INDIRES
Information Driven Incident Response

User Manual
Resilient, Survivable Environmental Sensors

3rd November 2020

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1 INTENDED AUDIENCE

An output of the INDIRES project is user documentation for each of the products produced during the project. However, the status of the various products differs and, for this reason, the intended audience for the *User Documentation* will be different for each product. It is necessary, therefore, to indicate the type of user who will benefit from this particular *User Document*.

The resilient, survivable environmental sensor unit described here was originally intended to be fully prototyped and tested in a mine environment. As work progressed, though, it became clear that decisions on so many aspects of the through-the-earth (TTE) communication system, that is essential to the operation of the fixed sensor unit, would be dependent on aspects of the mine including its size and layout and the geology. In particular, for optimal performance at minimal cost, it would be necessary to analyse the characteristics of the particular mine in order to select the type of antenna, the frequency of operation, the transmit power, the physical spacing of the nodes, and the network and routing algorithms. For this reason, a degree of flexibility was built into the electronic and software aspects of the sensor. However, it was not possible to offer such flexibility is all aspects of the design, and while the current prototype allows the operating frequency and the routing algorithms to be altered, the type of antenna and the maximum transmitter power are fixed. This led to the inevitable conclusion that the field tests that were to be carried should be considered as a proof-of-concept, in the sense that they would only prove the correct operation of a TTE system, including the fixed sensor unit, in a particular mine.

Unfortunately, the Covid-19 pandemic and its effect on industrial production caused problems with the manufacturing of the sensor housing, resulting in its very late and incomplete delivery. As a result of this delay, and bearing in mind that it became increasingly unlikely that it would be possible, due to Covid-19, to test the unit in a mine environment, those aspects of the design that would require adaptation to the specific mine were not completed. Accordingly, some additional development would be needed before the prototype developed in INDIRES would be in a suitable form for testing in a particular mine. Furthermore, following such a successful test, further research and development would be needed to establish a technique whereby the fixed sensor unit can readily be adapted to meet the requirements of a particular mine operator.

Accordingly, this *User Document* provides technical details about the sensor unit, as opposed to operational instructions, and it is, therefore, anticipated that it will mostly be relevant to organisations who intend to further develop and test the resilient, survivable environmental sensor unit. Such organisations are also referred to the *User Documentation* for the through-the-earth (TTE) communication system.

Developers who want to know more, and perhaps to discuss possible collaborative opportunities, are referred to *Section 9*.

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2 BACKGROUND

2.1 Requirement

Although the phrase “resilient survivable sensor” has been used in this project, the rather less verbose phrase “fixed (resilient) sensor unit” is used in this *User Manual* to refer to this piece of equipment. The word “sensor” can then be used in its correct sense, without ambiguity, to refer to the individual sensor elements used in the fixed sensor unit.

The rationale for the work, within INDIRES, on fixed sensor units, is based on the following facts:

1. Following an incident, rescuers are reliant on real-time data regarding the environmental conditions – for example temperature, and concentrations of carbon monoxide and methane – in the mine. This allows them to be fully informed of conditions that could pose a risk to the rescue operation.

2. Although environmental sensors are commonly used during the normal operation of a mine, such sensors, and their associated power and data networks, could be rendered inoperable as a result of incidents such as fire, explosions, mud or water inflow, rock bursts or falls of rock.

3. While the requirement isn’t quite as obvious as for environmental sensing, sensors capable of detecting signs of life, perhaps motion or sound sensors, could, potentially, alert rescuers to the location of any missing miners. This could influence decisions on where the most immediate rescue effort should be concentrated.

4. Sensors that are used during normal mine operation do not normally include a life-sign sensing capability.

The work carried out, therefore, aimed to provide an environmental sensing capability for post-incident use, that overcomes the main weakness of standard operational sensors, namely their susceptibility to damage.

2.2 Protection Scheme

The following decisions guided the overall protection concept:

1. The sensor unit should be mounted in the wall of the gallery, not the roof, to reduce the impact of hot gasses.

2. Facilities should be built into the sensor unit to provide protection against flooding. External high temperatures protection – a thermal shield – can be provided to cover the exposed parts of sensor’s enclosure, as the rock is a good heath shield for the buried part of the enclosure. The sensor should only be deployed when the temperature has reduced, and the water level has decreased.

3. Because protection from high temperatures and water has to be built into the unit itself, or through external shielding, the main risk that has to be protected

against by the method of mounting is an explosion blast, although some attention should be given to protection from falling objects.

4. Protection against an explosion blast can be provided by mounting the sensor unit in a recess or niche, not necessarily a hole, although the latter would be preferable.
5. If the unit is mounted in a recess, deployment could be achieved by a process internal to the unit.
6. In addition to batteries, the unit shall be provided with fixed power, to allow periodic monitoring and testing of the operational state of the unit. A capability for wired communications is to be included in the same cable.

2.3 Mounting Configuration & Installation Procedure – Drilling Constraints

Installation involves excavating a niche and drilling a borehole – see *Section 7*. Several possible orientations of the niche and borehole meet the requirements set out in *Section 2.2*.

As the method of installation was still open when the design work was carried out, the unit was designed to be installed using any of a variety of methods which are documented in an internal report, a copy of which can be made available to interested parties. However, a summary appears in *Section 7*.

These various constraints led to a decision on a fairly cylindrical shape for the enclosure. Moreover, the "sampling vents" that – when the device is opened – allow access of the external atmosphere to sensors, are located in the exposed end cap of the cylinder, rather than in one side.

A second constraint was the drilling capacity of the rigs commonly available in mines. A survey (details can be found in the above-mentioned internal report) among mining partners led to 130mm as the outer diameter. This diameter will allow enough room for installation of the electronics and sensors and will allow installation using commonly available134mm drill bits.

A third possible constraint was the length of the device. However, it was found that length was not a critical issue, as was only limited by practical handling and installation restrictions, like weight and roadway width, which in practice were not a limiting factor.

Summing up, the above considerations led to a cylindrical shape of the enclosure, with a 130mm outer diameter and a length of between 500 and 600mm. The enclosure allows a rebar to be attached to the back side for better anchoring in certain installation configurations, and sampling vents in the "front" side.

3 ELECTRONIC DESIGN AND SENSORS

3.1 Electronic Control Scheme

The electronics of the resilient sensor is largely based on the VLF Mesh Node prototype, that is the key element of the TTE communications system, which described in its own *User Manual*, but a summary of the requirements are provided below. When designing the mesh node electronics (dubbed XCVR-HF-01A), it was envisaged that it would at least fulfil a dual role, both as a mesh node and as the core for the fixed sensor.

To allow all the necessary sensors to be connected, an interfacing connector (marked as J7 in sheet 5 of the schematic diagram, included in this document as *Appendix A* (*Section* 10) was included in the design. A complementary sensor board, with a mating connector was designed to provide sensor support. This interface is identified as SIB-02 (Schematic diagram and PCB layout are included as *Appendix D* (*Section 13*) and *Appendix E* (*Section 14*14).

As XCVR-HF-01 was described in detail in the User Documentation for the TTE system, only a summary of its features is included in this document; while SIB-02 and sensors are described with more detail.

3.1.1 General Requirements

The general requirements of the electronics, are:

1. It shall be designed to be ATEX-compliant, M1 category (Ma EPL).
2. It shall have low power requirements, especially when in the sleep state. Possibly external power management shall be implemented.
3. It shall have the option of being powered either by an internal battery or an external, intrinsically safe power supply.
4. Awaking and going into sleep mode should be fast.
5. A real time clock is needed for maintaining synchronisation in the mesh networks (awake and listen at convened times).
6. It needs at least two serial ports, or ways of multiplexing two serial interfaces to a single serial port (one for the wireless and a second for the wired interfaces).
7. It shall have an integral LF or VLF wireless transceiver, including the power amplifier, although, depending on work in T1.2 that was still ongoing at the time this unit was being designed, it will probably be necessary to have an external antenna.
8. It shall have an isolated RS485 interface.
9. It shall support several types of interfaces, to allow the connection of standard and non-standard sensing devices (analogue, serial, I2C, SPI, etc.).
10. It shall be designed to fit in the pod enclosure.

It shall be noted that these requirements apply in full to a future commercial implementation. The prototype sensor complies almost all, but ATEX compliance was deferred to said commercial implementation. A path to ATEX compliance is provided in *Section0*.

3.1.2 Microprocessor Platform

The above will require the device to be designed around a microcomputer or a microcontroller.

3.1.3 Building Blocks

The electronic circuit of the fixed sensor unit had, therefore, the following building blocks:

a) Power supply (including the primary battery),

b) Microcomputer / microcontroller,

c) Facilities for external sensing devices,

d) Isolated wired communication interface,

e) Power amplifier (transmitting) for LF/VLF communication,

f) Antenna matching circuitry and, perhaps, the antenna itself,

g) Receiver LF/VLF front end,

h) Power interface for deployment device control.

3.2 XCVR-HF-01A

The XCVR-HF-01A was designed with a socket for a TEENSY class microcomputer module (32-bitARM architecture). In this socket, a TEENSY 3.5 module is plugged (TEENSY 3.5, manufacturer's data is included in *Appendix A* (*Section 10*). The selected module has enough I/O, memory and processing power for the application, fulfilling the requirements and having low-enough power needs. Most sensors can be connected directly – or with minimal interface circuitry – to it through a dedicated connector. Interfaces for a display and keyboard are also included.

A second building block comprises the radio (reception and transmission) interfaces, which allow great flexibility in the possible modes of operation, be they analogue or digital. An elaborated power supply circuitry, with low standby power and selective disconnection capacity, completes the design. Full circuit diagrams are included as *Appendix C* (*Section 12*). Details on the electronic design are provided the TTE system *User Manual*.

3.3 SIB-02 and Standard Internal Sensors

The SIB-02 module is basically a carrier for internal or integral sensors, and only includes them and the minimum circuitry needed for their operation and interfacing to XCVR-HF-01A. The circuit diagram, based on a well proven design already used in the

TELERESCUER project, is presented in *Appendix D* (*Section 13*), and its PCB layout as *Appendix E* (*Section 14*). The SIB-02 module includes 6 main sensors: CH_4, CO, CO_2, O_2, Relative Humidity + Temperature RH+T, and pressure P, and an interface for an external air speed sensor. Some of these sensors also provide their internal temperature T.

SIB-02 is pictured in *Figure 1*. In the top view, clockwise starting from bottom right are the O_2, CO_2, CH_4, CO and RH+T sensors. In the bottom view, the white dot on the left is the pressure sensor. It was designed to allow flexibility in actual implementations, so that some sensors (*CH_4, CO* and an auxiliary one) can be located remotely, or certain interfaces used for different purposes. In this implementation, CH_4, CO sensors are placed on the board, and the auxiliary interface is used for connecting a microphone for life sign monitoring. Depending on the type of microphone used, the connection can be made directly (three terminal microphones) or will need a few external components (for using two terminal electret microphones, for example).

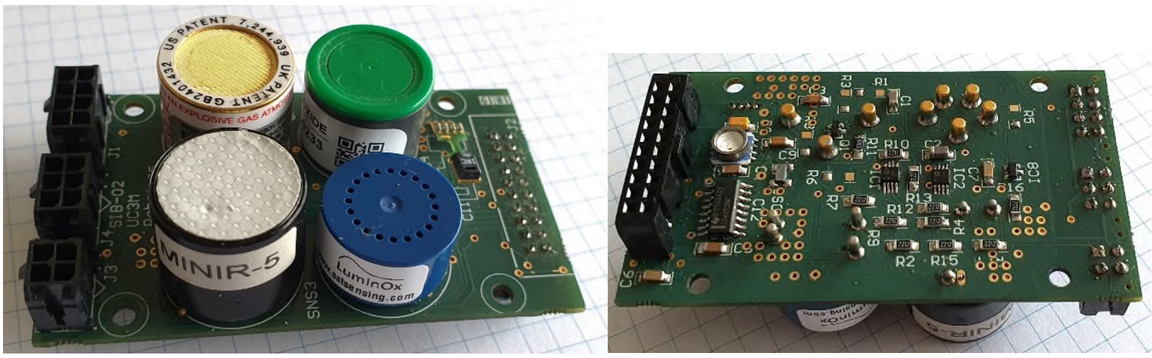

Figure 1 – Top (left) and bottom (right) views of SIB-02, with all sensors installed

Each sensor has its own, and in some case proprietary interface, and therefore dedicated interfacing circuitry was included in the design. In detail:

3.3.1 CH4 Sensor

This sensor is provided by DYNAMENT, with reference MSH2ia-LS/HC/5/V/P. This sensor has an analogue output, and a Full-Scale Range (FSR) of 20% V/V. Output electrical range is 0.4-2 V (a de facto standard for UK mining sensors). It uses infrared technology for measuring, so it is not affected adversely by high CH_4 concentrations or catalyst poisoning as are pellistor-based ones.

3.3.2 CO Sensor

The sensor is based on an ALPHA-SENSE electrochemical cell, of type CO-AE. This is a simple electrochemical cell, with a basic sensitivity between 10 and 25 nA/ppm CO. Therefore, it needs a potentiostatic circuit (built around IC2A) and a transimpedance amplifier (IC2B) to provide a voltage output, as needed by the core microcomputer. The whole circuit is designed to provide a voltage proportional to the concentration of CO in the air, with a sensitivity between 0,115 and 0.288 mV/ppm. Output electrical range is 0-2.5 V, providing a theoretical FSR in the range of 10000 ppm of CO, which is the limit for performance warranty (periodic calibration is needed, to account for changes in the performance of individual electrochemical cells).

3.3.3 CO_2 Sensor

This is a self-contained sensor using non-dispersive infrared (NDIR) absorption measuring technology, provided by CO2METER.COM (www.co2meter.com/). Its nominal measurement range is 0-5%, although in theory it can measure up to 0-100%.Accuracy is ±70 ppm ± 5% of reading at standard temperature and pressure (STP).

Readings are available in digital form, transmitted through a serial interface. Its parameters are as follows:

Parameter	**Value**
Baud Rate	9600
Data Bits	8
Parity	None
Stop Bits	1
Format	UART (normally high)
Hardware Flow Control	None
Voltage Voh	3V (MISIR Voh = Vsupply)
Voltage Vih	3V-5V

When powered on, the sensor starts transmitting a message with the format:

Z ##### z #####\r\n

where

Z ##### shows the CO_2 concentration after digitally filtering,

and

z ##### shows the instantaneous CO_2 concentration without any digital filtering.

The concentration is reported in ppm/10. For example, Z 01200 = 12000ppm = 1.2%

Note: the symbols "\r" and "\n" denote the ASCII characters <carriage return> (hexadecimal 0A, or 0x0A) and <line feed> (hexadecimal 0D, or 0x0D).

3.3.4 O_2 Sensor

The LuminOx family (LOX) is a range of factory calibrated oxygen sensors which measure ambient oxygen partial pressure (ppO_2) levels using the principle of fluorescence quenching by oxygen.

The model selected is LOX-02, which includes a barometric sensor. By default, LuminOx measures ppO_2 (partial pressure of O_2 in mbar) and temperature (°C). The pressure sensor included in LOX-02 model enables LuminOx to also measure barometric pressure (mbar) and to convert the ppO_2 reading to an oxygen concentration (% O_2).

Readings are available in digital form, transmitted through a serial interface. Its parameters are the same than in the case of CO_2 sensor:

Parameter	Value
Baud Rate	9600
Data Bits	8
Parity	None
Stop Bits	1
Format	UART (normally high)
Hardware Flow Control	None
Voltage Voh	3V (MISIR Voh = Vsupply)
Voltage Vih	3V-5V

The sensor has three operating modes (poll, stream and off). By default, stream mode is initiated on sensor power-up and supplies an output string approximately once every second. This provides the data for ppO_2, Temperature, Pressure, O_2 and Sensor Status. The format is provided below.

“O xxxx.x T yxx.x P xxxx % xxx.xx e xxxx\r\n”, where

O xxxx.x, xxxx.x equals the partial pressure of O_2 in mBar,

T yxx.x, y equals the sign ‘-‘ or ‘+’ and xx.x equals the temperature in °C,

P xxxx, xxxx equals the pressure in mBar,

% xxx.xx, xxx.xx equals the O_2concentration inpercent %,

and e xxxx should be “e 0000” = Sensor Status Good. Any other valuet indicates some malfunction (it is advised to contact the manufacturer).

Again, the symbols “\r” and “\n” denote the ASCII characters <carriage return>(hexadecimal 0A, or 0x0A) and <line feed> (hexadecimal 0D, or 0x0D).

The serial interface for O_2 and CO_2sensors is shared; and connected to one of the serial ports of XCVR-HF-01A board (Rx1). For this purpose, both the sensors’ serial outputs are connected to a multiplexor (IC4) and selected by Rx_Sel signal.

3.3.5 RH+T Sensor

This sensor is of the type SHT75 by SENSIRION. The SHT75 is a single chip relative humidity and temperature multi sensor module comprising a calibrated digital output; having the best accuracy in the SHT family. The device includes a capacitive polymer sensing element for relative humidity and a bandgap temperature sensor. Both are coupled to a 14bit analogue to digital converter and a serial interface circuit on the same chip.

The serial interface is two-line synchronous, and non-standard. Signals are clock and data. Clock shall be supplied by the external interrogator and has no minimum frequency. Maximum the clock frequency is 5MHz, although in practice it is much lower. The transmission speed is fixed by the clock rate. The data signal is bidirectional, and is used to several ends, ranging from starting transmissions to acknowledging them, and passing through actual data transmission. As the data exchange timing and method are non-standard and rather cumbersome, no more details are provided here (they can be found in SHXX datasheet).

What is important is that the sensor provides two basic readings: a humidity reading with 12-bit resolution (0-4095) and a temperature reading with 14-bit resolution (0-16383). Conversion to physical values is done using the formulae provided in the user manual. For temperature, the proposed formula is:

$$\text{Temperature} = d_1 + d_2 \bullet SO_T$$

where SO_T is the raw sensor reading for Temperature, d1 depends on power supply voltage and d2 equates 0.01.

