-11/12	
PC1	C	n	CN7-36	CN8-5	J10-9/10	
PC2	C	n	CN7-35		J9-13/14	
PC3	C	n	CN7-37		J9-15/16	
PC4	C	n	CN10-34		J5-33/34	
PC5	C	n	CN10-6		J5-5/6	
PC6	C	Y	CN10-4		J5-3/4	
PC7	C	Y	CN10-19	CN5-2	J11-17/18	
PC8	C	Y	CN10-2		J5-1/2	
PC9	C	Y	CN10-1		solder pad	
PC10	C	Y	CN7-1		J4-1/2	
PC11	C	Y	CN7-2		solder pad	
PC12	C	Y	CN7-3		J4-3/4	
PC13	C	n	CN7-23		J4-23/24	Blue Pushbutton
PC14	C	n	CN7-25		J4-25/26	32 kHz Xtal
PC15	C	n	CN7-27		J4-27/28	32 kHz Xtal
PD2	D	Y	CN7-4		solder pad	
PF0	F	Y	CN7-29		J4-29/30	HE Clk 8 MHz
PF1	F	Y	CN7-31		J4-31/32	

Table 2: NUCLEO-STM32F411RE to Baseboard connections

You will need to refer to these pin connections whenever you need to decide on which pin to use for a specific function. Some peripherals have only one or two options, so where you have the design freedom, make sure you plan for future possible pin uses too.

DO NOT CONNECT the following pins of the NUCLEO-STM32F411RE, in your application unless you have a specific requirement - `BOOT`*,* `5V`*,* `RESET`*,* `VIN` *and any of the* `NC` *pins. The NUCLEO-STM32F411RE operates normally without connections to these pins.*

3.11 Test-interface Connector

A test-interface connector (TIC) is provided by P13. This connector is designed to be stackable and consists of an Amphenol Bergstik 16-pin surface mounted connector soldered to the bottom of the baseboard (solder side - see Figure 9). This connector mates with a 16-pin Amphenol Dubox connector on the Automated Test board (top side) that will be used during demonstrations. The connections provide a power source (9 V), UART and 10 other connections during testing of the system.

This connector is supported by two solder connectors (J3 and J13) to connect to various ports or circuits.

More detail about the TIC, and its complete pin descriptions are given in Section 5.

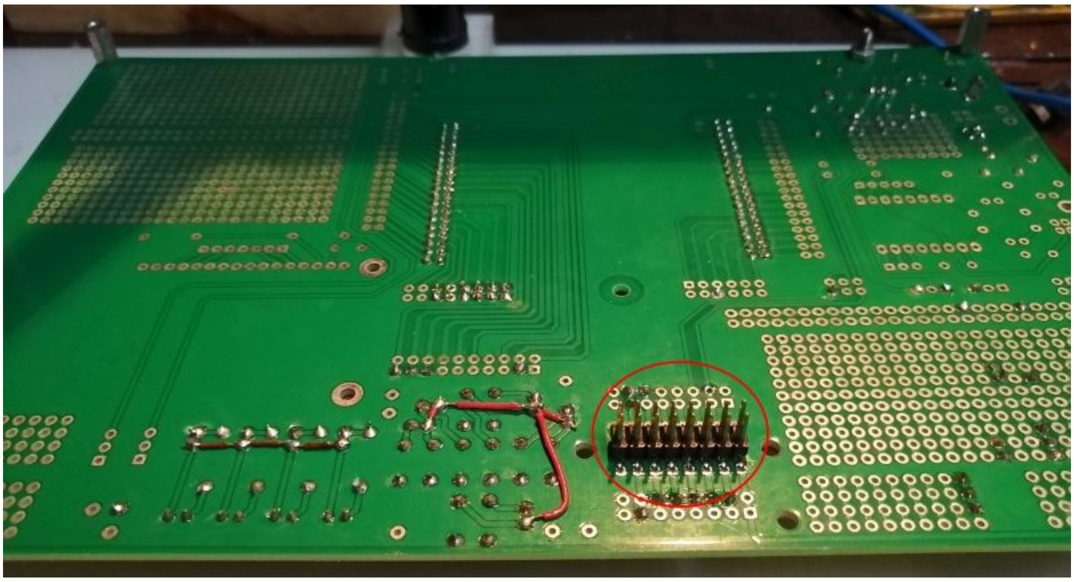


Figure 9: The TIC shown on the solder side of the baseboard.

4 Software Design and Considerations

4.1 System operational overview

As the system operates and receive user inputs (via buttons, and UART) it should perform the requested commands and output the required information via UART and LCD.

Command buttons operation is further detailed in section 4.8. and should specifically implement the functionality described.

The default start-up values of the system will be as follows:

- The startup state will be idle.
- The system will display the real-time power as measured continuously from the PV panel.
- The RTC value will be default: 19/09/2024 16:20:00.
- The active load (when present) will be set to its maximum value.

4.2 General software information

To develop software for this project, a similar environment and typical development process as used in Computer Systems 245 will be used: STMCubeIDE v1.11. There is however one significant change: The use of a software version control system: GIT, described in more detail in section 4.3.

> ⚠ *The use of STM32CubeIDE v1.11, with F4 Firmware package 1.27.1 is NOT optional. We cannot offer support for other versions.*

> ⓘ *In any of these project generator software set-ups, the user must be cautious. The software typically use comment delimiters to allow user code to be added, but this system is prone to deleting user code if the project is regenerated (adding new I/O for instance). Our advice is to add the minimum code in the project generated files and to use the project generator sparingly (ideally once only when generating the project for the first time). We recommend that you add files, with calls originating from the main C-file, which contain your user created code.*

For a small project such as this, adding the following minimum files will simplify your development:

- Header file with all global definitions and function prototypes;
- Source file with all your global variables;
- Source file with initialisation function and user code, which leaves the main while loop short. Call a run function from main to execute your user code.
- Additional files to handle each mode, inputs (trackpad, slider, and buttons), and LED driver functions are recommended.

4.3 Using GIT for Design E314

GIT is a form of source code version control. It not only keeps backup of your code, but also allows you to easily see changes in the code between checked-in versions, and facilitates collaboration on source code projects (although we will not use this latter functionality). Having knowledge of GIT and its processes is beneficial since it is used almost everywhere in industry where source code is part of the organization's Intellectual Property (IP). You will be ***required*** to use GIT and have your demo code (a separate version committed for each demo) in your GIT repository ***before*** you do your demonstration.

