# IoT node design

## Overview

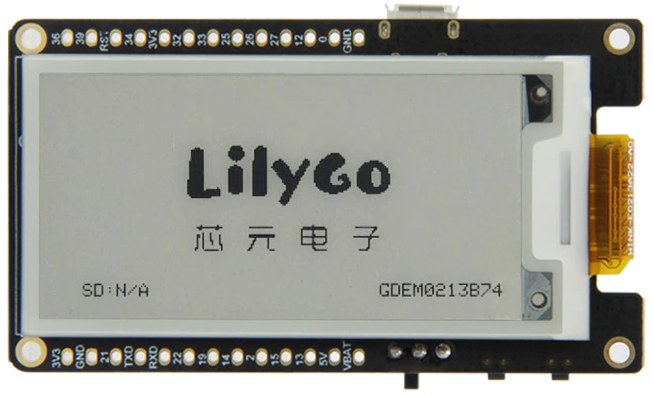
The Internet of Things (IoT) node is a combination of a microcontroller and hardware sensors that is installed in a GrowCube to record data automatically. This document describes the proposed components and associated costs.

## Microcontroller

The main requirements for the microcontroller are to

* provide connections for an appropriate range and number of sensors
* communicate over WiFi
* provide user interaction and feedback
* operate independently of a fixed power supply
* enable the local storage of data
* consume as little power as possible
* have a small physical footprint

The device selected is the [LilyGo TTGO T5](http://www.lilygo.cn/prod_view.aspx?TypeId=50061&Id=1393&FId=t3:50061:3) (Figure 1) which includes an e-paper display, programmable button and an integrated SD card reader.



66.3mm

36.8mm

e-Paper display

Programmable button

Reset button

Power switch

Micro USB

Figure : TTGO T5 microcontroller

The device will be packaged in a 3D printed enclosure (see below) that will protect the electronics while providing access to the controls shown in Figure 1 and for making connections to the sensors.

## Sensors

The proposed parameters that the IoT node will measure are

* Air temperature
* Relative humidity
* Light intensity
* Substrate pH
* Substrate electrical conductivity
* Substrate moisture
* Substrate temperature

The following sections provide details of the recommended sensors in each case.

### Air temperature and relative humidity

These two quantities are often measured by a single device and the recommended option for this project is the [Sensirion SHTC3](https://www.sensirion.com/en/environmental-sensors/humidity-sensors/digital-humidity-sensor-shtc3-our-new-standard-for-consumer-electronics/). This sensor is pre-calibrated and provides an accuracy of ±2% for relative humidity and ±0.2°C. It comes packaged in various ways, and the one shown in Figure 2 is mounted on a circuit board with a mounting hole. This is the version that would be used if the sensors are individually enclosed. Please see the ***Enclosures*** section for further details.

A picture containing electronics

Description automatically generated

Figure : Packaged SHTC3 temperature and humidity sensor

### Light intensity

The proposed sensor for light intensity is the [Rohm BH1750FVI](https://datasheetspdf.com/pdf-file/679289/Rohm/BH1750FVI/1) which provides output in lux (lx) with an accuracy of ±1.2 lx. For reference, ambient daylight typically ranges between 10000 and 25000 lx. The sensor is pre-calibrated and comes packed as the GY-30 board shown in Figure 3.

A picture containing text, electronics, circuit

Description automatically generated

Figure : GY-30 light intensity sensor board

### Substrate moisture

There are two main types of moisture sensor. The resistive type depend on the resistance between exposed metal traces and are prone to corrosion. The capacitive type do not have exposed electrical connections, and are usually preferred. The model proposed here, shown in Figure 4, is built using the Texas Instruments TL555I timer chip which allows the device to work at a voltage that is compatible with the T5. This sensor requires calibration.

Graphical user interface

Description automatically generated

Figure : Capacitive soil moisture sensor

### Substrate temperature

The temperature of the growing substrate may differ from the ambient air temperature. The device based on the [Maxim DS18B20](https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf) digital thermometer chip shown in Figure 5 is pre-calibrated.

A picture containing earphone, cable, adapter

Description automatically generated

Figure : DS18B20 waterproof soil temperature sensor

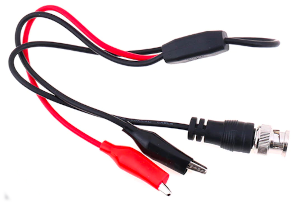
### Substrate pH

Typical pH sensors are relatively expensive in comparison to the other sensors above. They are composed of a probe and a signal processing board that are linked by a cable. One of the most popular pH sensors available is the [Gravity kit](https://www.dfrobot.com/product-2069.html) which costs around £26. A second issue with standard pH probes is that they are around 200mm in length which would not fit comfortably inside the GrowCube. Finally, the majority of pH sensors operate at 5V whereas the T5 operates at 3.3V.

Zimmer and Peacock (Z&P) offer a [solid state pH probe](https://www.zimmerpeacocktech.com/products/electrochemical-sensors/ph-sensor/) which is much smaller (25.4 x 7 x 0.625 mm) and cheaper than the standard ones. However, use the Z&P probes would entail the construction of bespoke connection cables based on the BNC adapter shown in Figure 8.

An installed pH sensor would consist of the items listed below and pictured in Figure 8 including a signal processing board from a Gravity kit. These sensors would require calibration using solutions of known pH.

1. Z&P solid-state probe
2. Connection clip
3. BNC cable (to be modified after delivery)
4. Signal processing board



a

b

c

d



Figure : pH sensor components

### Substrate electrical conductivity

The electrical conductivity (EC) of a substrate can be measured easily by measuring the resistance between two electrodes. The device shown in Figure 7 incorporates a waterproof probe and signal processing board.

A picture containing cable, connector, adapter

Description automatically generated

Figure 7: EC meter

### Costs

The estimated costs per unit for each of the sensors described above are shown in Table 1. These figures are based on information available at the time of writing and include costs for shipping, customs and VAT where relevant. The total cost for three sets of sensors in each of 138 GrowCubes comes to £15760.58 Please note that this figure is for the sensors only and does not include other hardware costs such as the T5 microprocessors, enclosures, batteries, etc.