VDD	d_1 [°C]
5V	-40.00
4V	-39.75
3.5V(3)	-39.66
3V(3)	-39.60
2.5V(3)	-39.55

For RH the proposed formula is:

$$RH_{linear} = c_1 + c_2 \bullet SO_{RH} + c_3 \bullet SO_{RH}^2$$

SO_{RH}	c_1	c_2	c_3
12 bit	-4	0.0405	$-2.8 * 10^{-6}$

where SO_{RH} is the raw sensor reading for relative humidity. In addition, if the temperature is significantly different from 25 °C the temperature coefficient of the RH sensor should be considered:

$$RH_{true} = (T_{°C} - 25) \bullet (t_1 + t_2 \bullet SO_{RH}) + RH_{linear}$$

SO_{RH}	t_1	t_2
12 bit	0.01	0.00008

Values higher than 99 shall be interpreted as saturation and displayed as 100% RH.

3.3.6 Pressure Sensor

This is an MS5540C device manufactured by TE Connectivity. MS5540C is a SMD-hybrid device including a precision piezoresistive pressure sensor and an ADC interface IC. It was designed as a miniature barometer/altimeter module and provides a 16-bit data word from pressure and temperature dependent voltages. A 3-wire interface is used for all communications with a microcontroller. This interface is electrically of the SPI (Serial Peripheral Interface) type, although the Chip Select is missing. However, this is not important in this application, as a one-to-one dedicated SPI (implemented in software) is used to extract data from MS5540C.

3.3.7 Auxiliary Sensor (Microphone) Interface

SIB-02 includes a spare analogue connector (marked as J4), with no pre-defined use. It is intended for connecting any type of 3-wire analogue sensor with 5V supply and analogue output, for example an air-speed sensor or a toxic gas (SH_2) sensor. In this case, a microphone, intended to detect “signs of life” is connected to this input.

3.3.8 Other Internal Sensors (Seismic)

The enclosure of the fixed resilient sensor has ample internal room, more than needed by its electronics and the above sensors. This extra space can be used to install a seismic sensor. For this purpose, the rear cover was designed with adequate thickness to allow the drilling of blind holes to install that seismic sensor (this was not implemented in the prototypes).

3.4 Sacrificial Deployment Sensors

The decision to deploy a fixed sensor unit (irrespective of whether that decision is made automatically or by human intervention) will depend, to a degree, on data concerning the environmental conditions in the vicinity of the fixed sensor unit. A decision to deploy could, perhaps, be made if power loss is detected but, preferably, there could be a few sensors, which can detect conditions that could be indicative of a serious incident having occurred, mounted externally to the fixed sensor unit’s protective pod. After some consideration, it was decided to install these on the front cover of the enclosure (*Figure 7*). Two sensors can be installed:

1. A temperature probe (using a M16 × 1.5 threaded hole), and
2. A pressure sensor (G¼" threading).

The first intended use is detecting nearby fires. Any 3mm temperature sensor can be used, for example thermocouples (requiring additional signal condition electronics) or resistance temperature-dependent sensors (RTD, for example PT100 type). A compression fitting (RS Ref: 839-9617) is used to hold and seal the device.

Figure 2 –3mm RTD Probe (left) and M16×1.5 Compression Fitting (right)

The pressure sensor is intended for a dual purpose: detecting shockwaves associated to explosions and for detecting flooding. For this purpose, a sealed gauge or an absolute pressure unit is needed. As the space available for installation is reduced, a small size unit, with G¼" process connection, like Keller’s PA-23SY (sealed gauge) or PAA-23SY (absolute pressure) shall be used. The full scale range shall be adapted to the foreseen risk. For detecting flooding, a unit with 1 Bar (PA) or 2 Bar (PA or PAA) FSR is most appropriate. For detecting explosions, 10 Bar FSR is more suitable. 5 Bar is a good compromise when both flooding and explosion detection are needed. Smaller sensors (for example PA-21C or PAA21-C) can be used, at the expense of reduced accuracy (50% of 23SY) and less over-pressure resistance (60% of 23SY), but with powering at 5V.

Figure 3 – Keller Pressure Sensors: 23SY on Left and 21C on Right

These sensors are considered potentially sacrificial, in the sense that they might be destroyed by a blast or fire so they might be able to provide data for only a short period of time following the start of an incident.

In some installations it may be decided not to use them. In this case, the drillings can be either be plugged or used to install flameproof glands for connecting external sensors or devices (this was the main reason for designing a M16 × 1.5 opening for temperature sensor installation. M16 × 1.5 is a common thread for electrical glands).

Finally, it must be noted that these sensors, not being intrinsically safe, are disconnected and rendered inoperative as soon as the fixed sensor is deployed (and anyway at this point they have already fulfilled their mission). A relay energized by the limit switch operated by the so-called locking plate is used for this purpose (for more details, see *Sections 6.2* and *0*).

3.5 Optional Additional Sensors

It was decided that an option should be provided to allow additional sensors to be added to a fixed sensor unit. Such sensors would be operable during normal conditions, that is not only in the aftermath of an incident, or during an incident affecting other areas of a mine. To minimise the cost overhead associated with this provision, and bearing in mind that not all mine operators will want to add extra sensors, it has been decided that a wired interface should be used. Needless to say, such sensors will not have the environmental protection that is provided for those sensors which are internal to the protective pod. As such, any additional sensors could be rendered inoperable following a serious incident. Having said that, it is recognised that, during the planning of the response to an incident, environmental data will often be sought from areas of the mine in which the conditions are not so severe as to destroy surface wiring.

A single connector will be provided to support a possible network of satellite sensors. It is important to consider which type of connector and communication protocol (serial, 485, 232, TCP, optical, Modbus, etc.) will be used, to ensure compatibility with standard commercial sensors.

Support for external sensors has been provided in XCVR-HF-01 through the interface marked as J9 in sheet 5 of its schematic diagram. It gives access to Serial Port 4 and control signals, which can be used to implement an RS-485 bus or a fibre optic interface for sensors, using any standard communication protocol, like Modbus. To complete this functionality, additional interface circuitry must be installed. However, no physical interface has been designed, as external sensors were not defined. On the other hand, implementing such interface is not a difficult task, and can be done quickly once the sensors are selected.

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4 COMMUNICATION

4.1 LF/VLF Through-the-Earth Communication

Information on the LF/VLF mesh transceiver (through the earth transmission, TTE) is provided in a separate *User Manual* so it is not fully repeated here..

In addition to the above, as monitoring the adaptation between the TTE transmitter and the antenna was necessary – or at least highly desirable –a power and standing wave ratio (SWR) meter was implemented (codenamed SWR-PWR-100),to be inserted between the power amplifier and the antenna. Its schematic diagram and PCB layout can be found as *Appendixes F* (*Section 15*) and *G* (*Section 16*), and a picture of the prototype appears in *Figure 4* (with a debug display installed –the display is not intended to be used in the resilient sensor).

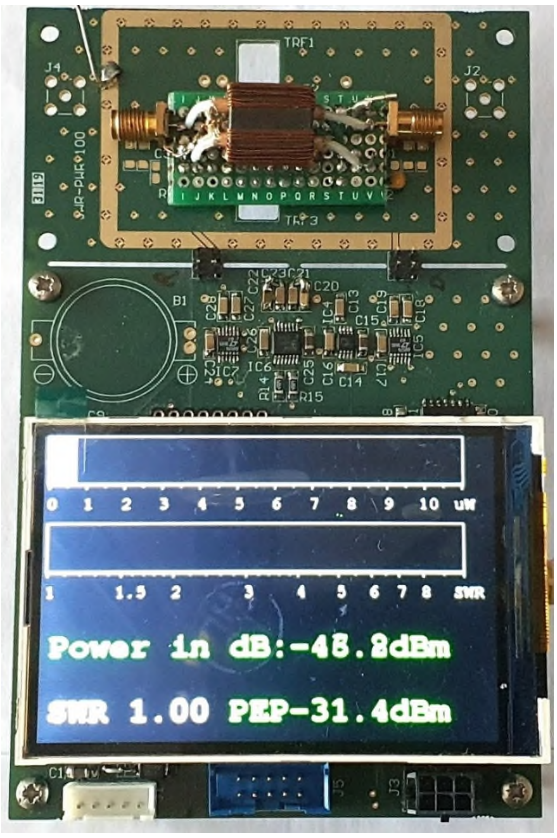

Figure 4 – Prototype of SWR-PWR-100 Power and SWR Meter with Debug Display

The meter is built around a reflection bridge (TRF1 and TRF3 in the schematics –as an alternative, a single transformer, marked as TRF2 can be used). The bridge samples a small part of the direct and reflected signals to the antenna and applies them to a logarithmic power meter (IC4) and to an RF power comparator (IC6). The last also provide relative phase information, although it is ambiguous, as only its absolute value is measured. To resolve the ambiguity, a second phase comparator was added (IC1A, IC5 and IC7), whose output indicates the sign of the phase between the direct and reflected signals. All signals are read and processed by a TEENSY microcomputer module. Moreover, two display interfaces were included, for testing and debug purposes.

The data collected by this meter is re-transmitted to the main controller (XCVR-HF-01) using an SPI interface (SCK2, MISO2, MOSI2), with all signals available in J5. Also, power and other lines that can be used as chip select, or to interface an external keyboard, are provided, to allow connecting more devices (like an automatic antenna tuner) to the same interface.

Finally, a general purpose RS485 interface was implemented, using TEENSY's Serial Port 5 and CI11 (configurable for simplex or duplex operation). Limiting resistors, with a view on future ATEX certification were inserted in all lines (R5, R6, R7 and R8). Also, an end-of-line resistor (R4) was included in the design.

4.2 Wired Communication

At an early stage of the design of the resilient sensors, it was decided that, since a wired connection to the fixed sensor units will be made to supply power for testing purposes, it was worth adding wired communication support. Wired communication is a convenient means for remote monitoring and testing the fixed sensors, while the cabling and installation cost overhead of such a provision is much reduced since a wired power supply is already present. Two main benefits of a wired communication facility were envisaged: power reduction and redundancy. Redundancy is a key to providing high levels of fault tolerance, an important consideration for safety critical equipment that will be used in a hostile environment following a serious incident. This approach offers benefits in the areas of increased service life during an incident and improved fault tolerance as a result of providing redundant communication interfaces. Moreover, after considering these aspects, it was decided that it would be more convenient that the primary communication will use the wired interface, with wireless used only if the wired communication fails.

Therefore, the routing algorithm, that is embodied in the fixed sensor units, utilises the wired network whenever it is available. When taking this decision, it was also considered that, although the fixed sensor units in the immediate vicinity of an incident may have no access to a wired communication network, it is probable that many of the fixed sensor units that constitute the mesh network as a whole will have access to such a provision.

4.3 Wired Communication Implementation

At the physical interface level, in practice, only RS485 and fibre optic are useable. Both have distinct advantages and peculiarities. Fibre optic has the advantage of its intrinsic galvanic isolation between fixed sensor units but would require a dedicated fibre optic cable, negating the advantage of using some wires in the power cable for data transmission. On the other hand, RS485, with isolated interfaces, is not difficult to implement. Experience in prior projects (for example, ECSC project 7220-PR133) shows that the speed-distance product rule can be extended far beyond the limits specified in the EIA-TIA standard (4000ft., 1200m), and reliable 9,600 bps communication can be established at a range of up to 20 km. Regarding the communication protocol itself, ModBUS is a simple and well proven option.".

After analysing carefully both options (fibre optic and RS485), it was concluded that the second offered more advantages than the first. However, both options are supported by XCVR-HF-01 hardware, and they can be implemented quite easily, although an external physical-level interface is required (for which real state is reserved in the lower part of the mounting tray of the resilient sensor). In both cases interface SPI port #2 (SCK2, MISO2, MOSI2) is used for this purpose. These signals are accessible in J9 (sheet 5 of the schematic diagram).

In the current implementation, advantage was taken of the RS485 interface available in SWR-PWR-100 (see *Section 4.1* and *Figure 5*). The microcontroller in this board, in addition to provide power and SWR readings, is used as a bridge to re-transmit data through its (wired) RS485 interface.

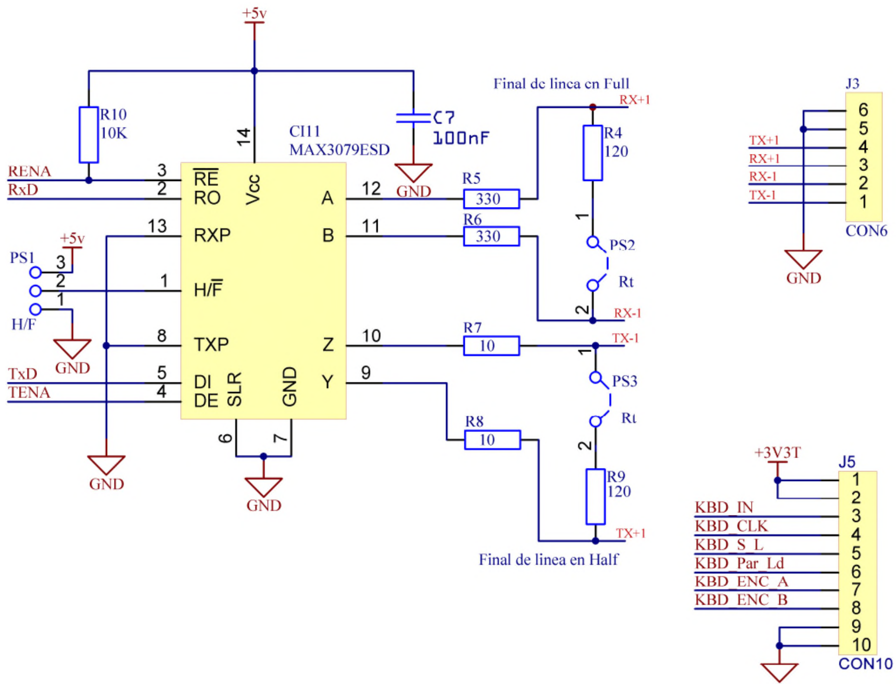

Figure 5 – SPI (J5) and RS485 (CI11 & J3) Interfaces in SWR-PWR-100 Board

Optionally, Teensy's serial port 6 (Rx6+Tx6) can also be used for direct RS485 communications, although a different interface board should be designed and included. SP6 signals are accessible through connector J8 of XCVR-HF-01 (sheet 5 of the schematic diagram), while control signals and power are provided through connector J9.

4.4 Communication Protocols

Information on the communication protocols are provided in the *User Manual* for the TTE equipment, while recognising that the network and routing algorithms will often depend on the characteristics of a particular mine. Therefore, it is to be expected that some adaptations will be needed in the firmware for use in each mine.

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5 POWER SUPPLY

The fixed sensor unit requires its own independent power source in the form of a cell or battery so that it can operate, following an incident, with no reliance on fixed power network which could have been rendered inoperable. The requirements for intrinsic safety, for ATEX certification, for example voltage and current, are acknowledged in this respect.

The decision of providing a wired supply of power, and of implementing wired communications, led to the use of secondary batteries. The main reason behind this decision was that the availability of a source of power for recharging the battery made its use more attractive than using non-rechargeable cells.

5.1 Requirements

5.1.1 Terminal Voltage

Most electronic circuits in the resilient sensor, including wired communications, can be powered from a source with a voltage down to 5V. However, the proper operation of the radio power amplifier requires a source with a voltage as high as possible (but below 12-13V). In laboratory tests it was found that the transmitter can operate reliably down to 8.4V (delivering approx. 850mW into 50Ω), so this is set as the minimum admissible terminal voltage.

5.1.2 Maximum and Average Current

On reception, the power consumption is around 90mA at any voltage, without displays.

On transmission, the current demand depends on voltage: 350mA @ 8.4V (Wout = 840mWinto 50Ω), 400mA @ 10.0V (Wout = 1200mW into 50 Ω),or 480mA @ 12.0V (Wout = 1730 mW into 50 Ω), again without displays.

Assuming a 5% duty cycle for the wireless transmitter, the average current needed for continuous operation (without applying energy-saving strategy) is around 112mA.

5.1.3 Minimum Capacity & Energy Density

A minimum operating time of at least 24 hours is desirable. Taking into account the above data, minimum capacity of the battery shall be 112mA × 24h = 2700mAh.

Energy density is not an issue in this application, as there is ample space available in the enclosure for installing the battery.

5.1.4 Shelf Life & Self-discharge Rate

The battery is charged using a trickle-charging strategy, and it is to be expected that it will be maintained at 100% capacity under normal circumstances. Therefore, shelf life or self-discharge rates are not significant issues in this case.

5.1.5 Size & Form Factor

Usually battery packs are of prismatic shape. The main constraints regarding size are that:

1. The battery shall fit in the space available between the mounting tray and the inner surface of the enclosure: cross section shall be less than 52mm (h) × 55mm (w). Up to 2mm more can be allowed in the height, but it will be required to mill a slot in the tray.
2. The length shall be less than 200mm.

5.2 Battery Selection

Secondary (rechargeable) batteries for use in explosive atmospheres shall be of one of the types (chemistries) listed in EN-IEC 60079-0 standard:

1. Pb-acid (Lead + H_2SO_4 electrolyte)
2. Ni-Cd (KOH electrolyte)
3. Ni-Fe (KOH electrolyte)
4. Li (Li-ion, Li-Polymer, $LiFePO_4$ + Non-aqueous organic salt)
5. Ni-MH (Nickel-Metal Hydride + KOH electrolyte)

Lead-acid are not convenient, as they can generate H_2 if overcharged, causing ATEX certification difficulties. Ni-Fe are non-standard. Li batteries, in their different variants are not too suitable, as in high capacities they are difficult to ATEX-certify. Among the remaining two, Ni-MH is preferred, for they are more environment-friendly, have no “memory effect”, have higher energy density and can be trickle-charged, not requiring complicated protection and safety devices.

The nominal selected voltage was 12V, well suited to power all circuits. A very convenient ready-made off-the-shelf pack was found, made of 10 C-size Ni-MH cells with a nominal capacity of 4000mAh. The nominal dimensions are 53mm (h) × 54mm (w) × 130mm (l). This is almost the maximum cross-section allowable, and suits very well the capacity needs of the resilient sensor.

5.3 Charging – ATEX Considerations

The batteries are trickle-charged at 120mA, according to the recommendations of the manufacturer of the pack (trickle charge at 0.03C → 0.03 × 4000 = 120mA). Expected charging voltage is less than 15V, typically around 14V.

To the above current, an allowance for operating the device shall be added. It has to be noted that the electronics will be in the “sleep” state most of the time, with very low power needs. It is estimated that, on average, no more than 10mA is needed, making a total of 130mA.