> ⓘ *Please refer to the GIT document on SunLearn for further detail on how to setup and use GIT in this course.*

4.4 Design of your Software Structure - Functions and Loops

The next question the designer (you) will encounter is what software structure must be chosen. The suitable choices depend on the requirements at system level and the peripheral response times.

Lets take an example approach:

The designer decides to put all the software in one big main loop with each function being executed sequentially before repeating indefinitely. What could go wrong?

Let us explore the possible problems by asking some questions about the software behaviour:

- How fast will the system respond to a UART command received? Will it consistently respond in this time?
- How fast will the system be able to sample digital inputs?
- How fast will the system be able to sample ADC inputs?
- How fast will the system respond to I2C inputs from the sensors?
- How long will the system take to do all the required calculations?
- How long will the system take to change the driver output parameters?
- How fast does the system NEED to do all the above, based on the specifications?
- Do all of these inputs/outputs require the same periodic attention from the system?
- How much resources will be consumed by the code? RAM, ROM and stack?

There is also a second, more subtle, reason for making a good software structure choice at the start of the project: How will any code additions or changes in sub functions affect the rest of the code? What you don't want is to have to rewrite a big part of your main loop (and maybe some other functions too), to accommodate a new function's requirements.

> *Modularity and well defined interfaces are key to keep the reworking of code to a minimum.*

In terms of the system design, we may attempt one of the following three approaches:

- The novice software writer will not consider a synchronous time-based structure for his code. Although it is feasible just to string all the functions together into one big while loop, the responsiveness of the system will be determined by the slowest function and recovery from time-outs and other errors are non-trivial to maintain.
- By using a timer-based schedule inside the while loop with interrupts can make the software much more robust. The choice of a tick-update period equal to $2\times$ to $5\times$ the largest response delay time will simplify the code (otherwise a state machine and elapsed timer will also be required).
- The use of a real-time operating system (RTOS), such as FreeRTOS, will simplify the structure further, but add some overheads. It also has a steep learning curve. In the simple case of each thread having the same priority, the behaviour will resemble a large while loop (equal priority from interrupt but with pre-defined execution order).

The large while loop (second option above), reacting to interrupt flags, is the preferred option for this project and learning phase.

4.5 HAL vs. LL Functions

A programmer may choose to write code at register level, or may want the abstraction that the HAL (Hardware Abstraction Layer) provide. The CubeMX initialisation generator will generate code for either the HAL or the LL (Low Level) libraries, but not register-level code directly. By using the CubeMX generator, the student can only choose LL or HAL code (per peripheral), and with the documentation bias towards HAL code, it is likely that most users will start off with HAL code.

The majority of tasks for this type of project can be written using the HAL functions only. If required, direct register access is still available using the STM32F303 header file.

Interrupts are accessible by using calls with IT-ending (e.g. `HAL_UART_Receive_IT()`) and a default interrupt handler for every interrupt is generated (e.g. `USART1_IRQHandler()` in the `stm32f3xx_it.c` file). You can process the flags to determine the cause of the interrupt in this file, but the recommended call-back function (e.g. `HAL_UART_RxCpltCallback()`) is a better option.

The supplied HAL library has a number of drawbacks and/or bugs. There are significant bugs in the I2C interrupt handler — what we have identified are:

- No checking for zero condition in the transfer (which may cause additional characters to be transferred);
- The restart is conditioned by write and read direction requests. The approach works for alternating directions but does not work for repeated writes;

The effect is that the only call allowing repeated writes (utilising interrupts) fails during parameter uploading during initialisation but work fine inside the main while loop while running.

A secondary effect is caused by the action that both the I2C and UART interrupt handler disables interrupts before returning — no problem if you are using deferred interrupt handling (setting a flag in the call-back and processing it in the main while loop) but back-to-back transfers through the call-back will not work.

4.6 Regular Interval Timing

The core ARM processor provides a Systick timer as standard, which is set in the HAL library at 1 msec intervals, so there is no need to provide any additional timers for this simple purpose. A call-back from the Systick timer will provide a 1 millisecond heartbeat. This is located in the STM32Flxx_it.c file.

```c
void SysTick_Handler(void)
{
    /* USER CODE BEGIN SysTick_IRQn 0 */
    /* USER CODE END SysTick_IRQn 0 */
    HAL_IncTick();
    /* USER CODE BEGIN SysTick_IRQn 1 */
    /* USER CODE END SysTick_IRQn 1 */
}

```

However in some cases you need to generate shorter duration timer delays, functions that might need sub microsecond accuracy. Hardware timers should be used in such cases, and you will have to add your own code to the timer interrupt vectors and create your own functions to implement these delays. For example you would want to call such a delay function:

```c
// Wait for 5 microseconds
myUsecDelay(5); // call self-created u-sec accurate delay function

```

4.7 ADC Conversions and measurements

4.7.1 Conversion

The ADC can be quite fast (as little as 2-3 microseconds conversion time), so for undemanding applications, there is no need to really use either multiple channel conversion scan chains or even simultaneous sampling schemes. A simple single channel conversion using polling can be sufficient. In this project your device will need to measure at least four (4) single input channels: 1) Voltage+ (PV voltage), 2) Voltage- (Voltage after current sense resistor, to calculate the PV current), 3) LM235 ambient temperature sensor, 4) SFH203 photodiode output.

The ADC can operate with as low as 1.5 clock cycle sampling for regular channels (if your input impedance is sufficiently low).

To convert a single channel, using the HAL library, we need to set up the channel, start the conversion, wait for completion and convert the result into the required scaled value.

You can also use the ADC in DMA mode to transfer the data directly to memory, bypassing the CPU. This is not required but can be useful when having to sample many times in succession, as might be required during the IV-curve measurement and calibration procedure.

4.7.2 Voltage measurements

You will use the internal ADC to measure the voltage and current from the PV panel. For this application, timing is less important, however, an accurate measurement is important as you want the current measured with as little as possible noise.

The PV panel voltage and current should be accurately measured to within 5% accuracy. Calibrating the ADC can assist you greatly in achieving good accuracy. You can calibrate your system's ADC by comparing its measurements to laboratory instrument measurements, like an oscilloscope measurement. Good calibration can be achieved if the signal is compared over the full range of the input and a correction factor is implemented in software to compensate for any non-ideal system response.