Table : Sensor costs

|  |  |  |
| --- | --- | --- |
| Sensor | Cost per unit (£) | Link |
| SHTC3 | 1.97 | https://www.aliexpress.com/item/1005003511936737.html |
| GY-30 | 0.87 | https://www.aliexpress.com/item/33004793427.html |
| Moisture | 0.47 | https://www.aliexpress.com/item/4001131897353.html |
| DS18B20 | 1.00 | https://www.aliexpress.com/item/1005003379804834.html |
| pH | 26.23 | https://www.zimmerpeacocktech.com/products/electrochemical-sensors/ph-sensor/  https://www.aliexpress.com/item/4000203388759.html  https://www.dfrobot.com/product-1782.html  https://www.aliexpress.com/item/1005002529535170.html |
| EC | 9.21 | https://www.dfrobot.com/product-1662.html |

## Electrical requirements

The T5 is powered by a 1000mAh lithium polymer (LiPo) battery which would power the device for around 36 hours at maximum consumption levels – i.e. assuming constant display refreshing during that time. Between image refreshes, the display consumes no power at all, and under normal operating conditions, one battery recharge is expected to last for up to a month. Tests will be carried out during development to provide a more precise estimate.

The original design was based on the idea that there would be three groups of sensors on each level that could be powered selectively. This was to optimise the use of input/output connections and to manage the power draw at any given moment. In practice, compromises were necessary to accommodate the behaviour of some of the sensors. In particular:

* It was not possible in practice to power a subset of the I2C sensors. The SHTC3 in particular caused communication errors on other sensors when it was not powered.
* It proved not to be possible to extend the I2C bus to all three levels. The signal to noise ratio was too low and caused communication errors. The I2C sensors are therefore only installed in the top level of the GrowCube.
* The power draw from the pH sensors proved to be to high to run on a signal pin despite this being theoretically possible. The sensor specification indicated a current requirement of 10mA which is below the maximum 12mA available on a signal pin.
* The communication requirements of the substrate temperature probes were such that they could not be powered selectively while sharing the same signal pin as planned.

Since the PCBs had been designed around the power switching scheme, some modifications were required before deployment (see below).

Table 2, Table 3 and Table 4 set out the original breakdown of sensors into sets. Note that I2C is a hardware communications standard whereby several sensors share the same two connections. These are accounted for separately in Table 5 and therefore any I2C sensors are shown with a pin requirement of zero.

To restrict the length of the I2C bus to the top level only, the SCL and SDA cores of the ribbon cable were severed at the top of the connection from the top GrowCube level to the middle.

Table : Sensor set 1

|  |  |  |  |
| --- | --- | --- | --- |
| Sensor | Current (mA) | Connection pins | Type |
| GY-30 (Light intensity) | 0.19 | 0 | I2C |
| GY-BMP280 (barometric pressure) | 0.18 | 0 | I2C |
| Water level | 1.0 | 2 | Digital |
| Electrical conductivity | 6.0 | 1 | Analogue |
| Totals | 7.37 | 3 |  |

Table : Sensor set 2

|  |  |  |  |
| --- | --- | --- | --- |
| Sensor | Current (mA) | Connection pins | Type |
| SHTC3 (Temperature, humidity) | 0.9 | 0 | I2C |
| Substrate moisture | 5 | 1 | Analogue |
| Substrate temperature | 1.5 | 1 | Digital |
| Totals | 7.4 | 2 |  |

Table : Sensor set 3

|  |  |  |  |
| --- | --- | --- | --- |
| Sensor | Current (mA) | Connection pins | Type |
| pH | 10 | 1 | Analogue |
| Totals | 10 | 1 |  |

The complete set of connections required between the T5 and the three sensor groups are shown in Table 5.

Table : Pin assignments

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| T5 pin no | Purpose |  | T5 pin no | Purpose |
| 0 | Level 1 select |  | 22 | I2C SCL |
| 12 | Level 2 select |  | 21 | I2C SDA |
| 27 | Level 3 select |  | 36 | Digital input 1 |
| 26 | Sensor set 1 select |  | 19 | Digital input 2 |
| 25 | Sensor set 2 select |  | 32 | Analogue input |
| 33 | Sensor set 3 select |  | GND | Common ground |

Based on the figures in Table 5, the connecting cable requires 12 cores. To allow for unforeseen requirements, a 16-core ribbon cable will be used which includes two spare channels and UART tx and rx in addition to the connections shown in Table 5. A further requirement on the cables is that they can be detached from the two enclosures for transportation and installation.

## Modifications to sensor groupings

Two sensors that were originally part of the design – atmospheric pressure and water level – were removed for practical reasons. This meant that only one digital signal pin was required for the substrate temperature probes. However, it was discovered that the communication protocol used (OneWire) required them all to be powered at the same time. This was achieved by activating sensor set 2 on all three levels simultaneously.

All three pH sensors required power from the 3v3 supply. Since this was not switchable, each sensor would need a dedicated analogue signal pin. The digital pin freed by the removal of the water level sensor was used for this purpose and the third connection was provided by the spare pin. Thus, all three pH sensors could be activated at the same time by selecting sensor group 3.

A further power issue was discovered with the I2C sensors whereby the voltage drop when using a signal pin was too great. The solution was to abandon the level switching and provide power to all sensors simultaneously from the 3v3 supply. The sensor sets could still be switched on and off which meant that signal pins could still be shared across sets. However, a knock-on requirement was that the analogue sensors (moisture and EC) on different levels would have to use dedicated signal pins like the pH sensors. Table 6, Table 7 and Table 8 show the final sensor grouping and pin requirements. Note that

* SHTC3 has been moved from set 2 to set 1
* Pressure and water level have been removed
* Analogue sensors require three signal pins, one for each level

Table : Sensor set 1 (final)

|  |  |  |  |
| --- | --- | --- | --- |
| Sensor | Current (mA) | Connection pins | Type |
| GY-30 (Light intensity) | 0.19 | 0 | I2C |
| SHTC3 (Temperature, humidity) | 0.9 | 0 | I2C |
| Electrical conductivity | 6.0 | 3 | Analogue |
| Totals | 7.09 | 3 |  |