These values are well suited for ATEX certification. As said before, the charger is not designed to be certified directly, but an ATEX charger with the above parameters is easy to design.

Moreover, the output of the battery shall be limited, in such a way that it has a short-circuit current lower than 2.33A (Data extracted from EN-IEC 60079-11, Figure A.5 for inductive circuits of Group I with 1.5 safety factor). For this purpose, a resistor of 6.5Ω shall be inserted.

When fully discharged, the voltage of the battery will be 11.0V (1.1V/cell). At 400mA, a 6.5Ω resistor will cause a voltage drop of 2.6V, and therefore the terminal voltage will be 8.4V (the actual voltage it will be higher, indeed, as the current needed at this voltage is 350mA), therefore meeting the terminal voltage specification.

Summing up, it can be said that the ATEX certification of the power supply as an Ex ia (M1 category) device will be straightforward.

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6 PROTOTYPE DESIGN AND CONSTRUCTION – PATH TO ATEX COMPLIANCE

6.1 Requirements

Although the output of the design exercise should be only a proof-of-concept prototype, it was decided to go a step further, and to design a device with a view on a possible future production.

The prototype was designed to be fully compliant with ATEX certification requirements, with no (or minimal) modifications. Consequently, the requirements of the ATEX directive and standards for group I (mining), which are as follows, were considered:

- Directive 1999/92/EC, on safety and health protection of workers,
- Directive 2014/34/EU (most recent revision of the ATEX Directive), establishing Essential Safety Requirements (ESR), and equipment classification into categories,
- Relevant standards as listed in the *Official Journal of the European Union* (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018XC0309(05)), the following being the most relevant:
  - EN-IEC 60079-0: Explosive Atmospheres – Part 0: Equipment – General Requirements,
  - EN-IEC 60079-1: Explosive Atmospheres – Part 1: Equipment protection by flameproof enclosures "d",
  - EN-IEC 60079-11: Explosive Atmospheres – Part 11: Equipment Protection by Intrinsic Safety ”i”,
  - EN-IEC 60079-25: Explosive Atmospheres- Part 25: Intrinsically Safe Electrical Systems,
  - EN 60079-14: Explosive Atmospheres – Part 14: Electrical Installations Design, Selection and Erection.

As resilient sensors will be active when the methane level is higher than the statutory levels set in each country, they must go further by meeting the requirements for M1 devices (as defined in Directive 2014/34/EU), or the equivalent Ma Equipment Protection Level (as defined in EN-IEC standards). Also, any power supply unit which cannot be switched off (battery power pack) must meet the requirements for M1 (or Ma) devices.

It should be noted that the requirements of the ATEX directive and standards had to be considered when designing printed circuits, housing, connectors etc., because any redesign later could be very difficult.

We must comply with the requirements of the ATEX directive and standards for group I (mining). Because, of the high cost of ATEX certification, and because a detailed design which is suitable for manufacturing is likely to be taken either outside the project or late in the project, consideration should be given to finding a test facility that is not in a coal mine so the requirements of ATEX certification or other approvals do not apply.

6.2 Enclosure Design –General Aspects

The overall size and shape of the enclosure of the fixed sensor unit are constrained by two main factors:

1. the size of the electronics and sensors to be installed inside, and
2. the installation constraints discussed above.

A cross section sketch of the electronic devices that are the core of the fixed sensor is shown in *Figure 6* (this initial concept was modified later, as the detailed design progressed). The width of the electronic printed circuit boards is 80mm. Assuming a cylindrical enclosure, a mounting plate 108mm wide is sufficient to hold the sensor and control electronics at one side, and the batteries and power supply circuits on the other.

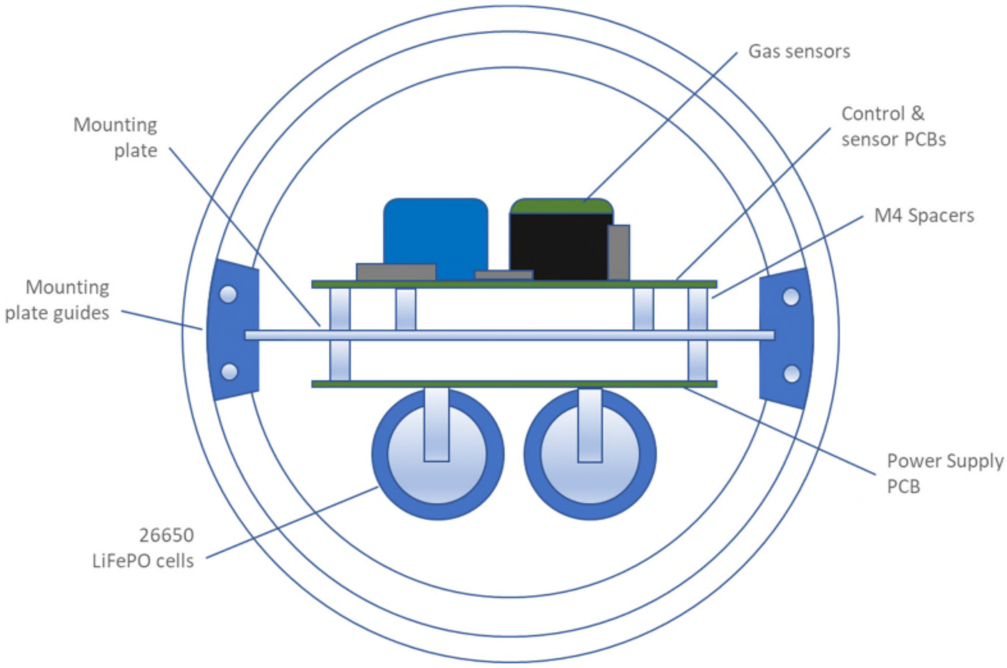


Figure 6 – Initial Sketch of Fixed Sensor Cross Section

On the other hand, ATEX compliance has an influence on design details, like external sensors, joining methods between housing components, cable entries, and the opening (when activating) method. Moreover, the enclosure shall be watertight when closed.

Most important is the actuator used for deploying the unit. A suitable high torque intrinsically safe actuator was not found and, therefore, a non-certified one had to be used.

This issue, in turn, made it necessary to design the enclosure to be flameproof while this actuator was powered, and to include provisions to de-energize it when the enclosure was opened for deployment, requiring manual rearming. Flame-proofness has an added benefit, as the high mechanical strength required by this protection mode make damage by shockwaves less likely.

This decision led an interesting technical problem: how to open reliably the enclosure, and how to de-energize the non-intrinsically safe components before the housing loses its flame-proofness. Eventually, it was decided to: i) use a single shell design and ii) placing the sampling vents in the exposed end cap of the cylinder. These had to be cylindrical, to make it easier to meet flameproof standard requirements. Moreover, they had to be:

1. Closed by a strong movable plunger, able to withstand the forces generated by any internal or external explosion.

2. Action should be spring-loaded, with a strong retaining mechanism, able to withstand the forces generated by any external and internal explosion or shockwave.

3. When released, it should move not too fast, in order to allow time for the automatic powering-off of non-intrinsically safe components.

These requirements were implemented with a compact design using a high torque servo as the actuator, the operation of which is described in *Section 0*.

All together, these factors led to the design shown in *Figure 7*.

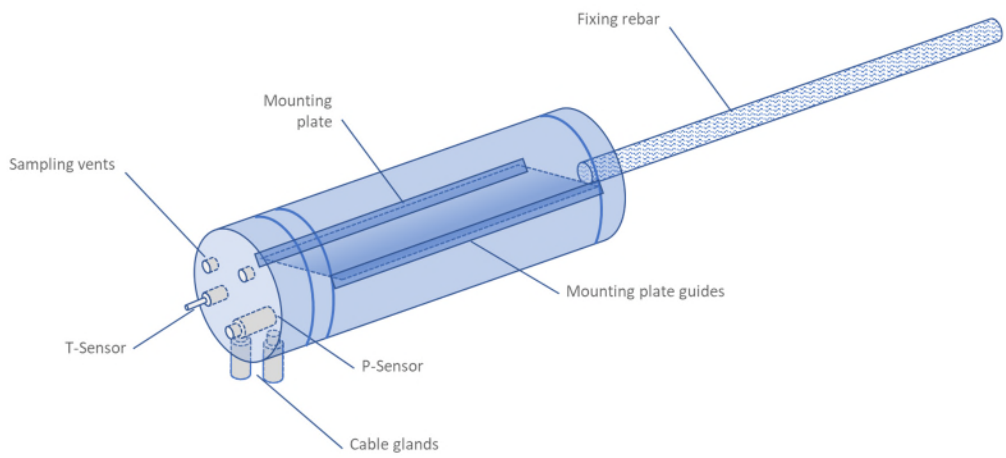


Figure 7 – Sketch of Fixed Sensor Overall Layout

Its main features are:

1. External diameter is 130mm, allowing the use of 134 mm drill bits for drilling its installation borehole.
2. The enclosure proper is composed of a front cover, an adapter ring (flange), a cylindrical body and a rear cover. Unions between them are flameproof (Ex d). Also, O-rings are fitted for water-tightness.
3. Can be open from the front, removing 6 hex socket (Allen) bolts. This allows easy inspection, servicing and resetting of the device. When the front cover (carrying

the glands for antenna and power / data cables) is removed, the mounting plate (or tray) can slide out, allowing access to electronics and batteries.

4. The body is 600mm long, much longer than needed for housing electronics and gas sensors. This allows the installation of seismic sensors on the rear cover, if needed. The rear cover is solid, and 25mm thick, so blind holes can be drilled without losing water and flame-proofness. Also, a rebar can be attached to the rear part, through a threaded blind hole.
5. It was considered unnecessary to add fire shielding. Rock will shield the sides and back, and, if needed, insulation material can be placed on the front cover.
6. The enclosure – and by extension, the fixed sensor – has two states: closed when sleeping and open when alive.
7. When closed it is watertight and flameproof (In the ATEX sense, protection mode Ex d).
8. When open, all operating circuitry is intrinsically safe (Ex i).
9. It has pressure and temperature sensors to allow the external conditions to be checked before opening.
10. When open, two 8mm sampling vents allow the ingress of external atmosphere for analysis by the internal gas sensors and to "hear" external noise with a microphone.
11. The vents are normally obturated by plungers. These plungers are spring-loaded and will open only when a locking plate is released. But, when closed, they are designed to make a flameproof joint with the cover. Moreover, they have O-rings for water-tightness.
12. The actuator for opening it is a high-torque servo (non-Atex certified), moving the retaining catch that holds the locking plate. A limit switch is fitted and wired to interrupt power to it when the retaining catch releases the locking plate (and plungers) (At this point, the enclosure is still flameproof (Ex d)).
13. Resetting (rearming, closing plungers and repositioning the locking plate and retaining catch) is done manually, as it will require an inspection of the device.
14. The enclosure has to be designed for a minimum of 25 bar overpressure, both internal and external.

6.3 Mechanical Strength – Overpressure Endurance

A key point for the survivability of the sensor is its capacity for resisting overpressures, both external and internal.

Typically, overpressures in the range of 10 to 15 bar are specified in ATEX flameproof enclosures certificates for individual testing (this is 1.5 times the maximum pressure measured during enclosure type tests). For this enclosure, the limiting factor is the strength of the bolts used to join the front cover to the adaptor or flange. The cylindrical part has a design strength of more than 350 bar, and the M122 × 1.5 threading has a similar rating. On the other hand, the six M5 bolts (A2-70 quality) have a combined proof strength of 38.34kN, equivalent to an internal overpressure of 33,9 bar. This strength is considered sufficient for guaranteeing flame-proofness.

When considering external overpressure, like that during flooding or by an external explosion, bolts have no influence, as they do not have to support any load. In this case, the literature reports overpressures in the range of 6 bars for methane explosions (Rongjun et al., 2012) and of 8 bars for coal dust explosions (Sulaiman *et al.*, 2011).

Again, the strength of the enclosure proper has ample safety margin (over 350 bars). In this case, the retaining mechanism of the plungers closing the sampling vents is the weakest link in the chain, but not too much (it is designed to bear more than 100 bars external overpressure).

Summing up, the enclosure is designed for internal overpressure up to 34 bar, and external overpressure in the range of 100 bars, offering ample margin to bear and resist the foreseeable actions on it.

6.4 Enclosure Detailed Design and Fabrication – Path to ATEX Compliance

In order to facilitate the manufacture of the enclosure, for easier servicing, and for also meeting the general requirements outlined above, the enclosure has been designed in such a way that it can be constructed from billets and raw stock readily available from usual suppliers. A 3D model was prepared, and detailed construction drawings generated from it. As a sample, *Figure 8* contains the manufacturing drawing for the front cover.

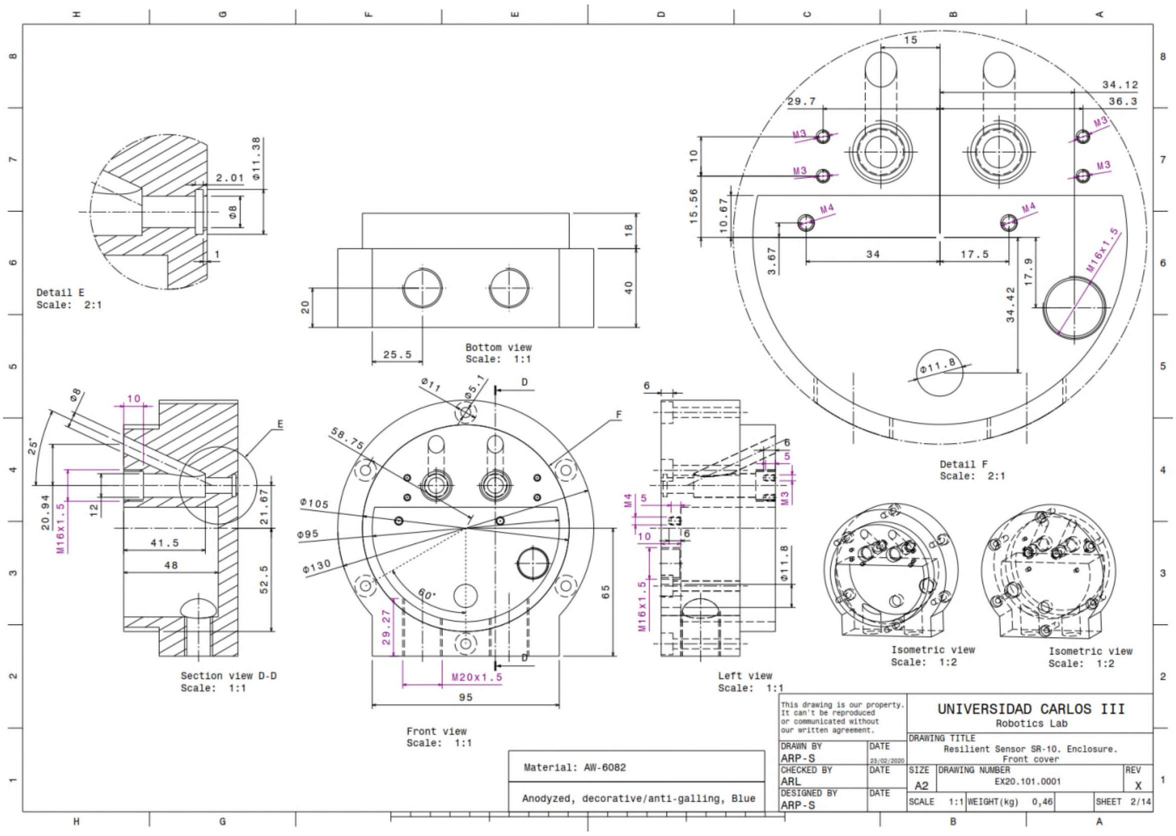


Figure 8 – Front Cover – Manufacturing Drawing

Machining is needed, but only common machine tools available in any CNC workshop are necessary.

The overall design and an internal view are shown in *Figure 9*, in which numbers make reference to sheet numbers containing the detail manufacturing drawings. Both front and rear views are shown (in the rear view the central part was removed to show the internal construction).

The enclosure is built starting from a metal cylinder or pipe, with 130mm outer diameter and 5mm thick. In the rear, it is closed using a threaded cover. Threading (M122 × 1.5) is designed to make a flameproof threaded joint according to the requirements of EN-IEC 60071-1. Moreover, an O-ring for water tightness is installed.

The front cover (*Figure 9*) is the most complex part of the enclosure. It contains several threaded openings for different purposes. It has two for glands in the lower part, one for power and wired communications and other for the antenna cable. At the front, it has other two, one for a temperature sensor (M16 × 1.5) and the other for a pressure sensor (G¼"). All threading is also designed to be flameproof and the openings watertight.

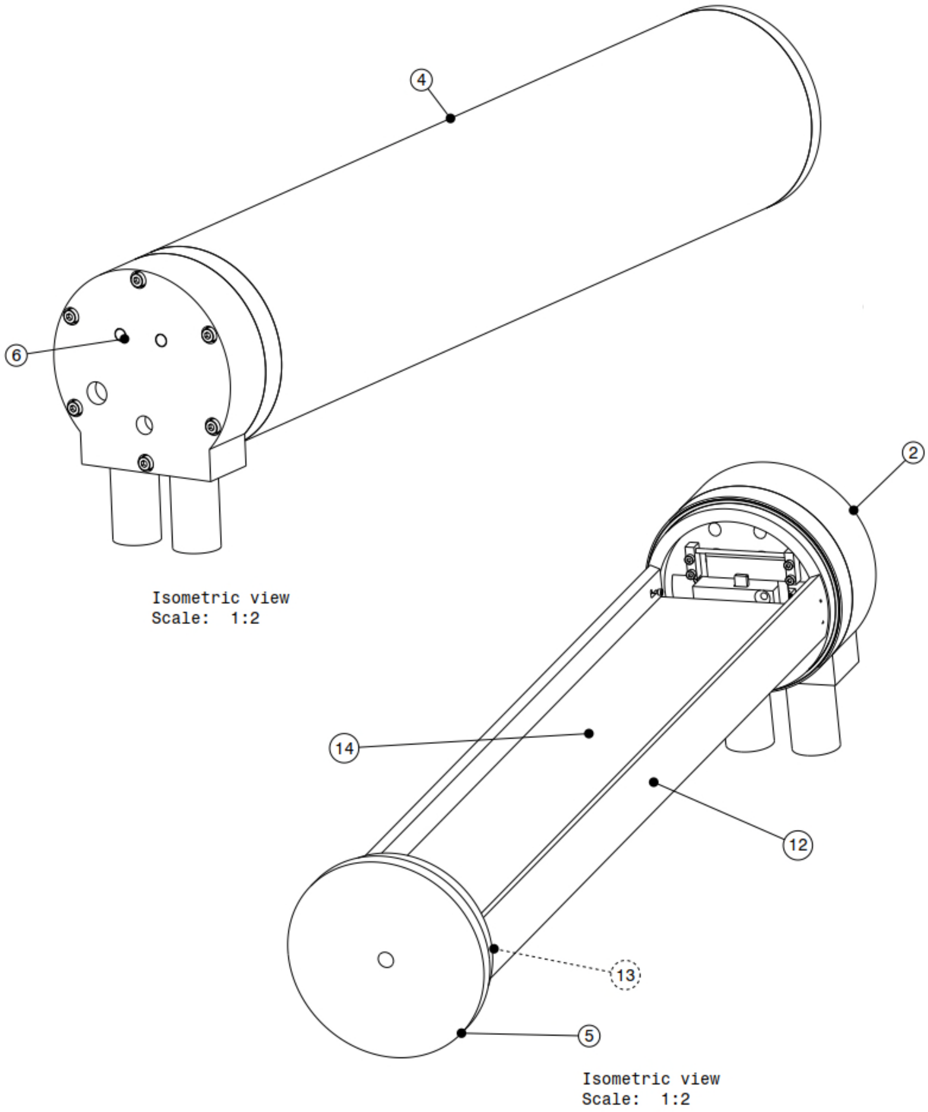


Figure 9 – Enclosure – Overall View.