4.7.3 Temperature measurement - LM235

The analogue output of the LM235 should be sampled using the ADC in single channel mode. Once sampled the value must be converted using the guidelines and information in the datasheet to convert the value to a temperature in degrees Celsius. This temperature must then be converted into a 3-digit string, theoretically representing temperatures from -99 to 999. However the LM235 operating temperature range is much less (see datasheet). The 3-digit string can then be sent via UART and be displayed on the LCD.

4.7.4 Light measurement - SFH203

The analogue output of the Silicon PIN Photodiode circuit must be sampled using the ADC in single channel mode. Once sampled the value must be converted to a Lux value using the datasheet information. More details about this sensor will follow in a later version of the PDD.

4.8 Button command operation

The system will implement a command interface by using the five push buttons as well as the UART input. Such a system is usually implemented using a software state machine. The interface to the system required by this project is defined below:

- Use the RIGHT button to initialise a calibration procedure which consists of a EN measurement followed immediately by an automatic PV module measurement. The system responds with LCD and UART output during the process - i.e both an EN and SP response is expected on UART within 10 s.
- Use the LEFT button to select the display mode for the LCD as defined in section 4.11
- Use the TOP button to measure, calculate, transmit via UART, and display on LCD, the temperatures (T_a, T_{sp}) and light intensity (Lx_d) as described in UR3. The first button press starts the measurement (averaging the samples) and the second button press ends the measurement and display / report the values.
- Use the BOTTOM button to measure, calculate, transmit via UART, and display on LCD, the PV parameters as described in UR2. The first button press starts the measurement process and the second button press ends the measurement.
- Use MIDDLE button to initiate an RTC clock set menu. Once in the RTC set menu, the TOP and BOTTOM buttons must operate as increment and decrement inputs to the vales while the MIDDLE button sets each entered value in turn until all date and time values have been entered. Once the complete date and time have been entered, the device must report the time via the UART.

4.9 Debug LEDS

The debug LEDs will be used as system state indicators as follows:

- D2 - Power efficiency measurement in progress (flashing), and completed (D2 = ON)
- D3 - Temperature and Light measurement in progress (flashing), and completed (D3 = ON)
- D4 - Calibration sequence in progress (flashing), and completed (D2 = ON)
- D5 - Cleanness index progress (flashing), and completed (D2 = ON)

> *The LED indicators are especially useful in the absence of an LCD screen*

4.10 UART

The UART shall operate at a baud rate of 115200 bps, with 8 data bits, 1 parity bit, and one stop bit, using TTL signal levels. The parity used will be odd parity.

UART messages make use of ASCII printable characters, to make it easy to interface with the student board debug connector using simple terminal programs, such as Termite, Realterm, and Teraterm in the absence of a test station.

The format of the UART receive HAL functions is slightly at odds with how UART communication normally occurs The HAL functions are geared towards known fixed length packets, while in reality, we use variable length packets. To use the HAL receive function, we can set it up for single-byte mode using interrupts (in effect to prime the receiver before the byte arrives), and as soon as we received a byte we can re-prime the receiver.

For UART transmission we can use standard block transmits.

4.10.1 UART Protocol

The SB UART will be used to send and receive messages to and from the PC (TS).

The SB will output messages to the PC (TS) with the formats as in Table 3. Each message starts with a '&' character and ends with a ' * ' character followed by a newline character (ASCII character code 10, or indicated in C string escape notation as '\n'). Each field in the message is separated by an underscore ' _ ' character. Except for the *StdNum* message that identifies the student board, all the transmit messages are in response to a message request received from the PC (TS).

> *For Demo 1 (see section 5.3): For the UART part, you will need to send the student number, using the correct message format, to the TS. Then the UART protocol will deviate for testing purposes. After sending the student number message you must echo each received character back to the TS.*

The UART will be used to receive configuration and command messages from the PC(or TS) to the SB. The SB will interpret a message following the formats as shown in Table 4. A configuration/command message starts with a '&' character and ends with a ' * ' character followed by a newline character (ASCII character code 10, or indicated in C string escape notation as '\n'). Each field in the message is separated by a ' _ ' character.

Example TX message:

- Start-up message for student 12345678:

  ```
  &_12345678_*(newline)
  ```
- Start-up then 'a', '1', characters received (for Demo 1 only):

  ```
  &_12345678_*(newline)
  a1
  ```

Field in bytes (13)	1	Sep	8	Sep	2
Student Number	‘&’	‘_’	<StdNum>	‘_’	‘*\n’

Field in bytes (18)	1	Sep	3	Sep	3	Sep	5	Sep	2
Environment Resp.	‘&’	‘_’	<T_a>	‘_’	<T_{sp}>	‘_’	<Lx_d>	‘_’	‘*\n’

Field in bytes (21)	1	Sep	4	Sep	3	Sep	3	Sep	3	Sep	2
PV Parameter Resp.	‘&’	‘_’	<V_{MPP}>	‘_’	<I_{MPP}>	‘_’	<P_{MPP}>	‘_’	<P_{EFF}>	‘_’	‘*\n’

Table 3: UART TX Message fields - Log from SB to PC (or TS)

Field in bytes	1	Sep	2	Sep	2
Command	‘&’	‘_’	<Command>	‘_’	‘*\n’

Field in bytes	1	Sep	1	1	Sep	2
Display on LCD	‘&’	‘_’	<RS>	<byte>	‘_’	‘*\n’

Table 4: UART RX Message fields - Configuration/Command from PC (or TS) to SB

- Response for environment measurement with
  $T_a = 25°C$, $T_{sp} = 33°C$, $Lx_d = 111 Lux$:
  &_025_033_00111_*(newline)
- Response for PV panel measurement with
  $V_{MPP} = 6500$ mV, $I_{MPP} = 45$ mA, $P_{MPP} = 292$ mW, $P_{EFF} = 58$ %:
  &_6500_045_292_058_*(newline)
- Response for CA measurement, within 10 s, with
  $T_a = 25°C$, $T_{sp} = 33°C$, $Lx_d = 111 Lux$:
  $V_{MPP} = 6500$ mV, $I_{MPP} = 45$ mA, $P_{MPP} = 292$ mW, $P_{EFF} = 58$ %:
  &_025_033_00111_*(newline)
  &_6500_045_292_058_*(newline)