Table : Sensor set 2 (final)

|  |  |  |  |
| --- | --- | --- | --- |
| Sensor | Current (mA) | Connection pins | Type |
| Substrate moisture | 5 | 3 | Analogue |
| Substrate temperature | 1.5 | 1 | Digital |
| Totals | 6.5 | 4 |  |

Table : Sensor set 3 (final)

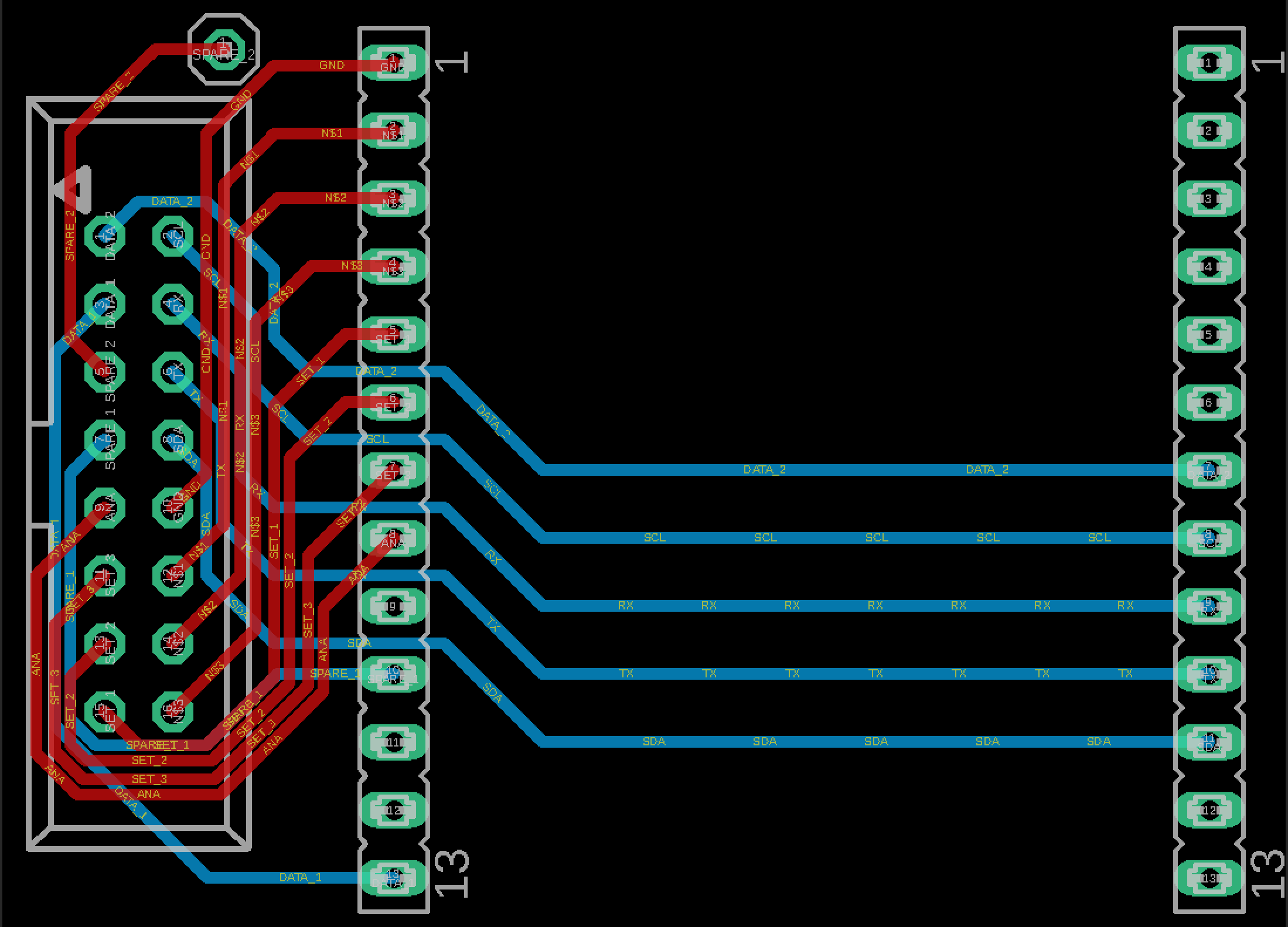
|  |  |  |  |
| --- | --- | --- | --- |
| Sensor | Current (mA) | Connection pins | Type |
| pH | 10 | 3 | Analogue |
| Totals | 10 | 3 |  |

Because of a limitation in the design of the ESP32 microprocessor, pin 36 could not be used for output as required by the OneWire protocol. An easy fix for this was to split off the first three cores of the ribbon cable at the T5 end and twist them over. This effectively swapped the assignments of pins 19 and 36 while leaving the intervening pin (22, SCL) unchanged.

## PCBs

A printed circuit board (PCB) was designed for each T5 enclosure and each sensor group enclosure. Both types of PCB house a shrouded IDC header for connection of the data cable.

The T5 PCB (Figure 8) included one spare signal pin connected to the T5 and a second spare pin that is not connected. This was to allow additional capacity for unforeseen requirements.