It also has two sampling vents, normally closed by a pair of plungers, whose operation will be discussed later. Again, the plungers make a flameproof joint with the cover and are watertight (O-rings are fitted) when they are in the standby configuration (closing the vents).

The front cover must be bolted, to allow its disassembly during manufacture, installation, inspection and maintenance. Six stainless steel M5 bolts, quality A2-70, are used for this purpose, providing enough strength for resisting internal pressures of more than 34 bars. However, the thickness of the central body walls is insufficient for directly drilling and threading the mating holes in it, so an intermediate adapter, or flange, is interposed (*Figure 10*).

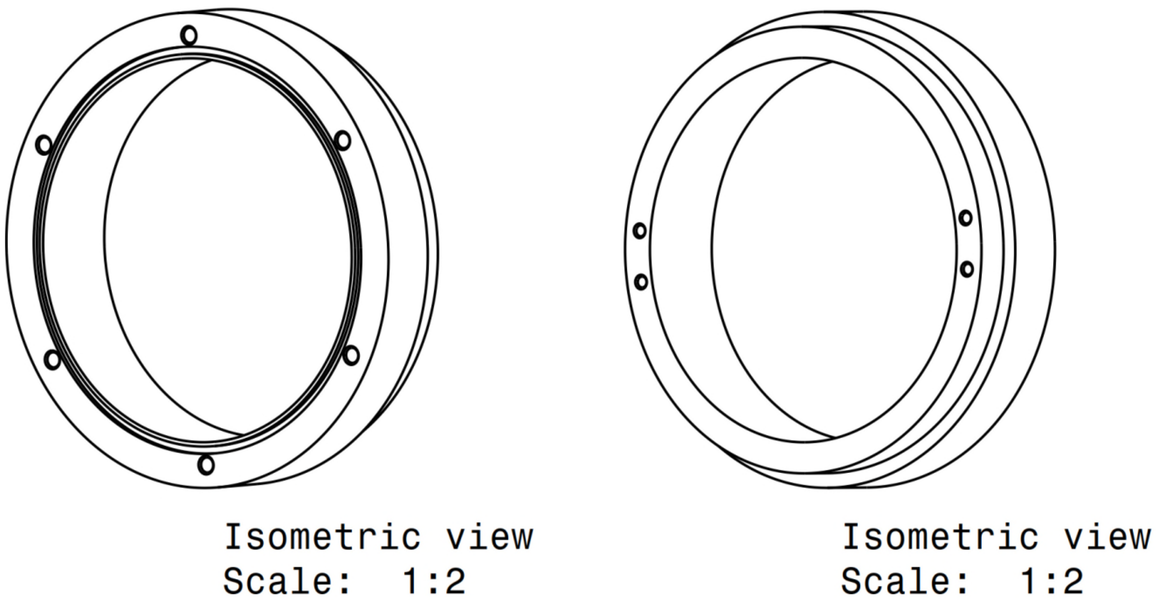


Figure 10 – Front Cover – Adapter/ Flange

This adapter has a threaded end (M122 × 1.5), like that in the rear cover. It is also flameproof, and watertight when screwed onto the main body. On the front side it has six blind threaded holes and a groove for an O-ring. The inner cylindrical part is designed to form a flameproof joint with the front cover.

A pair of mounting plate (or tray) guides is fitted to the adapter in the front and to the back cover in the rear. It is joined to the rear cover using cotter pins, and to the front flange spring-loaded plungers. These guides have a groove on which the mounting plate can slide, to allow it to be extracted, with all the electronics, when needed for inspection or service.

Finally, it must be noted that prototypes – which are ultimately a proof-of-concept – were made of aluminum alloy, to facilitate manufacture. Certifiable devices would be made of stainless steel, using the same drawings.

6.5 Operation of the Deployment Mechanism – Path to ATEX Compliance

Only the mechanical details of deployment mechanism are discussed here, as the criteria for triggering this operation will be discussed later. Mechanically, the deployment of the sensor is done by opening two sampling vents, 8mm in diameter, to allow the ingress of the external atmosphere to the internally installed gas sensors. It also allows sound to pass to the internal microphone. The mechanism for opening was kept as simple and compact as possible, while maintaining the high strength required to survive a shockwave.

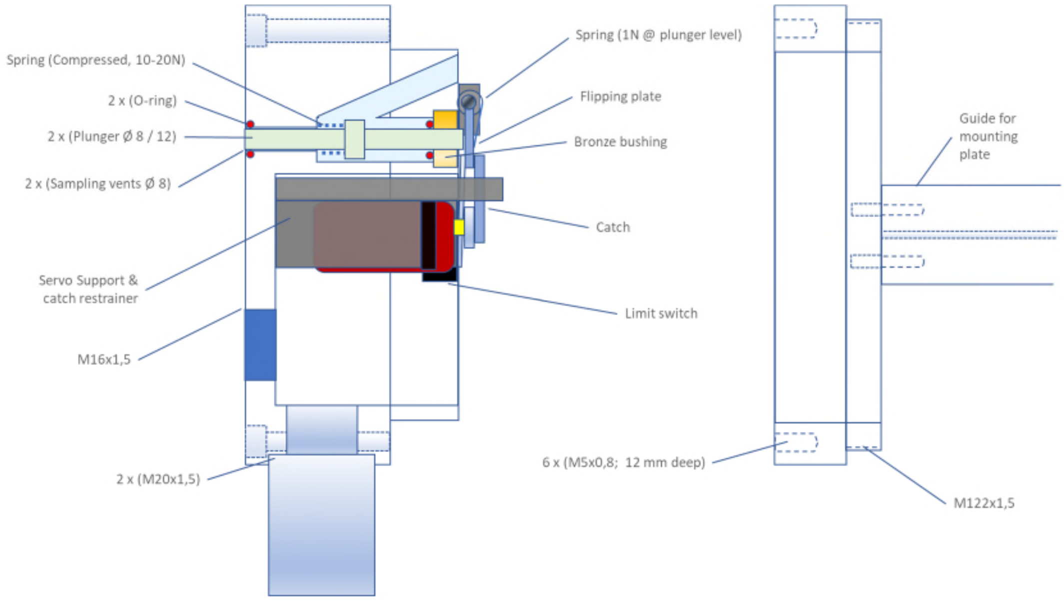


Figure 11 – Sketch of Front Cover and Flange Cross-sections

The mechanism is self-contained and built totally on the front cover of the housing. A cross section is shown in *Figure 11*. It has a vent piercing it with its axis parallel to that of the enclosure. This vent is 8mm in diameter on the outer side, and 12mm on the inner side. An oblique vent, 8mm in diameter, is also drilled (all these drillings are colored in pale blue)

In the closed state, the vent is closed by a stainless-steel plunger (in pale green in the sketch), with a maximum fitting tolerance of 0.4mm according to the 60079-1 standard. The engaged length meets the requirements of said standard, also 12.5mm. On the outermost side, a groove holds an O-ring for providing water and dust tightness. On the inner side of the cover, the vent is closed by a bronze bushing, on which the other side of the plunger slides.

The plunger has a shoulder on which a compressed spring exerts force. This spring would open the vent should the plunger be free to move. However, its movement is restrained by a locking plate. This plate can rotate on an axis in one of its sides, but the plate is locked by a catch. In turn, this catch is held in place by a catch restrainer and the arm of a high torque servo (dark red). The catch restrainer is integral with the servo support and made of high-strength material. A 3D model rendering of the assembly, showing inner details is shown in *Figure 13*. *Figure 14*, shows only the visible parts (the spring-loaded plungers on the left are used to hold in place the guides or rails for the mounting plate).

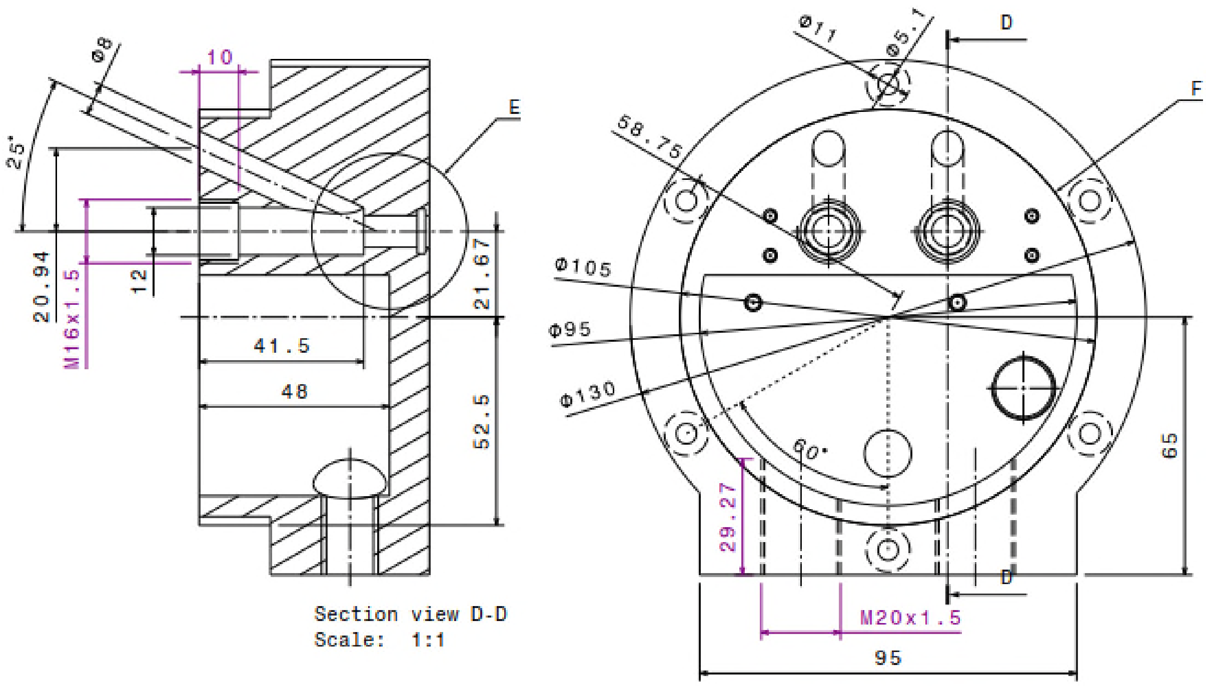


Figure 12 – Actual Front Cover Construction Drawings

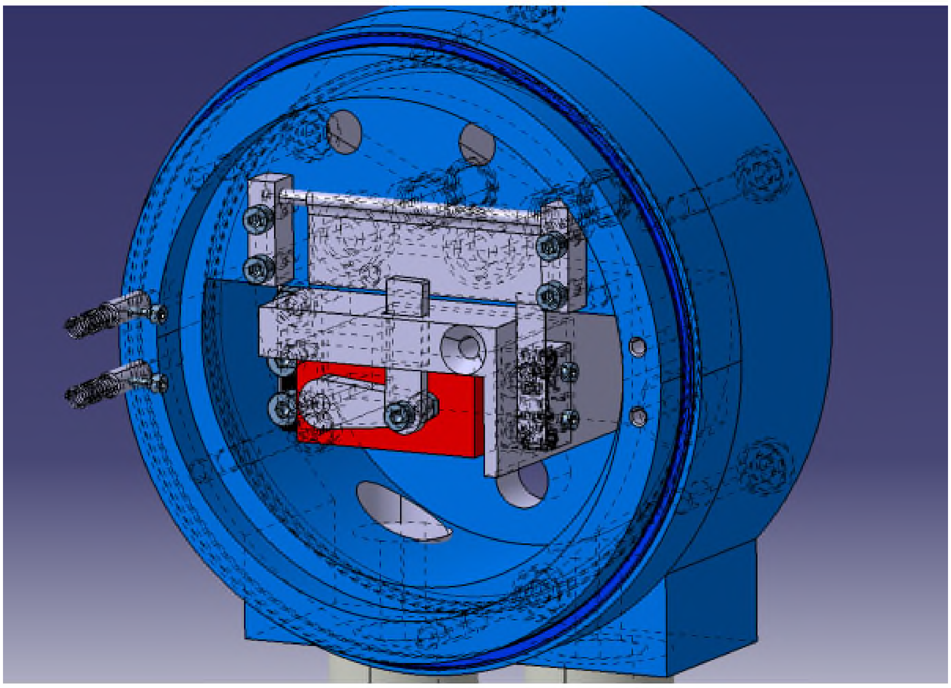


Figure 13 – Front Cover and Flange Rear View showing Inner Details

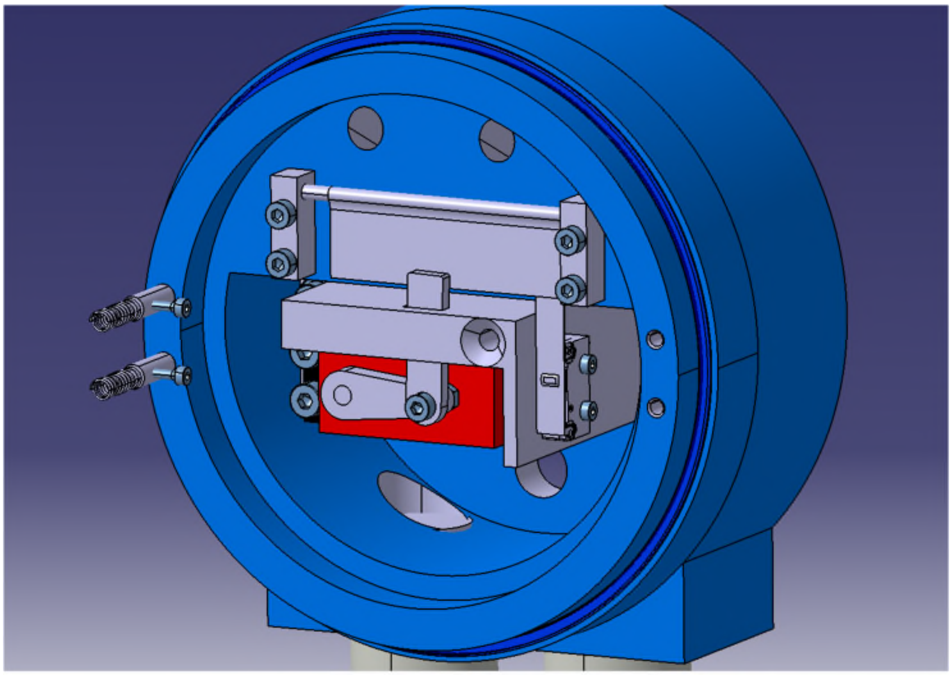


Figure 14 – Front Cover and Flange Rear View – Closed State

When the fixed sensor is to be deployed, the servo is commanded to turn its arm, retracting the catch and releasing the locking plate. This plate, pushed by the plungers' springs, turns and releases them, allowing the movement of the plungers and the opening of the vents (*Figure 15*).

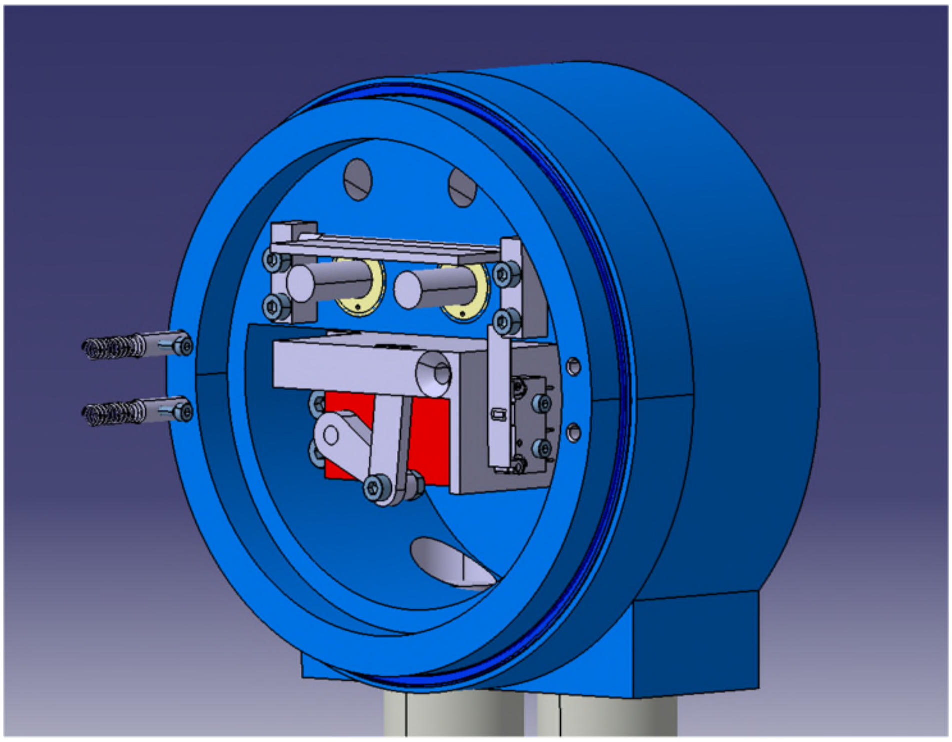


Figure 15 – Front Cover and Flange Rear View – Open State

The movement of the locking plate also releases the lever of a limit switch, which shuts down all non-intrinsically safe circuits, including the above mentioned servo. Moreover, the opening process is not instantaneous. The bushing and the shape and fit of the inner drillings constitute a dampening device that limits the speed of the plungers. In this way, the enclosure is still flameproof while the non-intrinsically safe circuits are being disconnected.