Example RX message:

- Command to measure environment:
  &_EN_*(newline)
- Display character ’A’ on LCD:
  &_1A_*(newline)

4.10.2 UART Value Representation

For the values transmitted and received via UART the following representation and ranges will be used:

- <StdNum>: 8-digit student number, Range: 1000000 to 40000000
- <T_a>: 3-digit (with leading zeros) ambient temperature in Celsius, Range: -99 to 999
- <T_{sp}>: 3-digit (with leading zeros) PV panel temperature in Celsius, Range: -99 to 999
- <Lx_d>: 5-digit (with leading zeros) light intensity in Lux, Range: 00000 to 99999
- <V_{MPP}>: 4-digit (with leading zeros) PV panel voltage in milli Volts (mV), Range: 0000 to 9999
- <I_{MPP}>: 3-digit (with leading zeros) PV panel current in milli Ampere (mA), Range: 000 to 999
- <P_{MPP}>: 3-digit (with leading zeros) PV panel power in milli Watts (mW), Range: 000 to 999
- <P_{EFF}>: 3-digit (with leading zeros) PV panel efficiency in percentage (%), Range: 000 to 100
- <Command>: The command can be one of three options:
  - ‘SP’: Measure PV panel parameters (UR2), V_{MPP}, I_{MPP}, P_{MPP}, P_{EFF}
  - ‘EN’: Measure the environment (UR3), T_a, T_{sp}, Lx_d
  - ‘CA’: Calibrate the monitor (UR5)
  - ‘DB’: Debug command you can use for general debugging purposes. No specific format required. (Note: This command will not be used by TS during demos.)

4.11 LCD display

The objective of the LCD screen is to present useful information to the system owner.

> *Make sure to read the LCD datasheets provided for assistance in coding the initialisation and commands for the LCD.*

The LCDs must be operated in 4-bit (nibble) mode as the D0-D3 lines are grounded on the main PCB. This design reduces the amount of GPIO lines needed for the LCD interface to only 7, but changes the complexity of the software driver a little. You will have to write the 2 separate nibbles of the commands and characters to the LCD, highest nibble first.

The display options of the LCD should function as follows.

1. Display Mode 1: Default state of the LCD is to always indicate the most recently measured voltage $V_{MPP}(mV)$, current $I_{MPP}(mA)$, power $P_{MPP}(mW)$ and PV module efficiency $P_{EFF}\%$ as output values of the PV panel, to be labelled respectively as: V, I, P, E. These values should only be updated by the system after a parameter measurement has been completed (UR2a, UR2b).

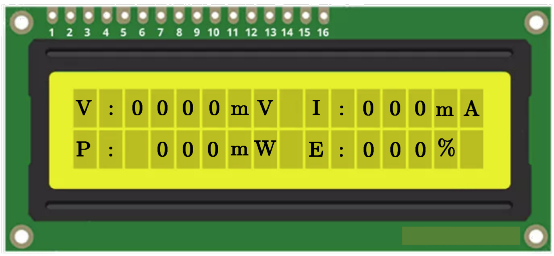
   

   Figure 10: LCD Display Mode 1

   Additionally, while the the system is BUSY measuring the PV parameters (UR2a and UR2b), the LCD is to indicate the real-time measured voltage $V_{PV}(mV)$, current $I_{PV}(mA)$, and power $P_{PV}(mW)$. While measuring the power efficiency should indicate '000'.

2. Display Mode 2: When the LEFT button is pressed 1x, then the LCD display should indicate the most recently measured ambient temperature T_a, PV panel temperature T_{SP} and light sensor Lux values, to be labelled respectively as: AMB, SP, LUX, using the same units as for the UART protocol.

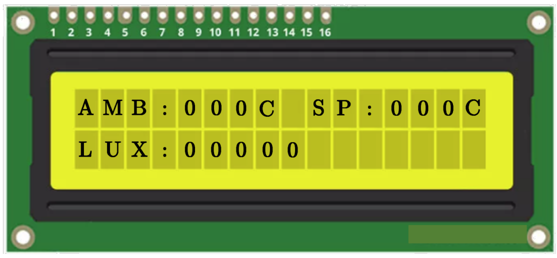
   

   Figure 11: LCD Display Mode 2

3. Display Mode 3: When the LEFT button is pressed again (2x), then the LCD display should indicate the current time: DD/MM/YYYY hh:mm:ss

4. Display Mode 4: When the LEFT button is pressed again (3x), then the LCD display should cycle through Display 1, 2 and 3 (as described above) at an interval rate specified by the user. The LCD exits Display mode 4, back to Display mode 1, when the LEFT button is pressed 1x again.

4.12 PWM genereation

You should use the PWM functionality of the MCU to drive the TIP31C as an active load. The GPIO pins only output either 0V or 3.3V. By changing the duty cycle of the PWM (0 - 100%) the effective average of the voltage placed onto the transistor pin will also change.

To enable the PWM mode on a GPIO pin, the pin should be set as a timer (TIM) with a specific channel. For example GPIO pin PC8 on the F411RE MCU can be set to TIM3_CH3. In the Pinout & Configuration menu there is a 'Timers' category where you can change the Parameter Settings for the specific GPIO Pin, which should act as a PWM signal.

To enable the PWM output, set the timer mode to "PWM Generation" mode for the particular timer channel. For our example here, it woudl be Channel 3.

For a specific PWM frequency, the prescaler should be changed, which determines the frequency of the timer. With the PWM frequency set, the duty cycle can be set by taking note of the difference between the ARR (Auto Reload Register) and CCR registers. The ARR counter value determines the period of the PWM signal (i.e. frequency). The CCR counter value determines the pulse width. This is demonstrated in Figure 12. In code, by incrementing the CCR value, you will also be incrementing the duty cycle. If CCR = ARR then the duty cycle is 100%.

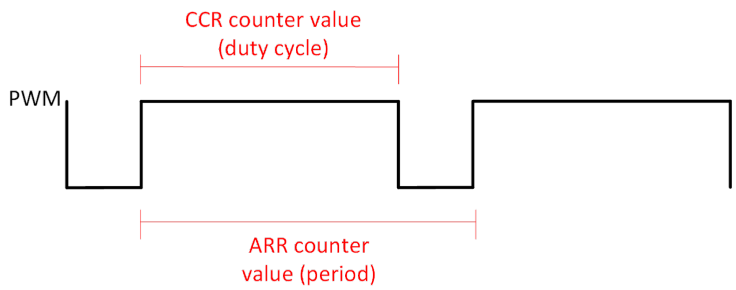


Figure 12: PWM signal setup with ARR and CCR counters.