47.93mm

35.55mm

vbat

5v

13

15

2

14

19

22

tx

rx

21

gnd

3v3

gnd

0

12

27

26

25

33

32

3v3

34

rst

39

36

22

Tx

Rx

21

GND

0

12

27

19

36

-

34

32

33

25

26

Data 2

Data 1

Spare 2

Spare 1

Analogue

Set 3

Set 2

Set 1

SCL

SDA

Level 1

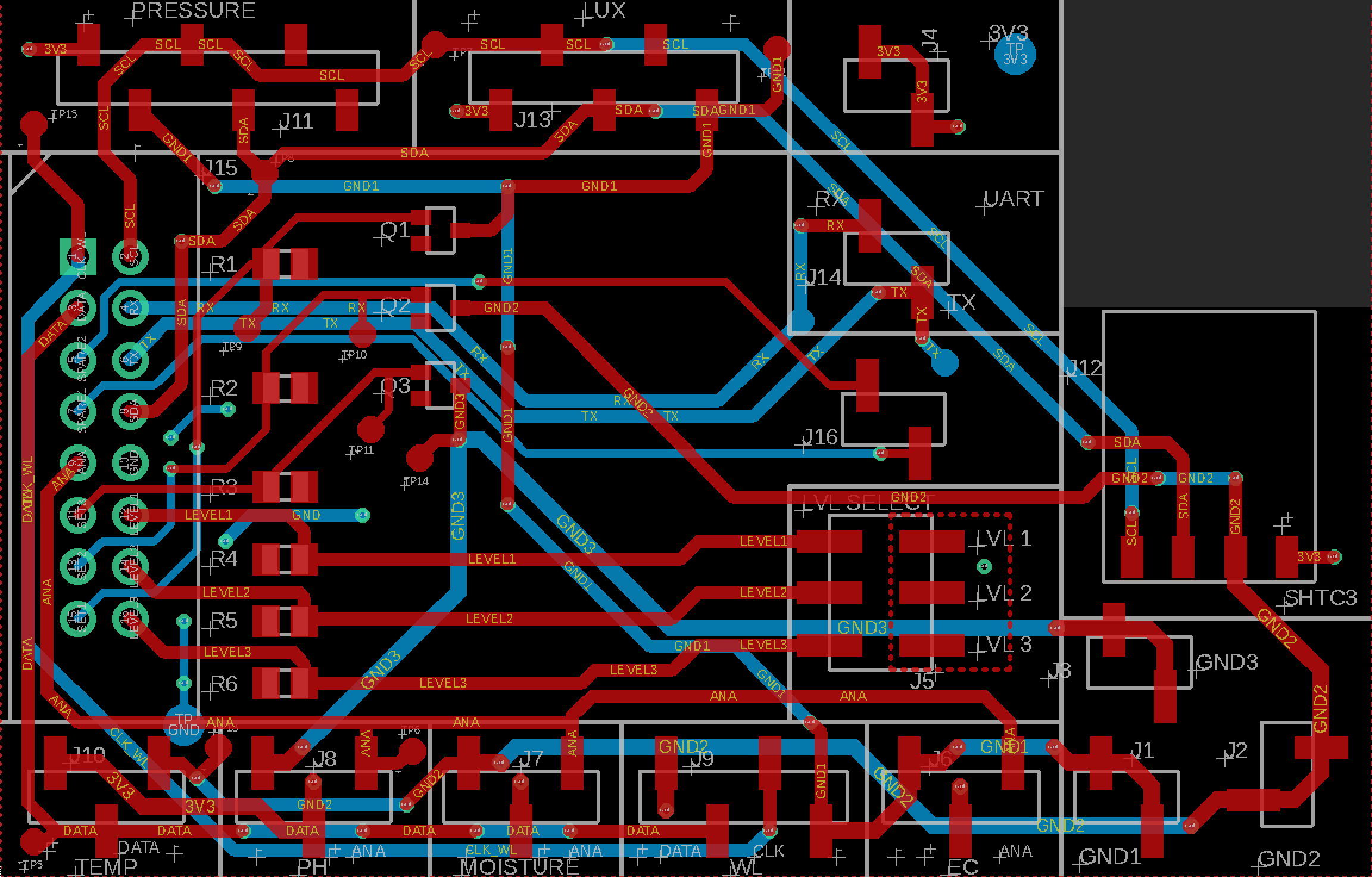
Level 2

Level 3

Correspondence between T5 pins and cable connector positions.

Figure : T5 PCB layout with planned pin assignments

The sensor PCB (Figure 9) houses a set of three jumper switches for level selection and a MOSFET for each sensor set. Each MOSFET is accompanied by a 47kΩ pull-down resistor to avoid false signals. In addition to the connections listed in Table 5, the sensor PCB breaks out the UART TX and RX connections to the T5, two spare signal pins that can be configured in software and power and ground connections for each sensor set. This is to provide extra capacity for unforeseen requirements. In the figure, red lines represent traces on the top surface of the board and blue lines represent traces on the bottom.



67.31mm

Light sensor

43.18mm

Switch MOSFETs for sensor set selection

Pressure sensor

Temperature/ humidity sensor

Jumper switch for cube level selection

Water level sensor

EC sensor

Moisture sensor

pH sensor

Temperature sensor

Cable connector

Figure : Sensor PCB layout

## Modifications to board design

The T5 board required two modifications:

* An additional female header had to be attached to compensate for the incorrect distance between the SMD headers
* The 3v3 power pin was routed via an additional wire to the unconnected spare pin

The second modification is shown by the black line in Figure 10.