6.6 Prototype Enclosures

In the following figures (*Figure 16* to *Figure 19*), some construction details and a general internal view of the enclosure prototypes (as built) are shown.

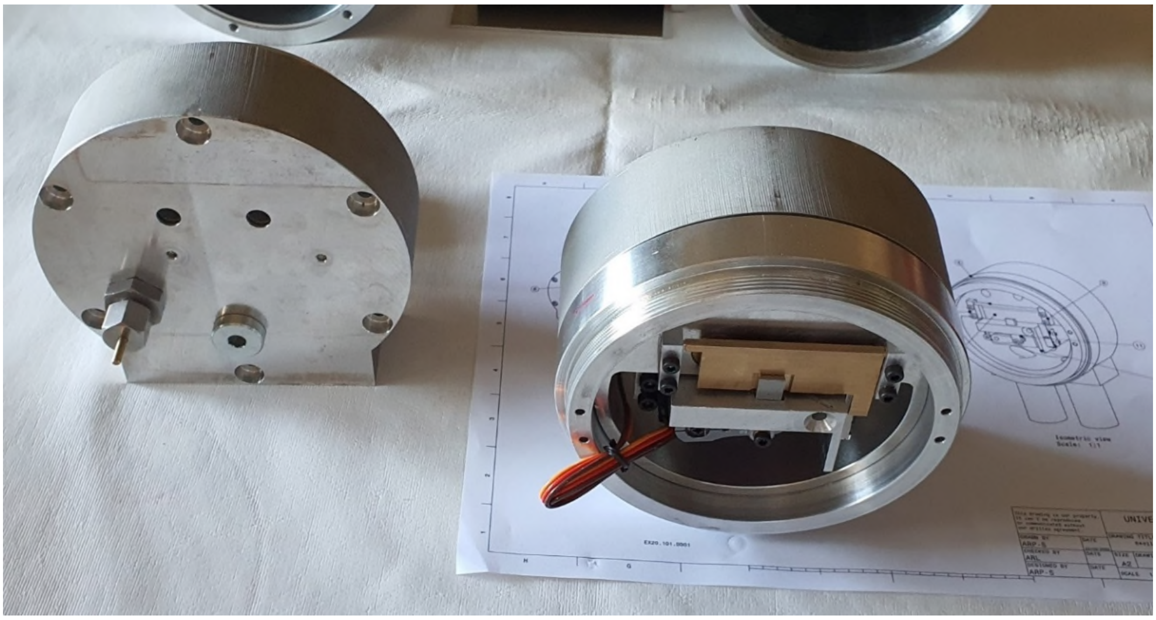


Figure 16 – Rear View of Front Cover and all Fittings –Armed, Vents Closed

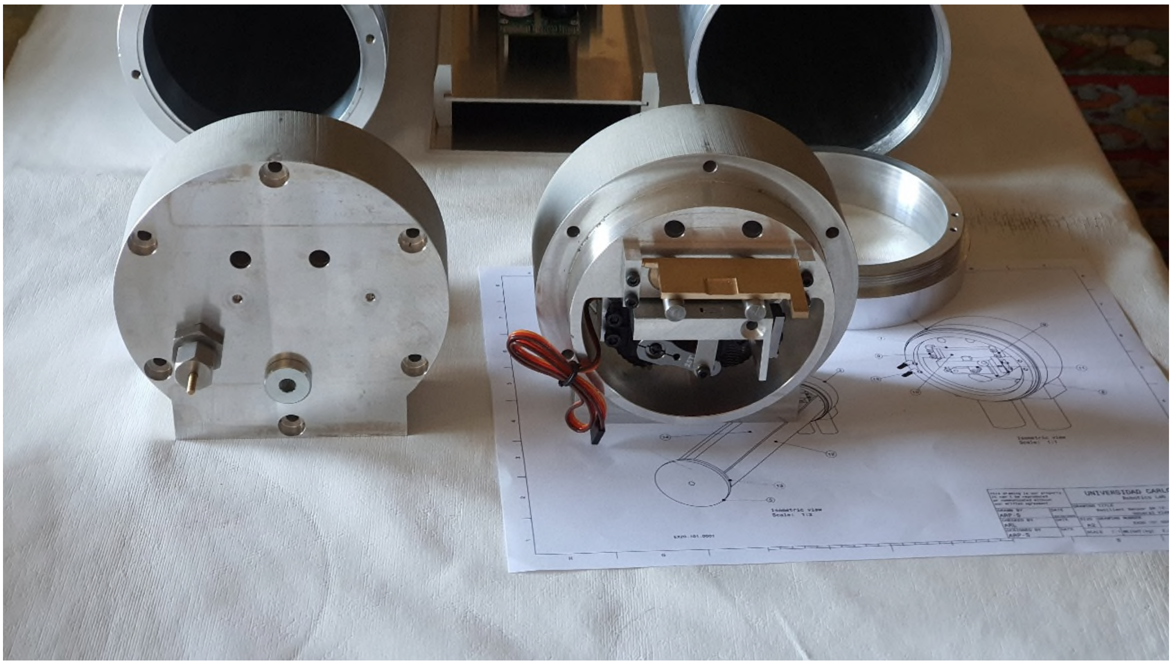


Figure 17 –Rear View of Front Cover and all Fittings – Deployed, Vents Open

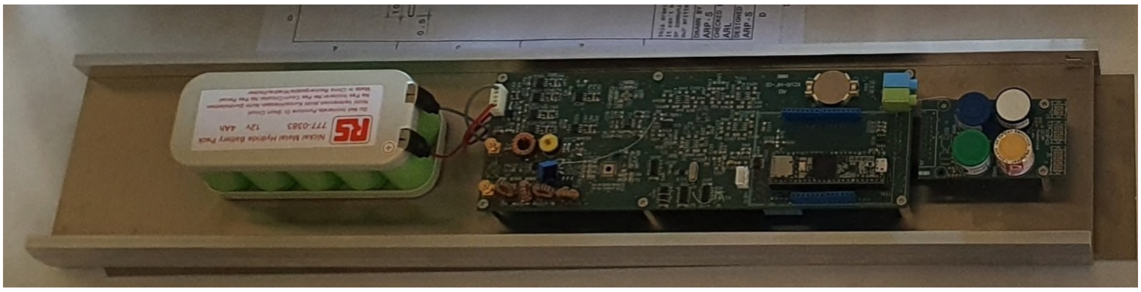


Figure 18 – Mounting Tray and Mounting Guides with Electronics and Battery

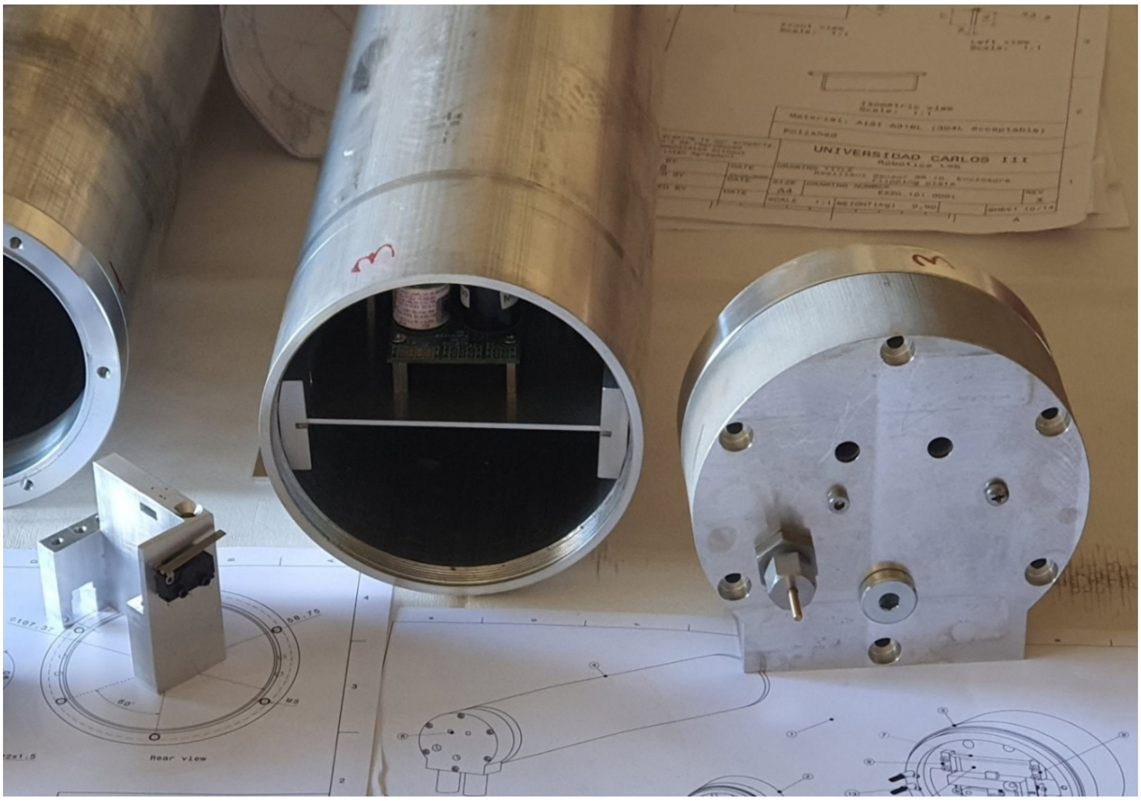


Figure 19 - Front View – Cover Removed, Mounting Tray Installed

6.7 Complete Prototype

A general view of the prototypes is shown in *Figure 20*. One of these is fully assembled and armed, while the enclosure of the second is open, showing again some details of the parts composing it (front cover and servo support / catch restrainer)

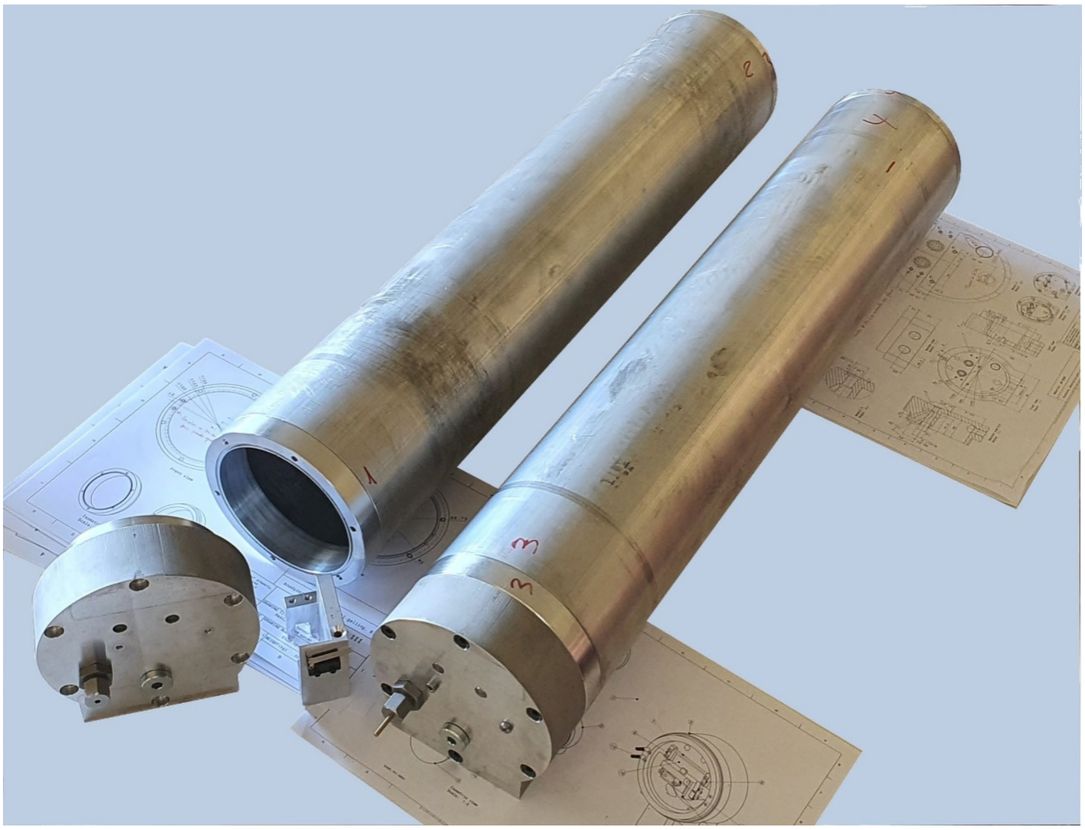


Figure 20 – View of the Enclosure

6.8 Possible Improvements and Path to ATEX Compliance

6.8.1 Improvements

As result of the assembling and testing of the prototype, some minor errors in the bill of materials (BOM) and the need for a few improvements to the design became apparent. Issues in the BOM were quickly fixed. Regarding the design itself, the following issues were detected (all were fixed in the lab, or did not affect the proper operation of the prototype):

1. The tray for mounting the electronics was 3mm wider than needed and could not be extracted when the front cover adapter was installed. This dimension should be reduced by 4mm to have enough clearance. Dimensions of the mounting guides should be modified accordingly (this issue did not have effect on the proper operation of the prototype –it is mainly a maintenance-related issue).

2. The lever of the limit switch, used to deactivate non-ATEX circuits when deploying the sensor, was not acted on by the locking plate as expected. Possible solutions are moving 2mm the drillings for fixing the limit switch or modifying the design of the locking plate (this last was the solution adopted for the prototype –a hand-made brass locking plate was prepared and operated satisfactorily).

3. The drillings for the machine screws that hold the servo are a bit misplaced (but not too much, so mounting was still possible).

4. More clearance is needed in the cable passing in the servo support, to allow mounting the servo (in the prototypes the support was milled to provide enough clearance).

5. The inner end of the plungers used to close the front ventings should be more rounded. In the initial design, the radius was too small, and this feature caused difficulties when arming the sensor.

6.8.2 Path to ATEX Compliance

Another strand of possible improvements is oriented to achieve ATEX compliance. As stated before, the approach used in the design of the fixed resilient sensor called for a dual protection mode: when armed, the enclosure is flameproof (Ex d), while it is intrinsically safe (Ex ia) when deployed. This aspect was implemented in full when designing the enclosure.

However, the need to use a non-intrinsically safe actuator (a high-torque servo) to deploy the sensor reliably was recognized. Therefore, as stated in *Section 0*, power to this actuator is removed as soon as it completed its function of releasing the locking plate, by means of a limit switch located appropriately. Moreover, it may be convenient that the external -and possibly sacrificial sensors be not intrinsically safe. They are useful only until the unit is deployed, and only its mechanical parts are protruding, as the electronics is fully enclosed in the sensor enclosure. In this case, they shall be de-energized, too, when the sensor is deployed, and they are not needed anymore. For this purpose, the same limit switch mentioned above can be used.

As the prototype was intended as a proof of concept, the limiting components needed to implement a fully compliant intrinsically safe (Ex ia, M1) design were not implemented.

However, the path to implement intrinsic safety is quite straightforward. No special issues are expected. The power requirements of the current version of the design are not too high (less than 500mA at 12V, see *Section 5.1.2*), and therefore can be supplied from an intrinsically safe power supply or battery.

Moreover, the power supply design must be modified, adding fuses and limiting resistors for limiting currents and temperatures. Zener diodes will be needed to guarantee a limited voltage in the output of the regulators, in order to allow the amount of capacitance (hundreds of μF) needed for the proper operation of the electronic circuits.

These modifications could be made after the end of the project, as part of exploitation strategy.

7 INSTALLATION

7.1 Mounting Configuration

Two different mounting configurations are recommended, the decision being made by the mine operator, based on local rock conditions. These two geometrical arrangements are summarised in *Figure 21*. In the first, the sensor unit is mounted in a hole in a prismatic-shaped niche; in the second, the sensor unit is mounted in a hole in a rectangular-shaped niche.

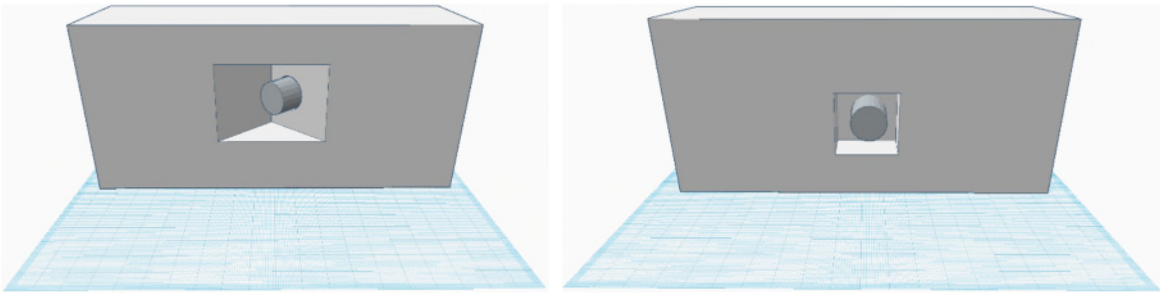


Figure 21 – Recommended Mounting Configurations

If conditions don't dictate the niche shape, a prismatic niche is recommended because it provides slightly improved airflow around the end of the sensor which will improve sensing of the atmospheric composition.

7.2 Installation Method

The installation process involves the following steps, although the first is optional:

1. Removing a steel arch support (only needed in mines with steel arches, and where those arches are too closely spaced to allow the niche to be excavated).

2. Creating a niche.

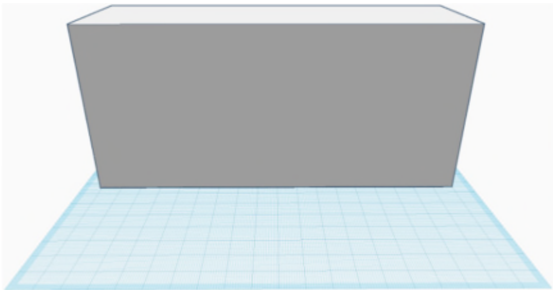
3. Drilling a hole in the niche (plus moving the drilling rig to the necessary location and removing it afterwards).