4.13 Main While Loop Statistics

Suppose we want to find out how long our loop times are for the main while loop. One way is to set up a timer (example of timer 7 here) with a prescaler that divides the 64 MHz clock frequency down to 1 microsecond intervals. The following code fragment illustrates how to do this:

```
while (1){
// Prepare timer 7 to get execution time statistics
__HAL_TIM_SET_COUNTER(&htim7, 0); // Reset the counter
HAL_TIM_Base_Start(&htim7); // Start Timer7 to get cycle time in usec

userProcess(); // Run the user process (your own cyclic program)

// Gather execution time statistics
HAL_TIM_Base_Stop(&htim7);        // Stop Timer7
elapsedTime = __HAL_TIM_GET_COUNTER(&htim7);

if (elapsedTime > maxElapsedTime)        // Update the maximum stats
maxElapsedTime = elapsedTime;
if (elapsedTime < minElapsedTime)        // Update the minimum stats
minElapsedTime = elapsedTime;
// Average stats:  Discrete IIR filter with 1/100 bandwidth
aveElapsedTime  = 0.99 * aveElapsedTime + 0.01 * elapsedTime;

__WFI();        // Wait for the next interrupt
}
```

This code will provide minimum, maximum and average cycle times (to give you an indication of the processor loading). With the regular Systick interrupt occurring every millisecond, the example of an average elapsed time of 20 microseconds indicate a 2% average loading.

⚠ *To use the timer in this mode, load the period value with a large value (such as* `0xFFFF`*) as it will count up, if you leave it at the default of zero then the timer will not count!*

4.14 Auto code generation

The STM IDE provides functionality to auto-generate code. We advise you to be cautious as if you auto-generate code half way through a project, it can delete some of your code. Make sure all your code is between the correct comments if you plan to use this feature.

⚠ *We recommend only doing this once at the start of your project! Back up your code frequently to avoid loss of code!*

5 Testing

Your student board (SB) will be tested during demo sessions, as specified in the module framework. The testing will occur in an automated fashion. Your SB will be plugged in to a test station (TS). The TS will provide power to your SB and generate a number of signals that are connected to your SB. Certain signals from your SB will also be monitored and checked by the TS.

5.1 Test Interface connector (TIC)

In order to facilitate testing, a test-interface connector (TIC) is provided by P13. This connector is designed to be stackable and consists of an Amphenol Bergstik 16-pin surface mounted connector soldered to the bottom of the baseboard (solder side). This connector mates with a 16-pin Amphenol Dubox connector on the Test-station board (top side) that will be used during demonstrations. The connections provide a power source (9 V), UART and 10 other connections during testing of the system.

The signal connections to the TIC is detailed in Table 5, and the pin numbering of J13, J3, and P13 are as shown in Figure 13.

From your board, you will have to route the signals listed in Table 5 to the test connector, P13, by making use of the solder connectors J3 and J13. The solder pads on J3 and J13 are routed to pins on the TIC (P13).

You will be required to bridge the jumper at J30 to ensure your board receives the 9V from the TIC.

P13 pin connection	J3/J13 solder connection	Signal	Direction
1	J3 - 1,2	`V_bat` - 9 V Supply from test station	`SB <-> TS`
2	N/C	`V_bat` - 9 V Supply from test station	`SB <-> TS`
3	J3 - 3,4	Load drive voltage as Analogue signal from SB, PWM output (direct from pin)	`SB -> TS`
4	J13 - 3,4	5V supply from student board (fed back to test station for verification/measurement)	`SB -> TS`
5	J3 - 5,6	UART transmit (TX from student board, RX of test station)	`SB -> TS`
6	J13 - 5,6	3.3 V supply from student board (fed back to test station for verification/measurement)	`SB -> TS`
7	J3 - 7,8	UART receive (RX from student board, TX of test station)	`SB <- TS`
8	J13 - 7,8	Analogue signal to TS, ADC input from voltage measurement circuit	`SB -> TS`
9	J3 - 9,10	Button TOP (connected to TS for control/verification/measurement)	`SB <-> TS`
10	J13 - 9,10	Analogue signal to TS, ADC input from current measurement circuit	`SB -> TS`
11	J3 - 11,12	Button MIDDLE (connected to TS for control/verification/measurement)	`SB <-> TS`
12	J13 - 11,12	Light sensor measurement as input to TS	`SB -> TS`
13	J3 - 13,14	Button BOTTOM (connected to TS for control/verification/measurement)	`SB <-> TS`
14	J13 - 13,14	Analogue Ambient Temperature sensor (T_a) measurement (ADC input) as input to TS	`SB -> TS`
15	N/C	GND	`SB <-> TS`
16	N/C	GND	`SB <-> TS`

Table 5: Test-interface Connector Pin definitions

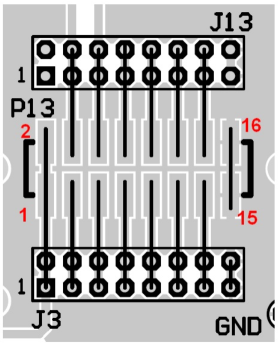


Figure 13: Pin numbers of J13, J3 and P13

> *Connections shown in grey in Table 5 are signals that are already routed on the PCB - you do not have to do anything to connect them.*

5.2 Test method during demonstrations

The tests that the test station will execute once a student board has been plugged in, are designed to verify the requirements of the student board (detailed in Section 2). These requirements, and the method in which the test station will perform the test are listed in Table 6. This version of this document only covers test methods up to Demo 3, more detail for the other demonstrations will follow in future versions of this document.

5.3 UART communications interface

To facilitate testing (both by the student and for automated tests) and debugging of the device, a UART link shall be implemented. The UART link shall operate ***in both directions***: transmitted from the student board and received by the test station or PC test program. The student board shall make use of the default UART2 channel on the STM Nucleo - This UART channel is connected to the ST-Link chip on the Nucleo module, and will automatically enumerate as a virtual COM port when the Nucleo board is connected to the PC via the USB debug cable. Thus, for debugging it will not be necessary to make any hardware connections.