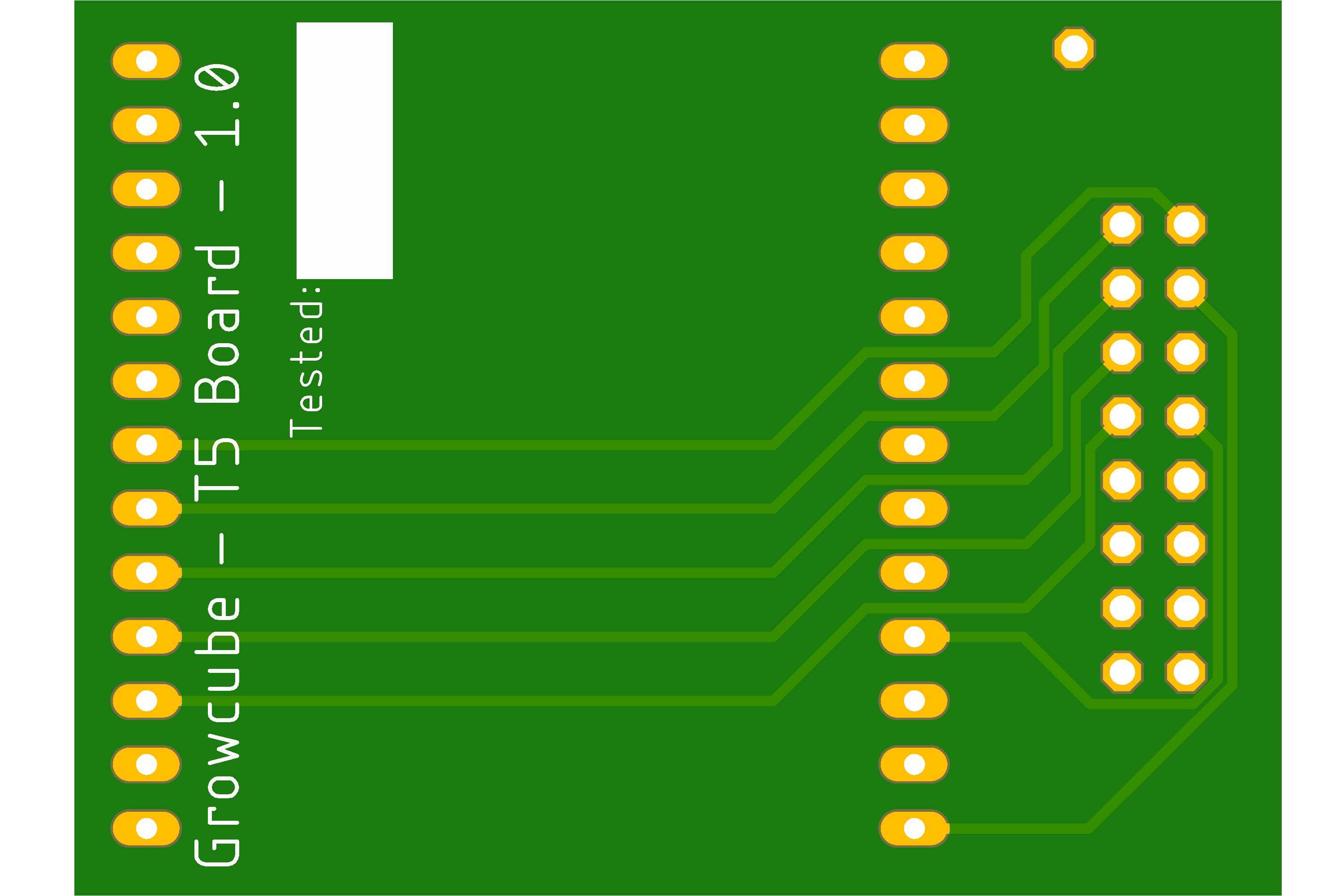
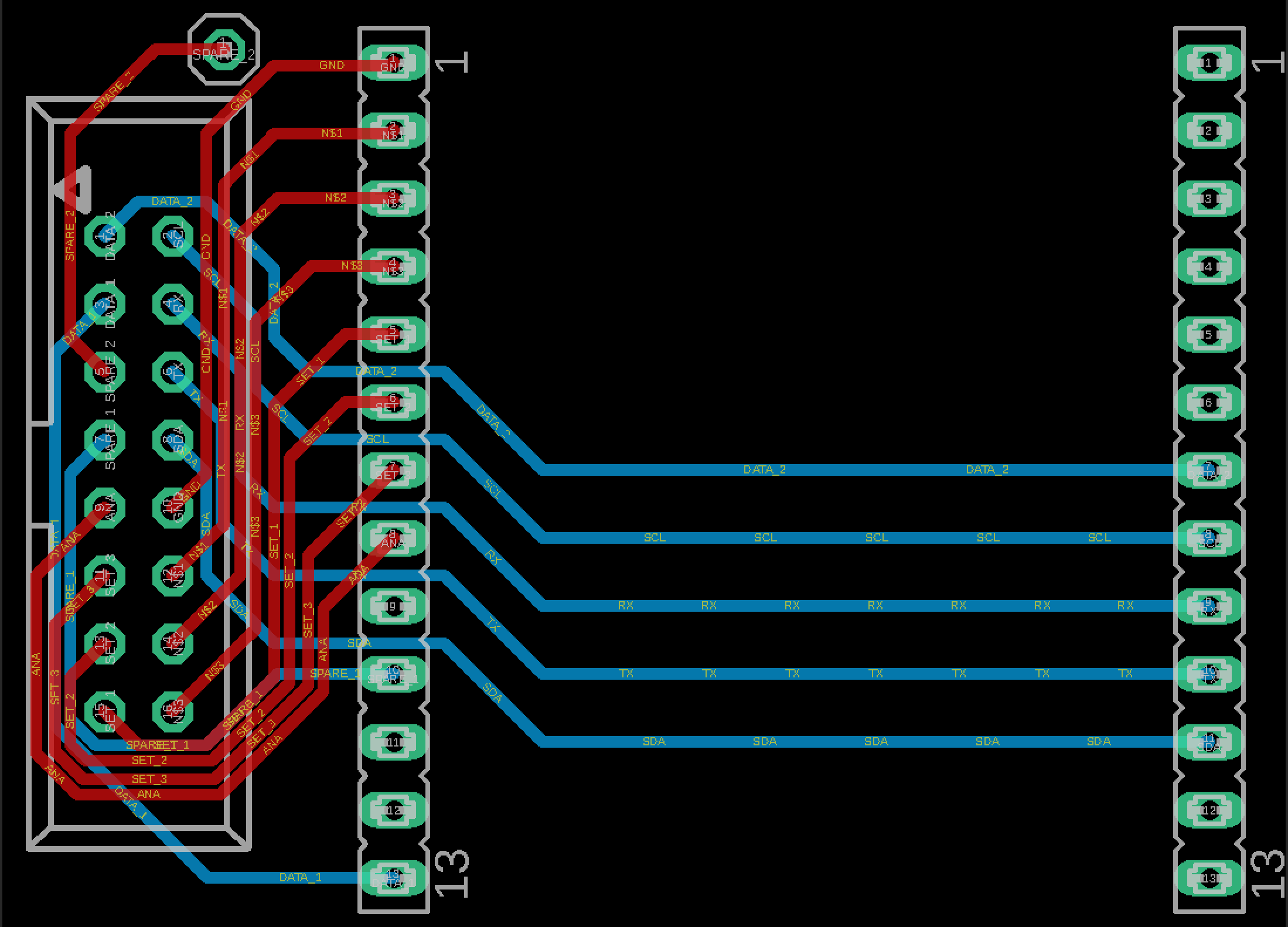


Figure : Surface wire modification to route 3v3 to the spare pin

In addition, the signal pin complement was changed from one analogue and two digital to three analogue and one digital.