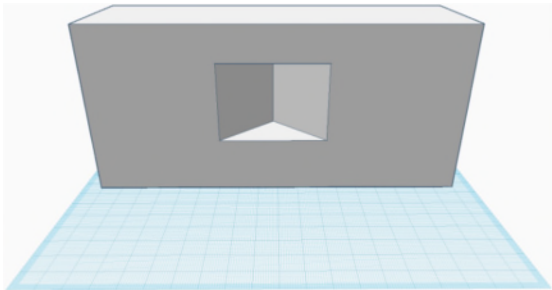
4. Injecting resinous grout into the hole.

5. Wiring the sensor unit to fixed power and communication networks.

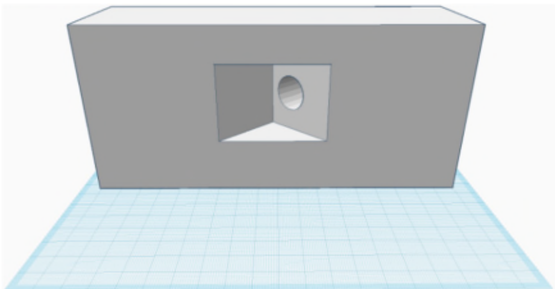
6. Inserting the sensor unit into the hole.

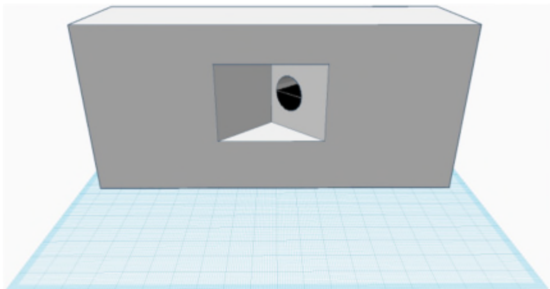
Steps 2, 3, 4 and 6 are summarised, pictorially, for the two recommended mounting configurations, in *Figure 22* and *Figure 23*.



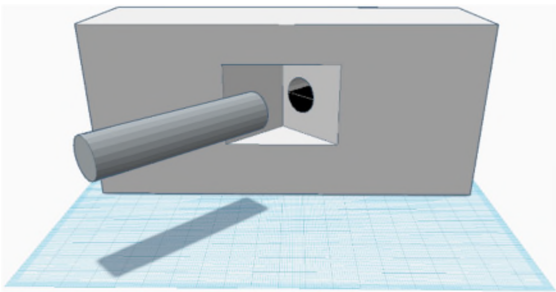


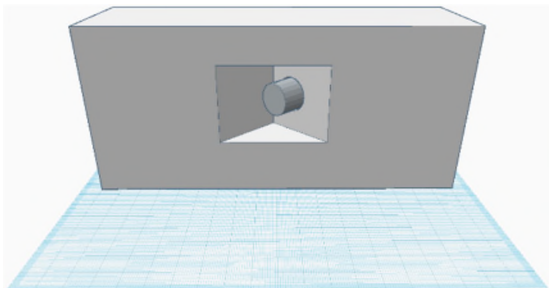
1. Gallery Wall Before Installation *2. Cut Prismatic-shaped Niche*





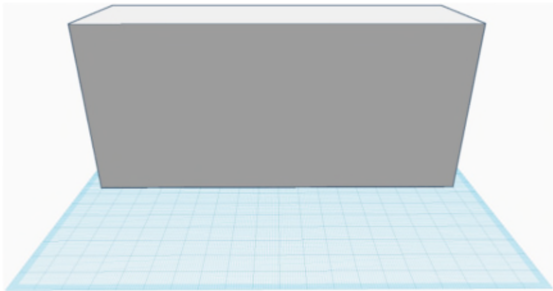
3. Drill Diameter Hole in Niche *4. Inject Resin into Hole*



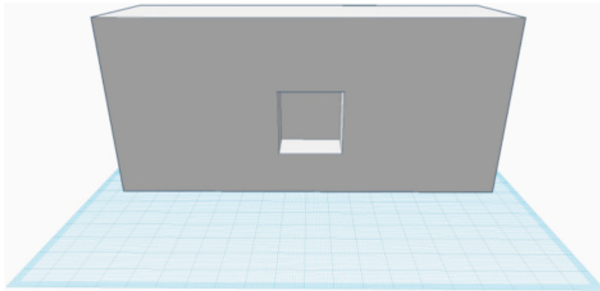


5. Insert Sensor into Hole

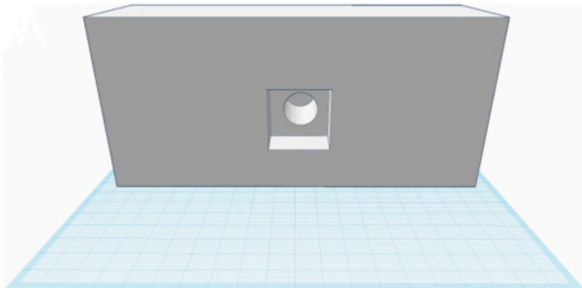
Figure 22 – Installation of Sensor Unit in Gallery Wall (Prismatic Niche)



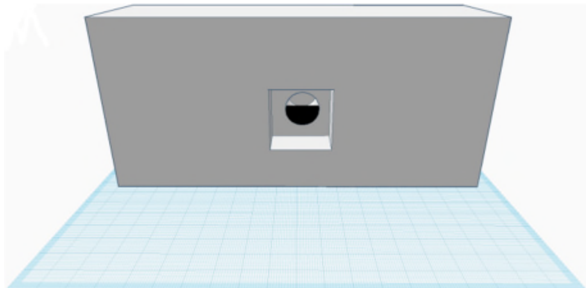
1. Gallery Wall Before Installation



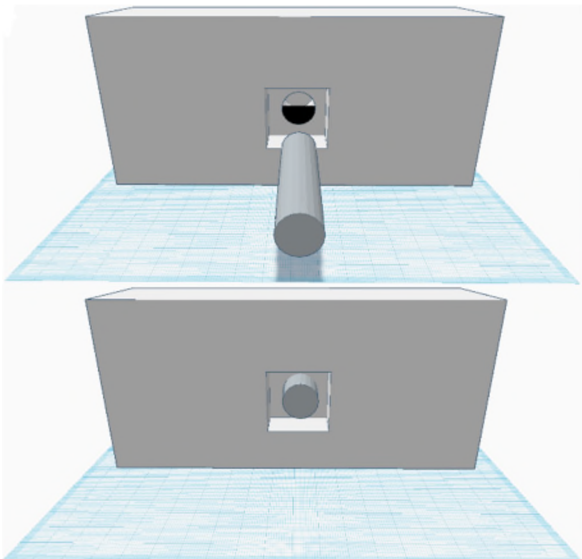
2. Cut Rectangular-shaped Niche



3. Drill Diameter Hole in Niche



4. Inject Resin into Hole



5. Insert Sensor into Hole

Figure 23 – Installation of Sensor Unit in Gallery Wall (Rectangular Niche)

Additional information on the installation steps follows.

7.2.1 Steel Arch Removal

This is only needed in mines with steel arches, and where those arches are too closely spaced to allow the niche to be excavated.

If it is required, is follows an established procedure so no further comment will be made here.

7.2.2 Niche Excavation

It is envisaged that the excavation of the niche will be a largely manual process involving the use of only hand tools. Depending on the hardness of the rock, either explosives or a pneumatic pick could be used.

The approximate dimension of the niche and hole are shown in *Figure 24* for a prismatic niche and in *Figure 25* for a rectangular niche. In both cases, the vertical dimension of the niche is 800mm, and the hole is centred vertically in the niche. These dimensions ensure that the end of the sensor unit is recessed sufficiently (150mm) from the gallery wall to provide protection from a blast wave and debris carried by that blast, and that there is sufficient space around the exposed end of the sensor to allow efficient sensing of atmospheric gasses. It should be noted that the dimensions are still preliminary and that details, especially the depth of the hole, are subject to change, and cannot be confirmed until the detailed mechanical design of the sensor unit has progressed further. However, because it is constrained by drilling capabilities, every effort will be made to ensure that the hole diameter remains as 140mm.

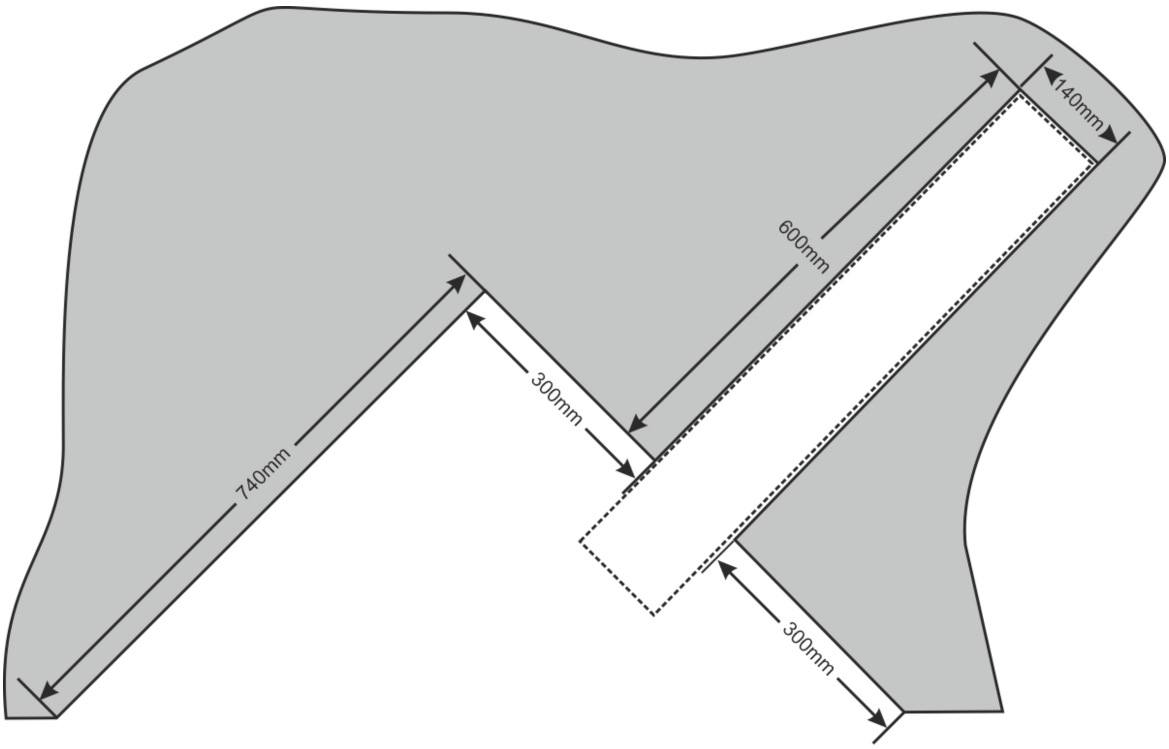


Figure 24 – Dimensions of Niche and Hole (Top View, Prismatic Niche)

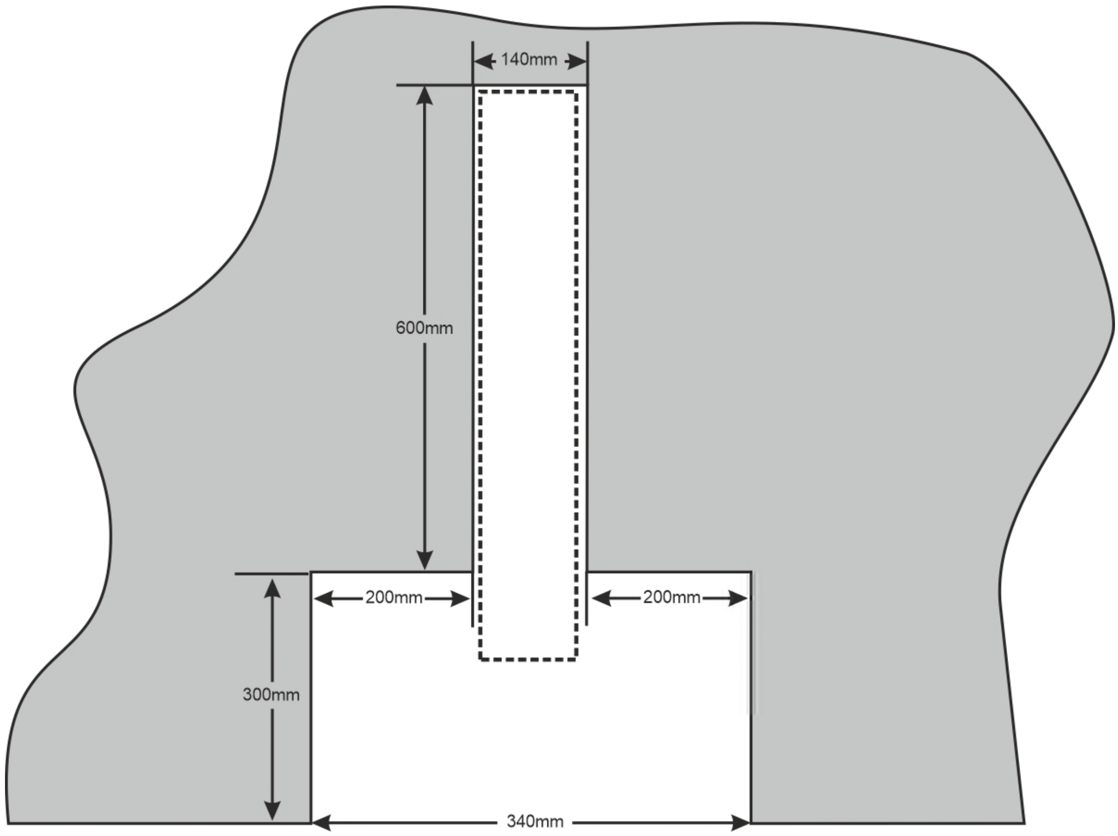


Figure 25 – Dimensions of Niche and Hole (Top View, Rectangular Niche)

7.2.3 Drilling and Pre-sealing

The method of drilling is not substantially different from that used for drilling other types of holes in mines so no further details are provided here.

However, a recommendation made by grout supplier Minova is that the hole is pre-sealed with a cement product to reduce the volume of resin required and to allow the volume required to be more accurately estimated. However, if this approach is taken, care should be taken not to reduce the diameter of the diameter of the hole substantially as a result of this process. Needless to say, pre-sealing is more important if the rock is soft and crumbing.

7.2.4 Insertion on Sensor into Hole and Securing with Resin

The following basic procedure should be used. Note that this does not cover the installation of the antenna, because no single type of antenna is thought to be optimal in all mines. In the case of a loop antenna of the same diameter of the sensor unit, however, a possible position would be in the borehole at the rear of the body of the sensor unit. This would require a longer borehole.

The recommended grout is Carbothix 2 from Minova.

1. Mix the calculated volume of resin (i.e. the volume of the hole minus the volume of the portion of the sensor unit that will be fitted into the hole, i.e. the portion excluding the end with the vents) and pump it into the hole.

2. Protect the exposed end of the sensor unit (i.e. the end that contains the vents and will not be fitted into the hole) by wrapping it with masking tape.

3. Attach the cables for the mine power and data networks to the connectors on the sensor unit.

4. Insert the sensor unit into the hole until only the end with the vents (now covered by masking tape) remains visible. Rotate the sensor unit clockwise and anticlockwise slightly during insertion (do not rotate it in one direction because of the cables connected to the sensor unit) to ensure that the resin encapsulates the sensor unit on all sides. If the hole is exactly the correct length, the insertion process involves inserting the sensor unit as far as it will go, but beware of inserting it too far if the hole is longer than necessary because this would result in the vents in the sensor unit being embedded in the hole, thereby jeopardising the unit's atmospheric sensing capability.

5. If possible, starting at the bottom, insert four equally spaced spacers around the sensor unit to ensure that the sensor unit remains centrally within the hole. If this doesn't prove possible, it is likely that the sensor unit will come to rest at the bottom of the hole with little grout at the bottom. Even in this configuration, however, it considered that the sensor unit will be adequate secured.

6. Clamp or prop the sensor unit in place.

7. Wipe away any grout that has been displaced from the hole and then remove the masking tape from the exposed end of the sensor unit.

8. After the curing time for the resin has elapsed (which could be over an hour, depending on the product used), remove the clamp or prop that was used to hold the sensor unit in place.

8 DEPLOYMENT, TESTING AND REARMING

This section discusses deployment in incidents, periodical testing, and the procedure for rearming / resetting the unit.

8.1 Deployment Criteria

The concept of the fixed sensor unit is that it could be deployed, following an incident, either automatically, or manually by remote control. The word deployed, in this context, means releasing the various protection mechanisms, so it can start sensing its environment.

Various potential criteria could be used to trigger deployment. This applies either to automatic or manual deployment .Much of the selection criteria depends only on the software so the exact behaviour can be defined easily, depending on the requirements of a particular mine operator.

Loss of power could be an indicator of an incident but, ideally, deployment should also depend on environmental conditions. Because the fixed sensor unit's main sensors are only operational after deployment, triggering a deployment due to environmental conditions makes uses of the external sacrificial deployment sensors described in *Section 3.4*. These sensors monitor temperature and pressure.

Another possible indicator of a serious incident is the loss of communication between the fixed sensor unit and the surface via some, or all, of the wired communication network. See *Section 4.2* for a discussion of wired networks and the rationale for its inclusion, in addition to LF/VLF through-the-earth communication.

Data from other systems, including those which are used in the normal operation of the mine, might also play a part in a deployment decision.

8.2 Data Analysis

Because external sensors, being sacrificial, might be able to detect adverse conditions only in the very early stages of an incident, it is unlikely that the output of any one sensor would be able to indicate, unambiguously, that a serious incident has occurred. It is probable, therefore, that an incident could only be detected reliably by analysing the output of several sensors, possibly in several fixed sensor units, whether external power is available, plus the state of the mesh network, and data from operational (as opposed to emergency) sensors and equipment, throughout the mine.