For test station purposes, it will be necessary to route the UART2 to the Test Interface Connector (TIC). In this case, you will have to make a connection from the correct pins of the Nucleo board (RX/TX) to the Test Interface Connector (TIC) (see Section 3.10 and 5.1). Both methods are shown in Figure 14.

> *Remember that the RX/TX indicators are as seen from the ST-LINK perspective! If you are unsure, first check the direction with an oscilloscope, while sending messages from the PC, before connecting the wires to the TIC pins.*

5.4 Demos

There will be a total of 4 demos which will test all the user requirements. The details of each demo are presented in Table 7. In this version of this document all details up to Demo 4 is listed.

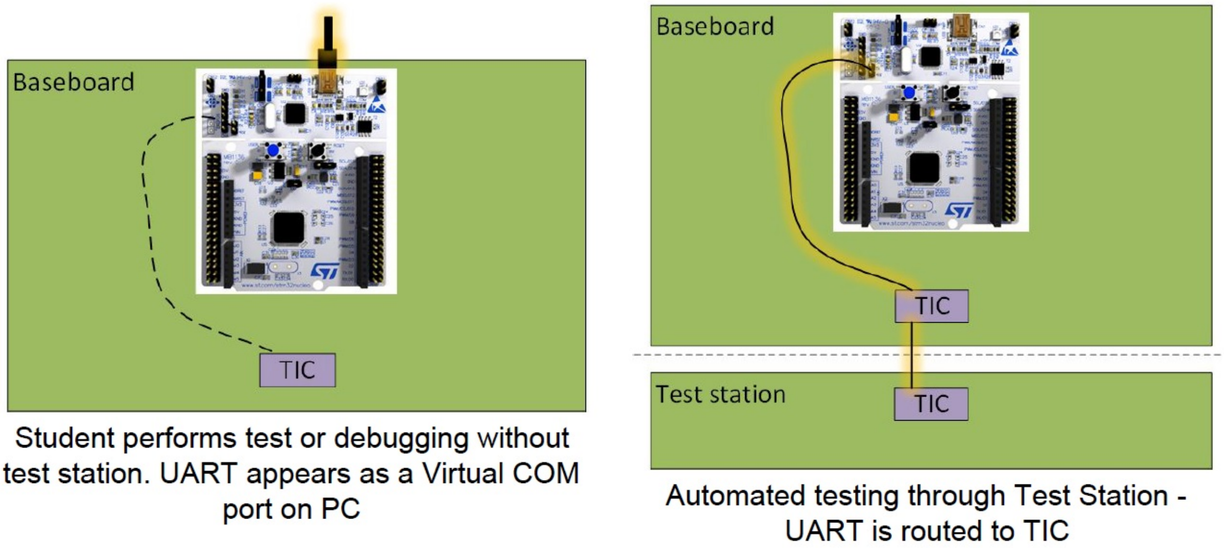


Figure 14: UART connections for debugging and testing.

UR	Method	Pass/Fail
UR1	The TS supplies board with 9 V switched power supply. SB will feed back the generated 5 V and 3.3 V supplies to TIC connector.	Test passes if TS measures the (1) 5 V and (2) 3.3 V supplies to be in 5% of expected values, and (3) the LED D6 is on when 5 V is present
UR2	PV module operating points will be measured by automatically changing the active load. A maximum time of 10 s will be allowed between start and stop commands/button presses then reporting/displaying the following data points: V_{MPP}, I_{MPP}, P_{MPP} and P_{EFF}. The TS will send a UART command "SP" to the SB, or activate the push button, to initiate the measurement of the 4 data points listed above. After 10 s the TS will send another UART command "SP", or push button activation, to stop the measurement sequence. A UART message, containing the 4 data points must be sent from the SB to the TS within 100ms. The LCD will be checked to display the appropriate values. *For reduced marks, the manual turning of potentiometer will only be allowed if automatic procedure fails.*	Test passes if the V_{MPP}, I_{MPP}, P_{MPP} values, as received via UART, are the same as measured by the TS, all within a 5% tolerance.
UR3	*The digital temperature sensor must be connected to the back of the solar panel.* The TS will trigger an EN command either via button or UART. The TS will compare BOTH temperature values received via UART, and analogue temperature measured via TIC, from the SB to the ambient temperature as measured by the TS. The light intensity will also be measured via TIC, from the SB, which will then be compared to the light intensity as measured by the TS. Light will be measured at max level and a lower level, then checked for correct proportional change. The LCD screen will be evaluated visually to confirm the correct display output. (This test will be repeated with UART input and manual button presses.)	Test passes if (1) the TS and SB ambient temperatures are with 3°C of each other, (2) the digital sensor value changes appreciably when the solar panel is exposed to light and (3) the light intensity is proportionally within 5% of the TS light intensity measured.
UR4	The device should indicate if cleaning is required after a SP measurement is completed, as initiated by the TS via UART or button presses. First unobstructed measurement will be done, followed by a measurement with some obstruction on the panel to simulate a dusty panel.	The test passes if LED D5 flashed or illuminates to indicate the correct cleanness state.
UR5	The device should do a complete calibration procedure when the right button is pushed by hand. This consists of a EN measurement followed immediately by a SP measurement, all automatically controlled by the SB.	The test passes if the SB reports within 10 s the EN ans SP values with same evaluation criteria as UR2 and UR3.
UR6	The device should display the appropriate values on the LCD screen, depending on which display mode is selected by hand. Upon startup, the default LCD state should be Display Mode 1.	Test passes if the default LCD mode is Display Mode 1, and when the LEFT Button is pressed, the LCD should change to display mode 2, 3, 4 with successive presses while displaying all the expected information in the correct format and timing.
UR7.1	The TS will receive UART messages from the SB. The TS will compare received UART messages to the expected values.	Test passes if the expected UART messages are received correctly by the TS.
UR7.2	The TS will send UART configuration/command	Test passes if the SB responds in the