After resolving several issues with the board design itself and the connection of sensors in the full configuration, the final system is as follows.



47.93mm

35.55mm

vbat

5v

13

15

2

14

19

22

tx

rx

21

gnd

3v3

gnd

0

12

27

26

25

33

32

3v3

34

rst

39

36

22

Tx

Rx

21

GND

0

12

27

36

19

-

34

32

33

25

26

--

Data 1

3v3

Analogue 2

Analogue 1

Set 3

Set 2

Set 1

SCL

SDA

Level 1

Level 2

Analogue 3

Correspondence between T5 pins and cable connector positions.

Figure : T5 PCB layout (final)

The top-level sensor board required one modification with three components to move the SHTC3 sensor from set 2 to set 1. The components were

* Cut the upper trace between J2 and the adjacent via (GND2)
* Cut the lower trace between vias opposite J12 (GND2)
* Make good the GND2 circuit with a surface wire having isolated the SHTC3

These modifications are illustrated in Figure 11 where the red lines indicate cut traces and the black line represents the surface wire connection.

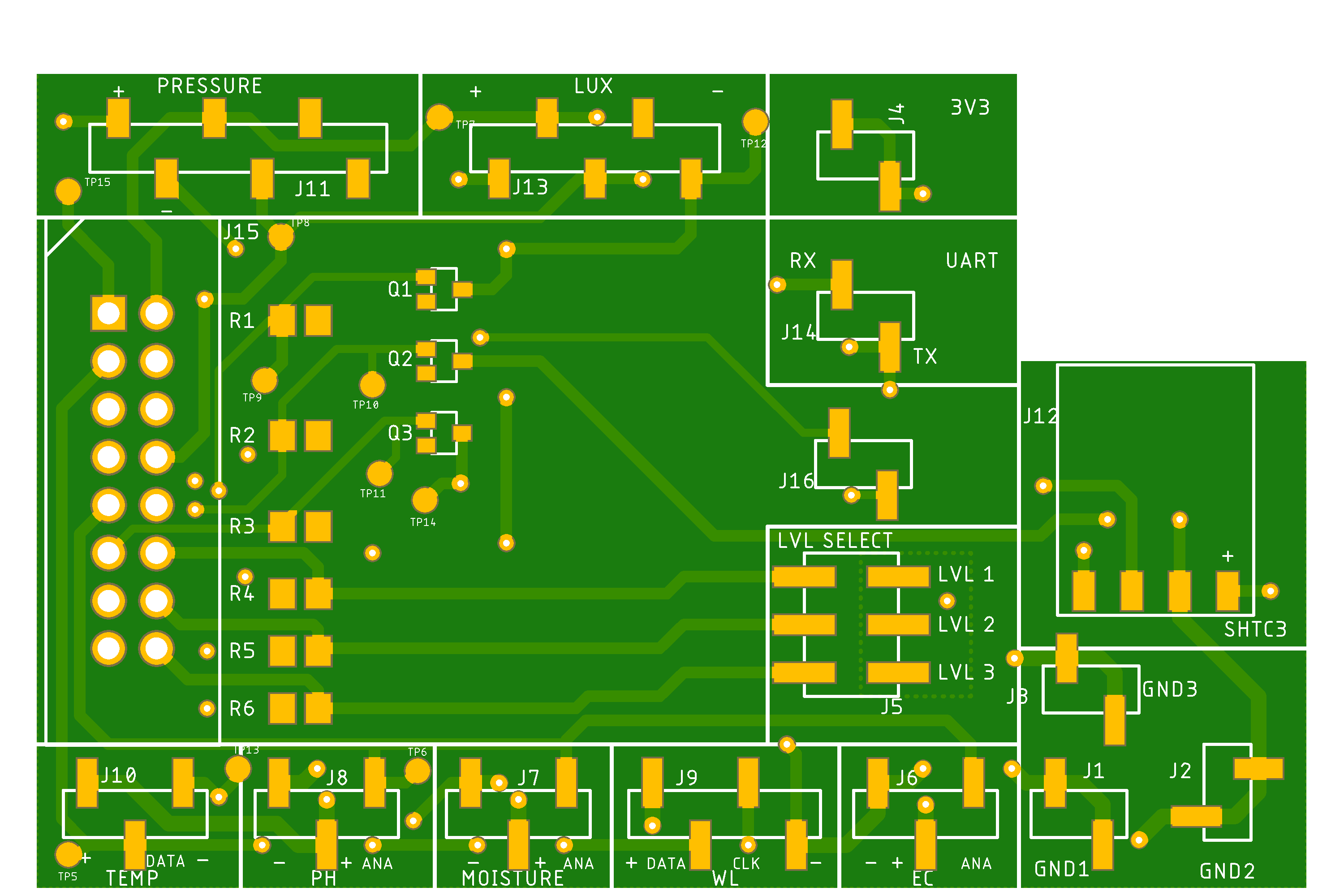
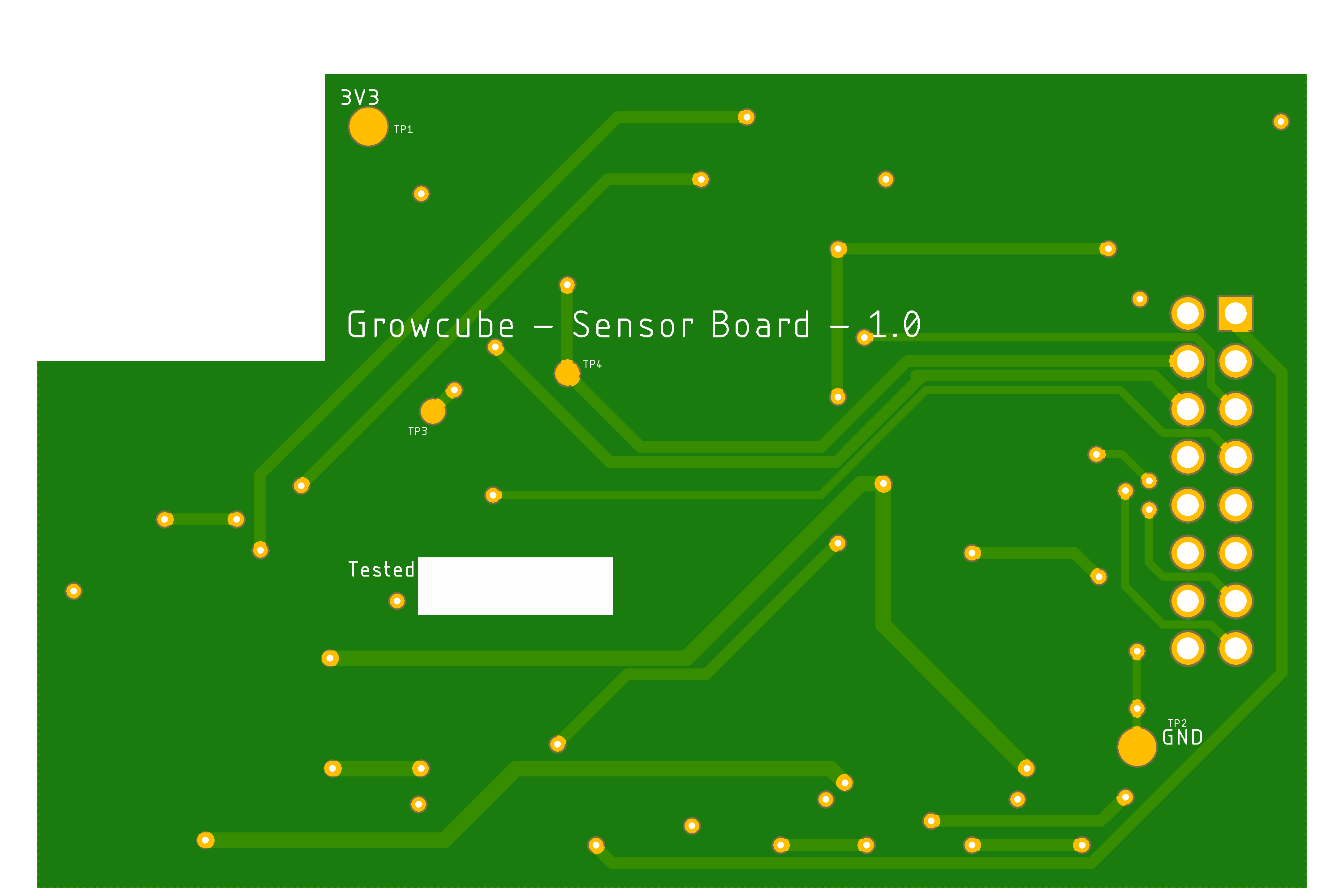