The implication of this is that recognition of an incident involves analysing several data streams, perhaps from several systems and from several locations within the mine. This is something that could be carried out by a suitably knowledgeable expert such as a responsible person (supervisor) in the mine control room or, perhaps, by a software-based expert system. And crucially, because the data used to recognise an incident might include data which is external to any one fixed sensor unit, any such expert system could not be implemented inside any single fixed sensor unit, without allowing external data to be shared with that sensor in real time. The implication of this is that any expert system would have to be implemented externally, resulting in a deployment command to whichever of the fixed sensor units are deemed likely to be able to provide relevant data.

8.3 Manual vs. Automatic Deployment

Because of the argument presented in *Section 8.2*, the hardware has been designed for remote deployment. This then gives the mine operator the option either to rely on human experts to deploy the fixed sensor units, with the choice of which particular unit(s) to deploy, or to develop a software-based expert system. Deployment should, perhaps, be adapted to individual endangered sectors. The important point, however, is that any decision to use automatic deployment would be the decision of the mine operator, as opposed to being inherent in the design of the fixed sensor unit.

It is also pertinent to point out that manual operation is likely to reduce the likelihood of false deployments. Because the fixed sensor units have been designed so they cannot be “un-deployed” remotely, false deployments would result in maintenance staff having to visit the site of the device, inspect it for any signs of damage as a result of the deployment or the introduction of any foreign material and, once its condition is assured, return it to its armed state. Because such false deployments would represent a manpower overhead, it is a concern that such events might cause mine operators to lose confidence in the devices and, perhaps, decommission them. In the case that a mine operator had chosen to adopt an automatic deployment scheme, however, the option would be available to revert to manual deployment, at least until the problems with the expert system could be investigated and resolved.

Although not relevant to the design of the fixed sensor unit, there are also some implications to the surface control and monitoring system, if manual (in the sense of human) deployment is to be used. Perhaps the most important requirement is that each of the data streams that will be taken into account when deciding if deployment is necessary, should have an associated alarm to draw the attention of the human operator. Any increase above a set value or signal interruption should trigger an alarm.

8.4 Local Deployment

The addition of a pushbutton for manual deployment is a possible extension. In the event that miners involved in an incident find a fixed sensor unit in an affected area had not been deployed, they could initiate its deployment manually. This manual deployment would also signal the location of the affected miners to surface staff. Indeed, such a button could also be used, even if the fixed sensor unit had deployed, to transmit the location of affected miners.

The pushbutton has not been implemented in the prototype, but can be easily added, using one of the signals available in J8 of the main control PCB (XCVR-HF-01). This signal could be routed out of the enclosure through the cable providing power and the communication line, and a pushbutton installed in the nearby junction box.

8.5 Testing and Rearming

Deployment of the sensor can be the result of an incident or of a periodic inspection. In both cases, after such deployment, it shall be tested and rearmed, in order to have it in the ready condition again.

The first operation to be carried out is detaching the front assembly, removing the six bolts in its periphery. This will give access to the tray on which the electronics, sensors and battery are mounted. It will also allow access to the rear part of the front cover, including the inner end of the plungers closing the sampling vents, and their ancillary elements. The locking mechanism shall be closed and rearmed, after a visual inspection shows that there is no apparent damage. This is done by pushing the plungers and lowering the locking plate. Once it is in its closed position, the locking catch shall be actuated manually, until it engages and locks the plate. If any damage is detected, the whole assembly shall be taken to the surface for servicing.

The next operation is re-establishing wired power and communications. Satisfactory telemetry data should than be received from the unit, including sensor readings. If these are not received, or power cannot be re-established, the tray with all active components should be extracted and taken to the surface for further testing and / or servicing.

If wired power and communications are re-established satisfactorily, the wireless interface should be tested. Again, if test fails, the tray with all active components shall be extracted and taken to the surface for further testing and / or servicing.

The next operation is to test and calibrate the gas sensors, as these may have been affected by an incident (or as a periodic calibration). Calibration data is stored in the EEPROM (a kind of non-volatile memory).

Once these operations are completed, the unit shall be closed, bolting the front cover to the body with all six machine screws. With this operation, the unit is armed and ready for a new deployment.

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9 FURTHER INFORMATION

Further information about the robotic vehicles deployment is available from the Robotics Lab Research Group at Universidad Carlos III de Madrid, Avda. de la Universidad 30, Leganes 28911, Madrid, Spain, http://roboticslab.uc3m.es.

Please contact Alberto Jardón at ajardon@ing.uc3m.es.

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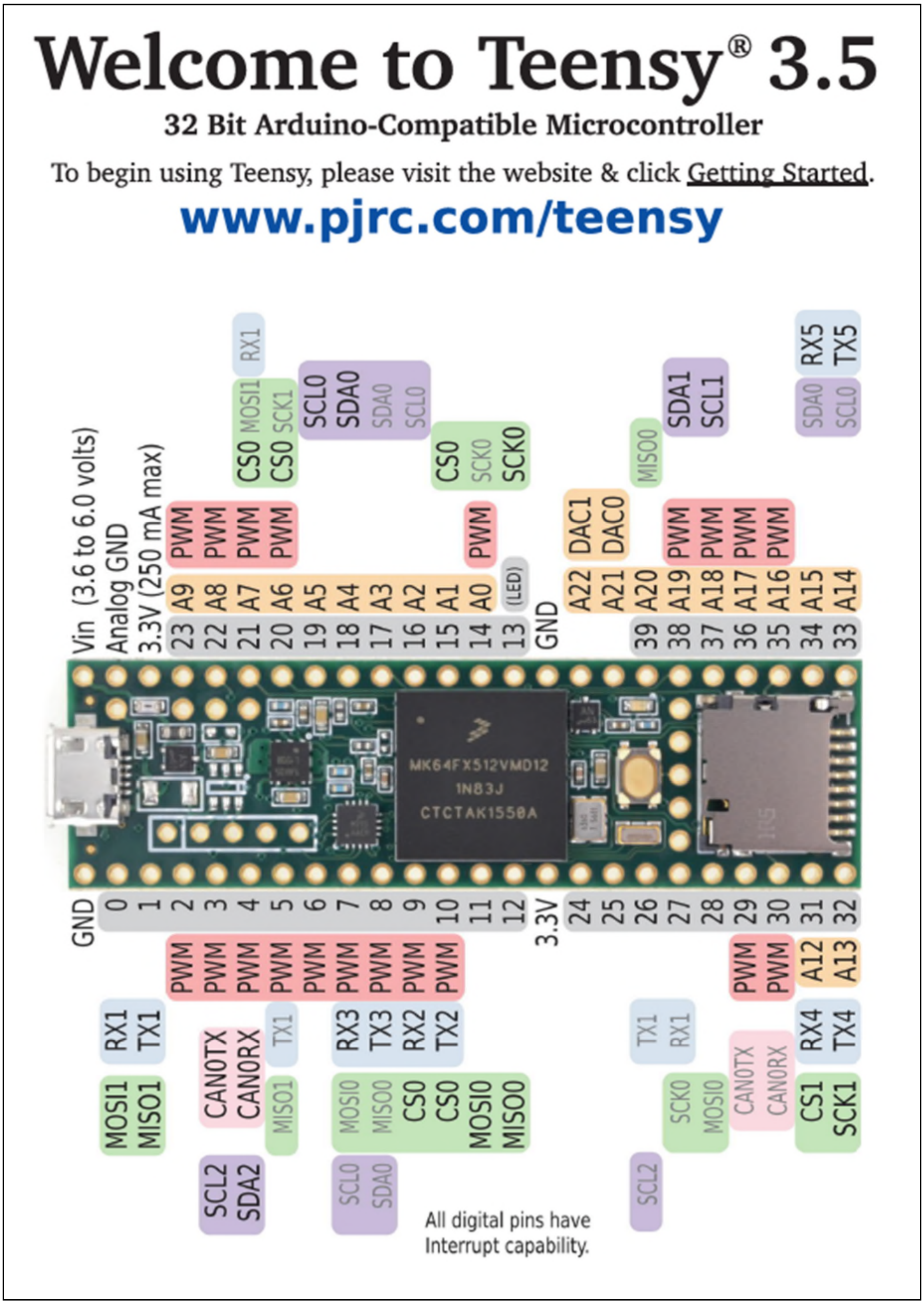
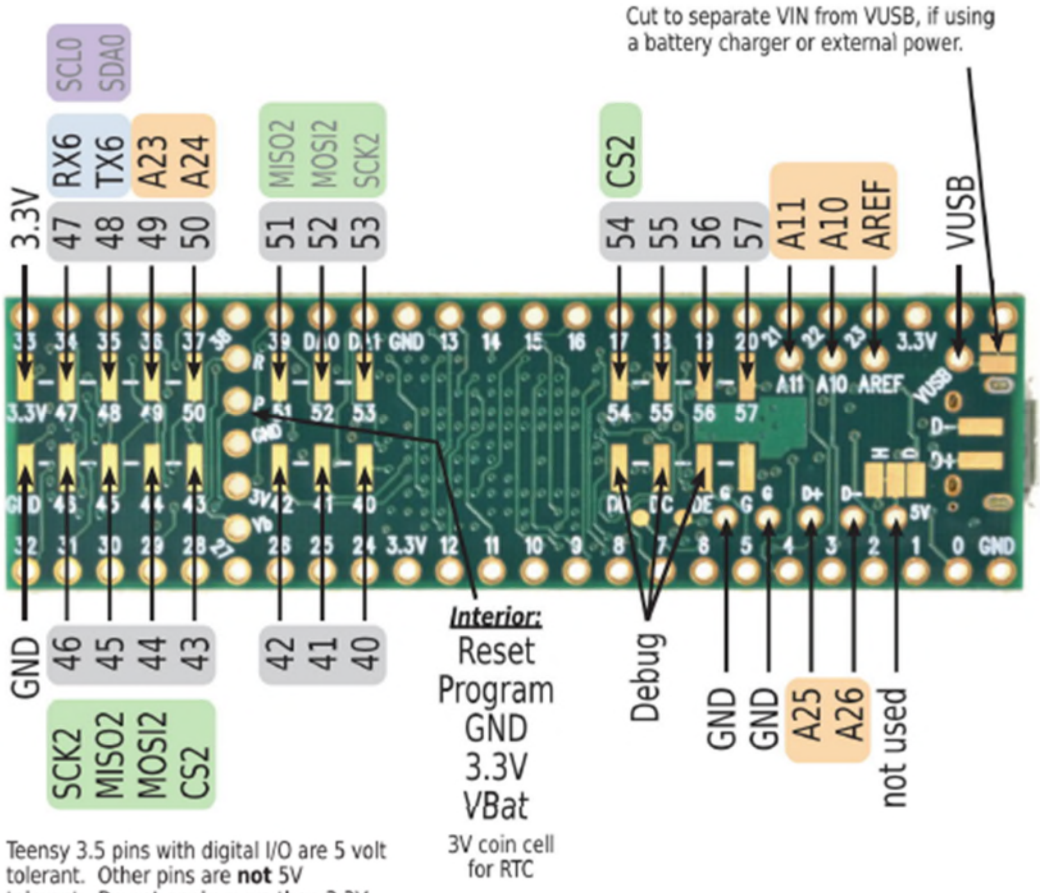
10 APPENDIX A – TEENSY 3.5 MANUFACTUER'S DATA



Teensy® 3.5 Back Side

Additional pins and features available on the back side



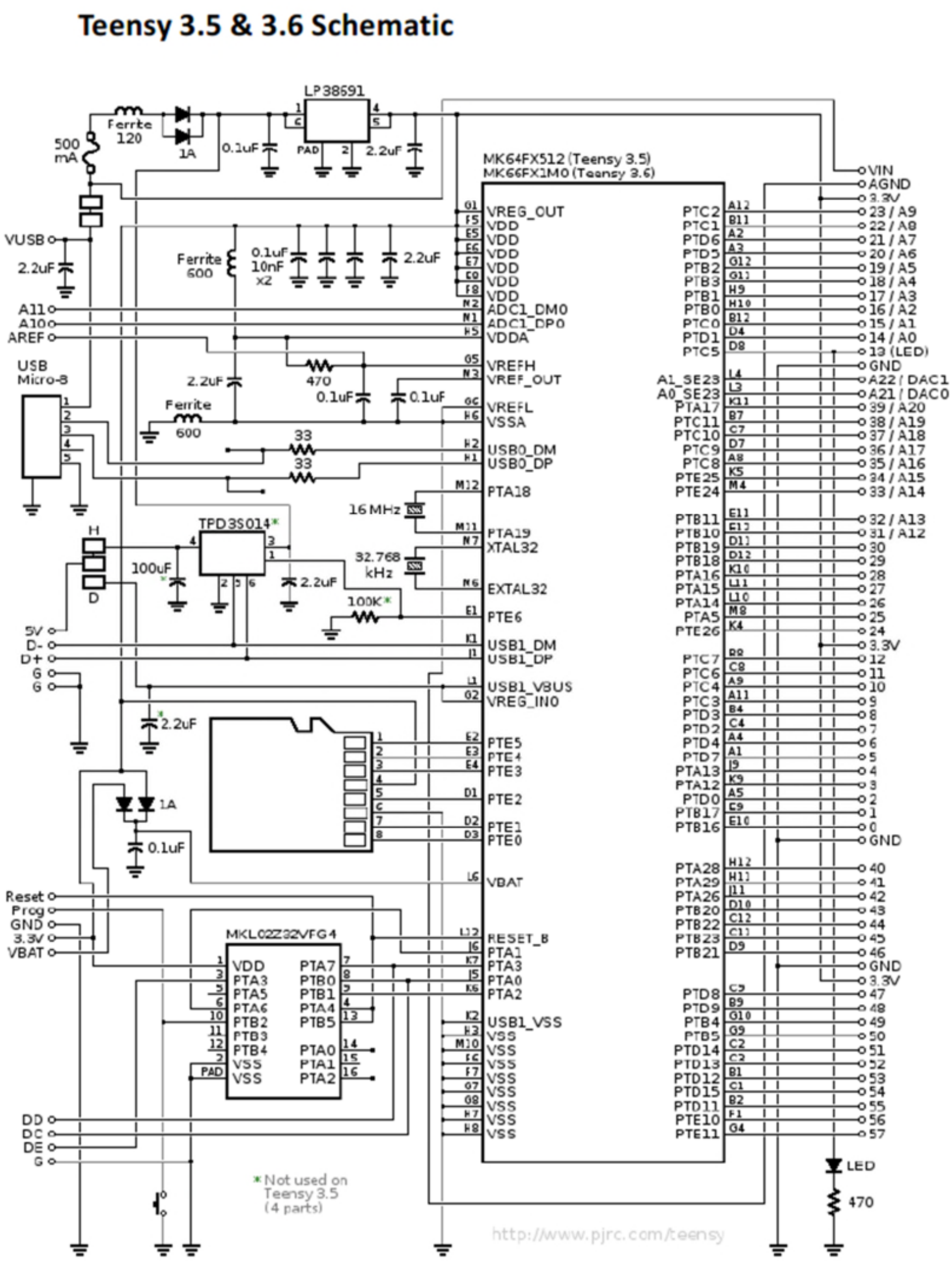
Teensy 3.5 pins with digital I/O are 5 volt tolerant. Other pins are **not** 5V tolerant. Do not apply more than 3.3V to A10, A11, A21, A22, A25, A26, AREF, Program or Reset.

For solutions to the most common issues and technical support, please visit:

www.pjrc.com/help

Teensy 3.5 System Requirements:
PC computer with Windows 7, 8, 10 or later
or Ubuntu Linux 12.04 or later
or Macintosh OS-X 10.7 or later
USB Micro-B Cable

7 14833 87942 8


Teensy 3.5 & 3.6 Schematic
LP38691
Ferrite 120
1A
500 mA
0.1uF
PAD
2.2uF
MK64FX512 (Teensy 3.5)
MK66FX1M0 (Teensy 3.6)
VUSB
A11
A10
AREF
USB Micro-B
Ferrite 600
0.1uF 10nF x2
470
33
16 MHz
32.768 kHz
TPD3S014
100uF
100K
5V
D-
D+
G
H
D
VREG_OUT
VDD
ADC1_DM0
ADC1_DP0
VDDA
VREFH
VREF_OUT
VREFL
VSSA
USB0_DM
USB0_DP
PTA18
PTA19
XTAL32
EXTAL32
PTE6
USB1_DM
USB1_DP
USB1_VBUS
VREG_IN0
PTE5
PTE4
PTE3
PTE2
PTE1
PTE0
VBAT
RESET_B
PTA1
PTA3
PTA0
PTA2
USB1_VSS
VSS
Reset
Prog
GND
3.3V
VBAT
MKL02Z32VFG4
DD
DC
DE
* Not used on Teensy 3.5 (4 parts)
http://www.pjrc.com/teensy
VIN
AGND
23 / A9
22 / A8
21 / A7
20 / A6
19 / A5
18 / A4
17 / A3
16 / A2
15 / A1
14 / A0
13 (LED)
A22 / DAC1
A21 / DAC0
39 / A20
38 / A19
37 / A18
36 / A17
35 / A16
34 / A15
33 / A14
32 / A13
31 / A12
LED