Demo	Description	UR's
1	On power-up, transmit your student number via UART using the prescribed message format, no sooner than 100ms after power-up and no later than 500ms after power-up. The TS will monitor and test the 3.3V and 5V lines. The TS will send a series of single characters via UART to the SB, with 500 ms delay between transmissions, and the SB must echo back each character on the UART immediately after receiving it.	UR1, UR7.1 (student number and echo), UR7.2 (modified - only echo)
2	On power-up, transmit your student number via UART using the prescribed message format, no sooner than 100ms after power-up and no later than 500ms after power-up. The TS will monitor and test the 3.3V and 5V lines. The TS will override the TOP button (via TIC P13 pin 9) while monitoring the UART, LM235 outputs (via TIC P13 pins 5, 7, 14), and taking photographs (for debug LEDs) to check for correct system operation. UART EN commands will be sent by the TS to the SB and the SB responses monitored for correct system functioning. The minimum delay between consecutive UART commands will be 500 ms. The TOP button will be manually pressed too and the system response monitored for correct system functioning. The system should update and respond IMMEDIATELY (<100 ms) to any input.	UR1, UR3 (no Light sensor, no LCD), UR7
3	Same startup procedure and electrical interface on TIC as for Demo 2. The TS will override the BOTTOM button (via TIC J3 pin 13) to initiate the PV module measurement sequence. While monitoring the UART, the TS will measure the PV module voltage output (via TIC J13 pin 8), PV module current output (via TIC J13 pin 10) and will be taking photographs of LEDs to check for correct system operation. The LCD will also be photographed to confirm the correct display mode is active. UART commands 'EN' and 'SP' will be sent by the TS to the SB and the SB responses monitored for correct system functioning. The minimum delay between consecutive UART commands will be 500ms. The TOP, LEFT, and BOTTOM buttons will be manually pressed and the system response will be monitored for correct system functioning. The system should update and respond IMMEDIATELY ($< 100ms$) to any input.	UR1, UR2a(manual adjustment, excl UR2.6), UR3, UR6, UR7
4	**Similar assessment as demo 3** with the following **added/modified**: Automatic load control during PV panel measurement instead of manual potentiometer turning. A calibration will be initiated from the TS with full light conditions, after which a minor/no obstruction EN ans SP measurement will be done. The PV panel will be partially obstructed and an EN, SP measure sequence repeated. The LCD display modes will be checked by manual left-button presses. The RTC setting will be tested via TS/manual button presses. The system should update and respond IMMEDIATELY (<100 ms) to any input.	All of UR1 to UR8.

Table 7: Demo descriptions

6 Preliminary Report

Consistently documenting your work is critical in all engineering projects.

The goal of the preliminary report is to give you exercise and feedback in writing parts of a technical report. You will mark your peers' reports, which should give you further insight into what is expected and some examples of interpretations of the tasks.

In the task descriptions that follow, the page limits refer to the total content length for that task ***excluding all cover pages, content lists, and references***. Also provided, is a rubric to guide you in creating the report content. There are formatted templates for you to use on SUN Learn, in both MS Word and LaTeX formats.

6.1 Task 1

(maximum 2 pages)

You have to report on the hardware design details of the LMT01 sensor, Top push button, and LED circuit.

Document your effort by drawing circuit diagrams (schematic diagrams) and include the necessary explanations for your design values in a short report. You may make any reasonable assumptions where the user requirements are not explicitly defined. Your diagrams and explanations should clearly cover the required calculations and assumptions to motivate the design decisions, and how these designs will adhere to the specifications/requirements.

6.2 Task 2

(maximum 2 pages)

You have to report on the software design details to implement the measurement and conversion of the LMT01 temperature sensor signal in your code.

You should clearly document your specifications and requirements and proceed to design the software approach that dictates the timing and interpolation of data points for the LMT01.

Similar to how a final circuit diagram without proper context and design does not constitute as a "design", so too is the case for software. All code is written according to a planned structure, and those structures should be represented as software flow diagrams, state machine diagrams, timing diagrams, etc. Raw code listings will not be marked.

You have to document the following:

- Software design choices and the justification of these choices.
- A diagram to clearly show the logic you envisioned to implement in software.

6.3 Task 3

(maximum 2 pages)

To ensure the successful operation of the project is the final step of development.

In this task you should present the test methods in detail, as implemented by yourself. Ideally, you should provide proof of the measurements and setups which were used to ensure that the specifications of your project were met. The measurements and tests must be representative of the separate design elements (Task 1), as well as the combined UR1, UR3, UR7.1 and UR7.2b (table 1) system. Extensive testing of the system is encouraged and will help develop a mindset of continual testing of designed systems and the documentation of data.

6.4 Assessment of tasks

These tasks will be assessed through peer assessment - you will have to mark three other reports, and your report will be marked by three other students.

The marking will be carried out using the SunLearn peer assessment module. You will be given a marking rubric to use when carrying out the evaluation. The tasks and your peer evaluations will count towards your report mark. The report portion of the module mark counts 33.3% of the final module mark. These tasks making up the preliminary report, and peer evaluation of them, will contribute 10 (14.285%) of the 70 marks of the report portion of the final module mark.

The 15 marks total in the rubric, for the submitted report, plus the 15 peer review marks, based on the quality of the peer review, will be scaled to a mark out of 10. Misconduct in carrying out the peer evaluation (i.e. if you make up random marks, fail to complete the peer evaluation, or give marks for clearly incorrect work) will be penalized by receiving 0 for the peer evaluation part. This will be done by doing checks on the evaluations of reports.

6.5 Hand-in and Rubric

Due dates for the preliminary report hand-in and peer-review thereof are stated in the Module Framework schedule and will be strictly applied.

6.6 Rubric

Criterion	Description	Mark
1.1	Based on the calculations and schematic, it should be sufficient for you, the reviewer, to see how the student designed the LMT01, Top push button, and LED circuit to meet the requirements, including choice of resistor, and GPIO pin selections and setup.	4
2.1	Measurements must be provided to motivate and illustrate that the LMT01 output signal voltage values are sufficient (min, max) to be identified as "low" and "high" by the STM32.	1
2.2	Based on the software design diagram presented, it should be clear how the proposed software will correctly retrieve the averaged LMT01 temperature value when either a push button or a UART command is received.	2
2.3	Details regarding software structures and components required to implement the code as well as the configuration of peripherals, like GPIO pins and settings, must be clear and sensible.	2
3.1	Testing method(s) should be appropriate and detail the setups and measurements to show that requirements/specifications are achieved: • the LMT01 circuit output (2 marks) • the Top push button and LED circuit (2 marks) • the LMT01 functionality (2 marks), using GPIO pin input to read values and to demonstrate LMT01 sensor reaction to changing temperatures	6
Total		15

Table 8: Preliminary Report rubric.