Figure : Sensor board modifications (left: top surface; right: bottom surface)

These modifications essentially isolated the SHTC3 sensor by cutting its connection to the set 2 ground (GND2) while keeping its power and I2C connections intact. The cut locations also ensured that the SHTC3 ground connection included the spare GND2 pins at J2. This meant that reconnecting the ground to GND1 was simply a matter of using a standard jumper cable to connect J2 to the spare GND1 pins at J1.

Because the I2C sensors could only be used in the top level of the GrowCube, these modifications were not required on the boards for the middle and bottom levels.

A second modification to the top-level sensor board was also required to provide a pull-up resistor for the substrate temperature probes. Because of the communication protocol used (OneWire), all three of the probes were activated at the same time with the shared signal wire acting as a bus. Thus, a single resistor on the top level board was sufficient for all three sensors. The resistor was added between the probe’s data connection and a conveniently located test via as shown by the dotted rectangle in Figure 12

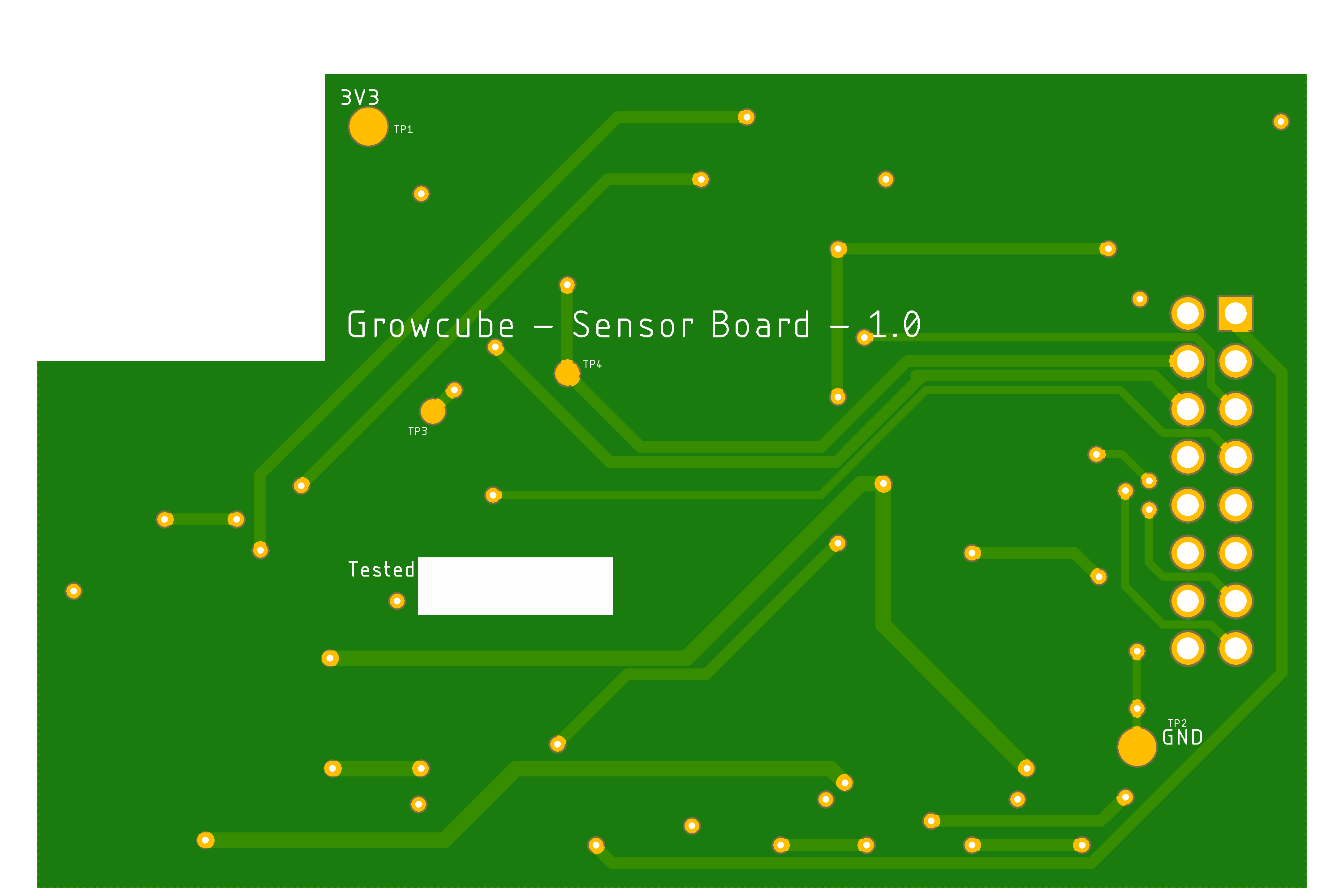


Figure : Pull-up resistor for the substrate temperature probes

## Connection re-routing

Accommodating the issues mentioned above in relation to the sensor power requirements meant that some data connections had to be changed on the sensor boards. A jumper cable was used to route the 3v3 power from the spare pin at J16 to the load side of the jumper pins at J5. This rendered the level select pins redundant

## Enclosures

The T5 microcontrollers will be housed in 3D printed enclosures similar to the one shown in Figure 11 which has been sourced from [3dmdb.com](https://3dmdb.com/en/3d-model/case-for-ttgo-t5-esp32-epaper-by-megacadler/8344093/?q=ttgo+t5+battery). The design will be adapted for the requirements of the Dandelion project.

Calendar

Description automatically generated

Figure : Example T5 enclosure from 3dmdb.com

Each sensor group will be housed in its own enclosure with additional smaller enclosures for the pH, moisture and water level sensors. The sensor enclosures will be connected to the T5 enclosure using a 16-core ribbon cable with each sensor group connected in parallel (see next section).

## Installation

The schematic in Figure 14 illustrates the position of the microcontroller and sensors in the GrowCube.

T5 microcontroller

Sensor group

16-core ribbon cable

Cable-mount male IDC connector

750mm

750mm

Figure : Schematic representation of GrowCube installation

There are several aspects of the physical installation that can only be finalised once an example GrowCube is available. This mainly refers to the length and precise route of the data cables. Figure 13 shows the layout for the sensor group in the middle layer of the GrowCube. In order to avoid congestion at the back of the cube, the position of the sensors will be offset so that they appear in position B1 in the top layer and D1 in the bottom layer. The patches shown are approximately 14x14cm giving 25 patches per layer with one of those taken up by the sensors. Patches may be combined in different ways for different experiments. For example, an experiment with one factor and three levels (e.g. Physical touch: no touching, gentle tickling, moderate tickling) would require three groups of plants. Each group could be confined to a single patch to leave room for other experiments. Alternatively, each group could occupy eight patches to fill an entire tray.

Main sensor unit

Substrate probes

596.54mm

631.54mm

BACK

FRONT

A

B

C

D

E

1

2

3

4

5

Figure : Layout of sensors and growing patches in the middle layer

## Data transfer

For security reasons, data transmission from the IoT nodes will be one-way. That is, only traffic from the nodes to the server will be permitted and not in the other direction. Transmissions are also encrypted using [AES 128](https://www.trentonsystems.com/blog/aes-encryption-your-faqs-answered).

The data will be formatted as JSON in the following way:

{

"timestamp": "2022-04-05T13:15:30Z",

"mac": 12:34:45:78:9A:BC,

"battery": "75",

"top": {

"quantity1": 1.23,

"quantity2": 2.34,

"quantity3": 3.45,

"quantity4": 4.56

},

"middle": {

"quantity1": 1.23,

"quantity2": 2.34,

"quantity3": 3.45,

"quantity4": 4.56

},

"bottom": {

"quantity1": 1.23,

"quantity2": 2.34,

"quantity3": 3.45,

"quantity4": 4.56

}

}

The meaning of each field in the structure is described below.

|  |  |
| --- | --- |
| Field | Explanation |
| Timestamp | The timestamp of the row of data in ISO format: <https://www.cryptosys.net/pki/manpki/pki_iso8601datetime.html> |
| MAC | The MAC address of the node. This is a hardware-level identifier used to identify the node to the app. Before data can be uploaded, the school superuser needs to associate their node’s mac address with their school through the app |
| Battery | A representation of the battery’s charge level expressed as a percentage.. |
| Top, middle, bottom | Data for the three levels of the cube |
| Quantity1, quantity2, etc | Named quantities measured by the sensors. In reality, these placeholder name will be replaced by the actual names of the quantities (‘temperature’, ‘pH’, etc.) |

## Interface

The user-facing features of the node will be accessible via a menu system that can be accessed by using the single button on the device. To make the best use of this limited interaction, the following conventions are adopted.

|  |  |
| --- | --- |
| Interaction | Description |
| Short press | Move forwards in the current menu level. On the last item in the current level, a short press will return to the first item. |
| Long press | Select current menu item. Where the current item is a sub-branch, the next item displayed is the first item in the sub-menu. Where the current item is a value option, a long press selects the option and returns to the parent menu level. |
| Double press | From a sub-menu, a double press returns to the parent item in the level above. |
| Triple press | Returns to the menu root from any point in the menu system. |

* Menu root (home display)
  + Top level
    - Most recent values
      * Calibrate water level
      * Calibrate substrate moisture
      * Calibrate pH
      * Calibrate EC
  + Middle level
    - Repeat structure for top level
  + Bottom level
    - Repeat structure for top level

The UI is laid out as follows.

250 px

128 px