7 Final Report

The Final Report is due by the end of the semester and will be in electronic format and submitted to SUN-Learn. In general, the content of the report should enable a student with the same background as yourself (3^{rd} year E&E student, 4^{th} year M&M student) to be able to repeat your project with the same results. It is not a "story" progression of how you built your project, but rather a structured design description with the following elements:

1. What the system is supposed to achieve (high-level system requirements)
2. Which design alternatives were considered
3. How to go from concept design to refining the detail elements (report on concept design, block diagram, interfaces between blocks, then elaborate on the detail of each block. Include calculations, decisions and justification, schematic diagram, software flow diagram, timing diagrams and all other relevant information)
4. How to test for various functionality, and report on the results (Test method, and test results)
5. Summary of whether the system does achieve all the required functions in (1). (Compliance)

Point 2 above would normally appear in a good design report, but as was mentioned earlier in the module – the lecturers already made some of these design choices for you in order to manage component procurement, standardising on tests and demonstrations etc. For the EDesign report we will thus only expect you to elaborate on point 2 where there was no initial specification for the particular hardware element.

It is expected that your report is organised into the following main sections:

1. Introduction and System description/concept design
2. Hardware design and implementation
3. Software design and implementation
4. Testing
5. Conclusion

7.1 Marking Scheme

7.1.1 Overall

The following overall remarks apply:

- Use the templates provided.
- The report may not exceed 25 pages (Page count should be a maximum of 25 pages, counting from Introduction to Conclusion, and excluding appendices, table of contents, list of images, list of tables and abbreviations, and references).
- Do a spell check and proofread.
- Use diagrams and tables to supplement your text. Make sure all diagrams are properly labeled and captioned.
- Your report will be checked through TurnitIn for plagiarism.

Marks will be awarded for:

Table 9

Report element	Max. marks
Language and grammar	1
Table of contents, list of figures, tables, abbreviations, etc.	2
Overall presentation/impression	2
Sub-total	5

7.1.2 Introduction and System description / Concept Design

Give a brief description of the system. It must describe what the system does, and not how it is done. Include only the most necessary technical details. A short overview of the contents and structure of the report may be given (although this is a bit boring). Write the rest of the report first, then the introduction and lastly the summary (abstract).

- Show block diagrams of the system
- Explain the functioning of the system (in relation to the different blocks)
- Do NOT include design detail

Marks will be awarded for:

Table 10

Report Element	Max. points available
High level system description	1
Summary of requirements/user needs	2
Sub-total	3

7.1.3 Hardware design and implementation

- Provide a (high level) description of your program.
- Provide a description of the design of each hardware element.
- Show all calculations (e.g. resistor values, calibration formula etc.).
- The detail must be sufficient to enable another knowledgeable person to utilize the information to do a similar design.
- Motivate design choices.
- Show the sections of the circuit diagram to which the calculations apply. The given diagrams may be adapted and used, but acknowledge all sources.

Marks will be awarded for:

Table 11

Report Element	Max. points available
Hardware Block diagram and description of interaction	2
Power supply	2
LEDs (debug)	1
Buttons	1
Temperature sensing	2
LCD	2
V / I Sensing circuit	2
LUX Sensing circuit	2
Active load and RC filter	2
Sub-total	15

7.1.4 Software design and implementation

- Provide a (high level) description of your program.
- Use state diagrams, flow diagrams, or timing diagrams, or any other applicable diagrams or explanations to explain:
  - Logic for changing states
  - Data flow and processing
- Describe which peripherals (timers, ADC, etc.) of the STM32 are used, and how they are setup. If necessary, provide calculations to motivate register values. (Do NOT include screenshots from the Code Generator)

Marks will be awarded for:

Table 12

Report Element	Max. points available
Software Block diagram and description of interaction	2
Debug LED + system state indication logic	1
Button bounce handling	1
UART communications (protocol, data conversion)	2
LMT01 interface, timing, synchronisation	2
ADC, Setup and channel management	1
Processing (convert & calibrate): Temp, Lux, V, I, P, Active load, Efficiency	3
LCD interface (control, data conversion)	2
RTC handling and setting procedure	1
Sub-total	15

7.1.5 Measurements and Results

- The intention of this section is to demonstrate that the built hardware will perform the functions as defined by your hardware design requirements.
- For each element, provide the method that was used to verify the functionality or perform measurements, and report on the result (measurement results, and/or successful verification).

Marks will be awarded for:

Table 13

Report Element	Max. points available
Power supply	2
UART communications	2
Buttons	1
Temperature sensors	2
Light meter	2
LCD	1
V, I, P, Efficiency	2
Active load	1
RTC	1
Complete system	1
Sub-total	15

7.1.6 Conclusion

- Mention any of the required specifications that your system does not comply with.

- Identify shortcomings in the design/implementation and make recommendations for future expansion or improvements.

Marks will be awarded for:

Table 14

Report Element	Max. points available
Discuss non-compliance's	1
Identify your design short comings	1
Provide recommendations and possible improvements	1
Sub-total	3

7.1.7 Appendices

- Complete circuit diagram (schematic) must appear in an appendix.
- All connections and component values must be shown. The information must be sufficient to allow someone else to build the circuit.
- A table with the pinout of the STM32 module (which pins connect to which hardware elements on your board) must be supplied in the appendix.
- A complete and correct reference list.

Marks will be awarded for:

Table 15

Report Element	Max. points available
Complete schematic	2
STM32 pins used and their configuration	1
References	1
Sub-total	4

7.1.8 Marks Summary

Table 16

Report Element	Max. points available
Overall	5
Introduction and System description/Concept Design	3
Hardware design and implementation	15
Software design and implementation	15
Measurement and results	15
Conclusion	3
Appendices	4
Total	60

References

[1] *RM0316 Reference Manual, STM32F303xB/C/D/E advanced Arm®-based MCUs*, ST Microelectronics, DocID022558, Rev 8, filename=`rm0316-stm32f303xx`, January 2017.

[2] *NUCLEO-F303RE*, ST Microelectronics, `https://www.st.com/en/microcontrollers-microprocessors/stm32f303re.html`, accessed 2022-03-01.