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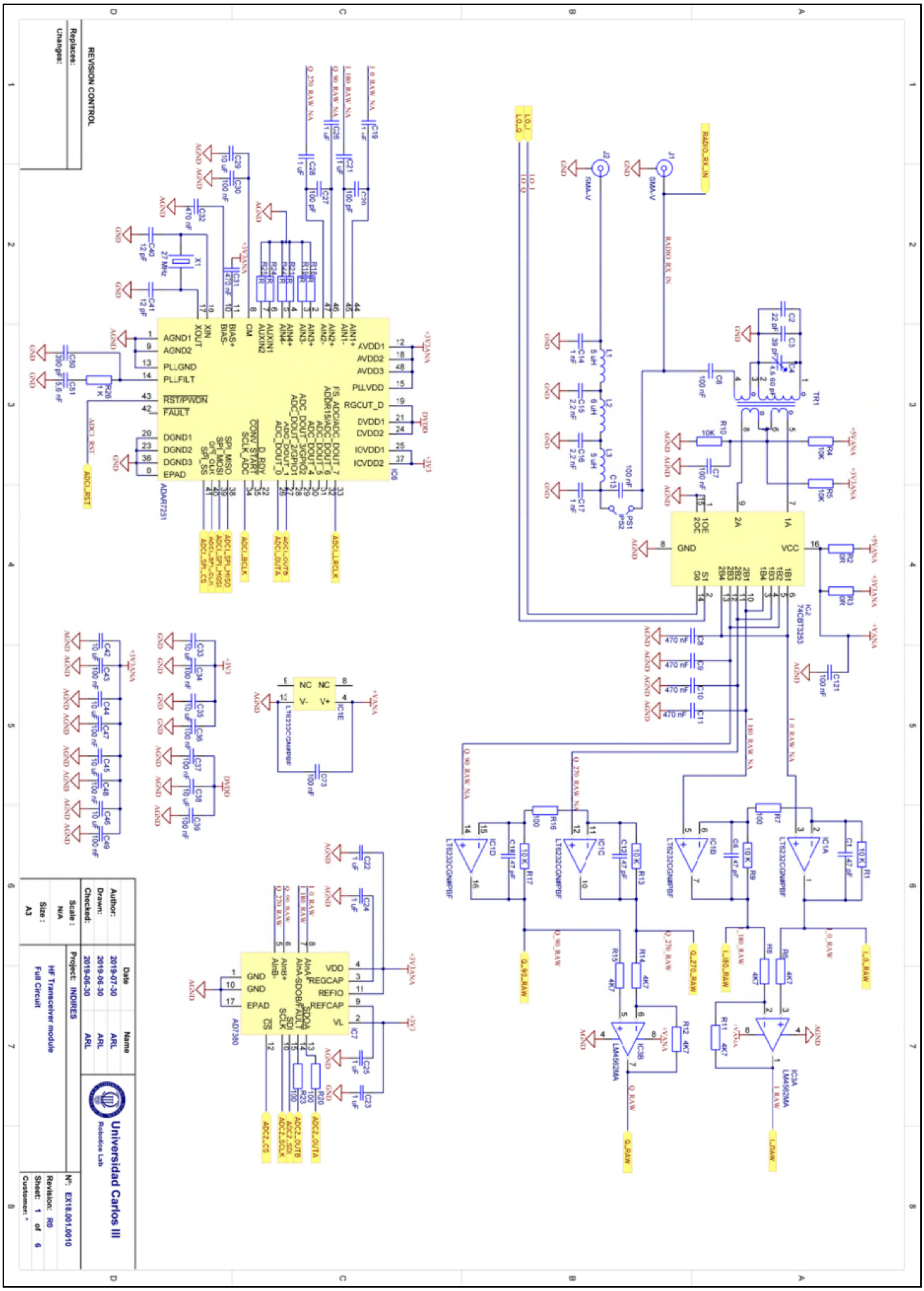
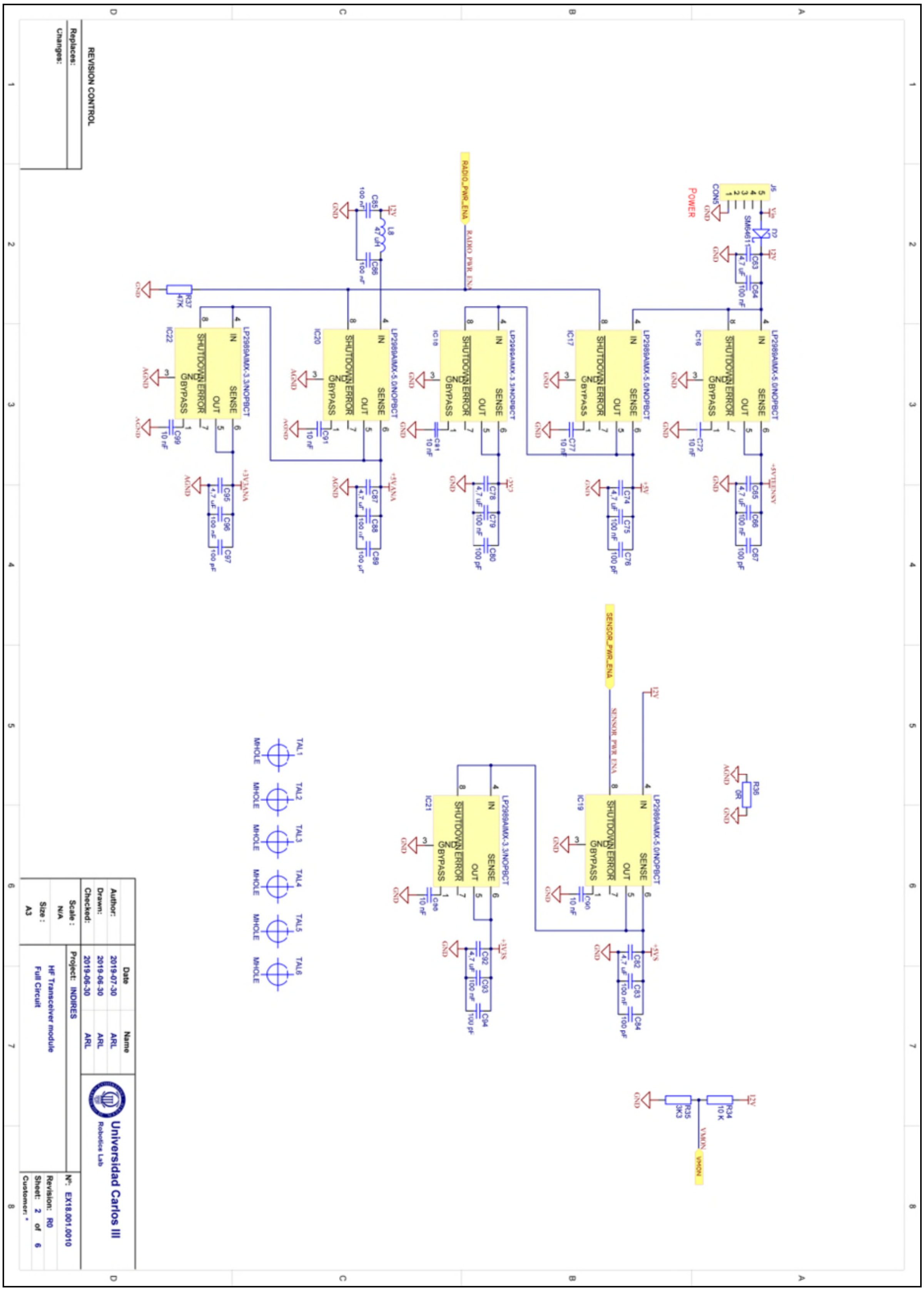
11 APPENDIX B – XCVR-HF-01A WMN CIRCUIT DIAGRAMS

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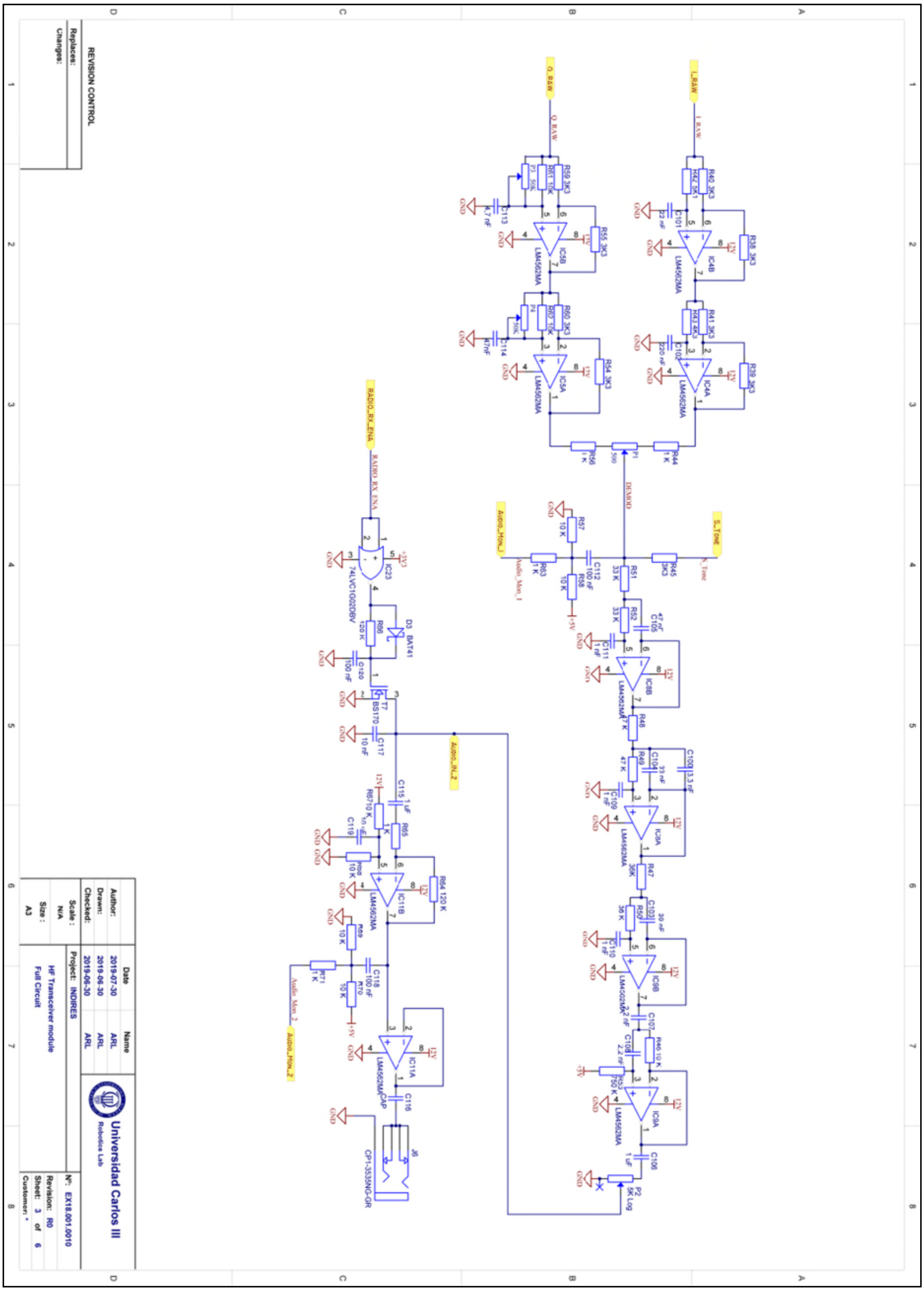
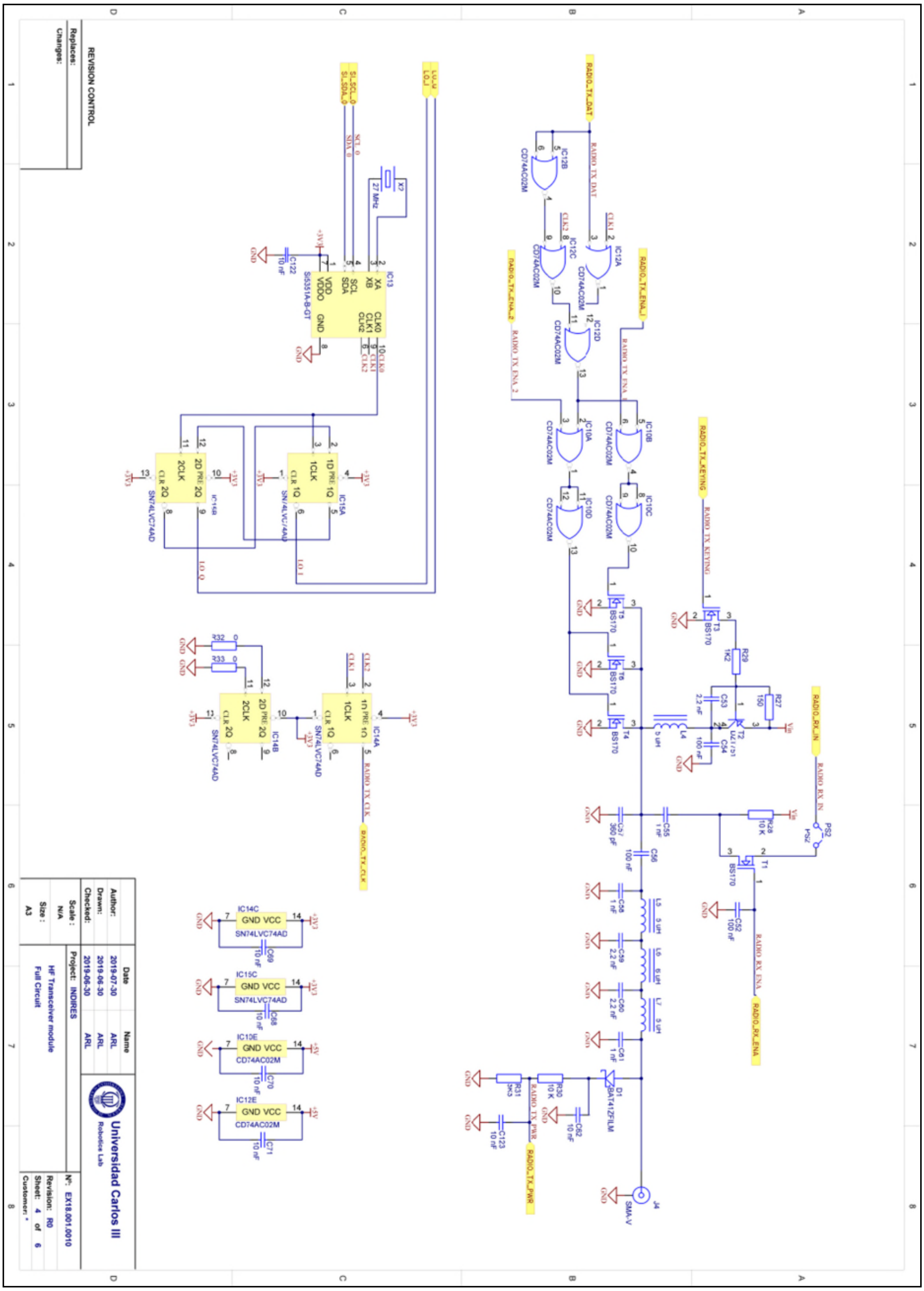
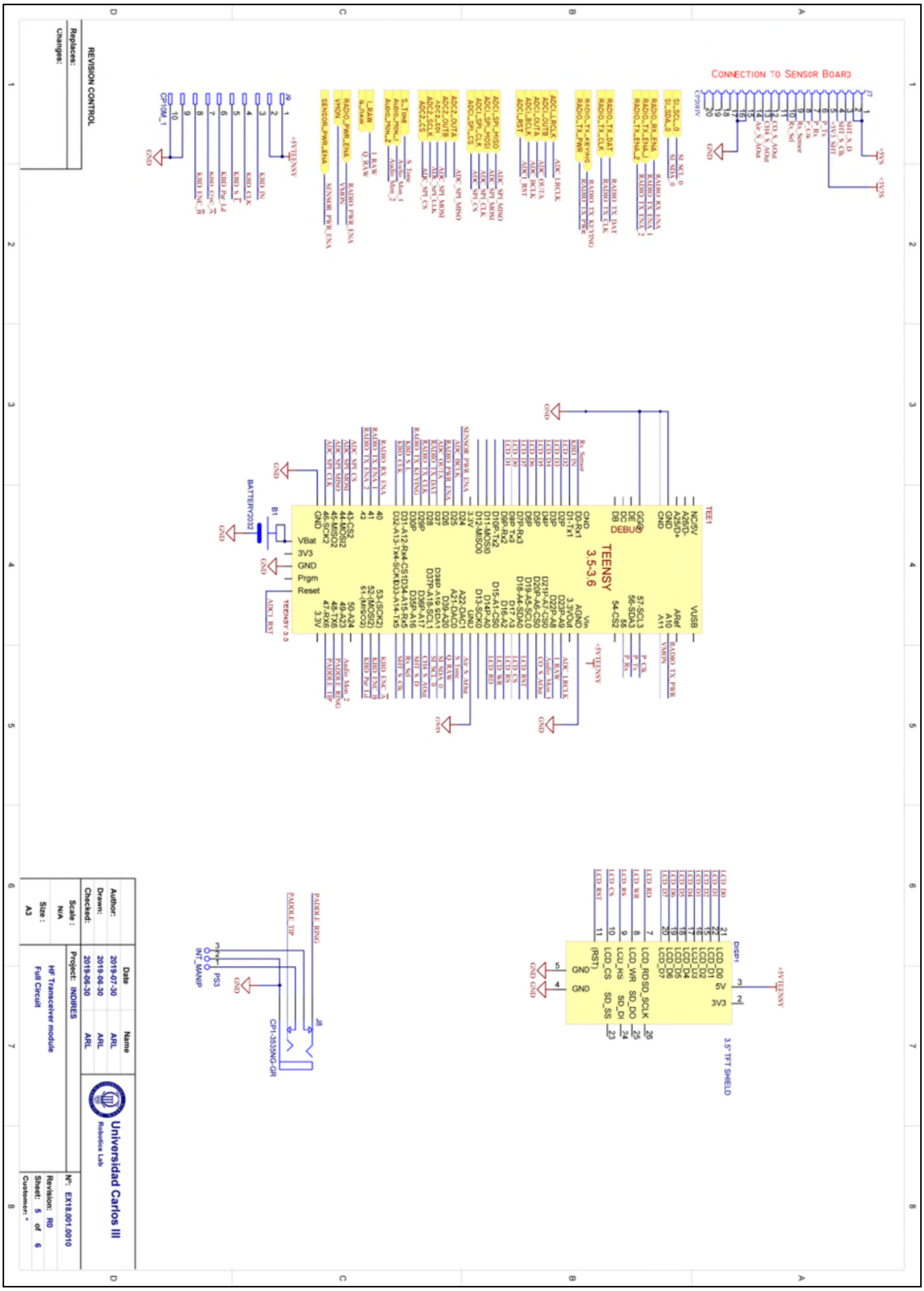
Changes:
RADIO_PWR_ENA
SENSOR_PWR_ENA
POWER
LP2989AIMX-5.0/NOPBCT
LP2989AIMX-3.3/NOPBCT
IN
SENSE
OUT
ERROR
SHUTDOWN
GND
BYPASS
MHOLE
VMON
Universidad Carlos III
Robotics Lab
Project: INDIRES
HF Transceiver module
Full Circuit
Size: A3
Revision: R0
Sheet: 2 of 6


REVISION CONTROL
Replaces:
Changes:
I_RAW
Q_RAW
RADIO_RX_ENA
S_Tone
Audio_Mon_1
Audio_IN_2
Audio_Mon_2
Universidad Carlos III
Robotics Lab
Project: INDIRES
HF Transceiver module
Full Circuit
N°: EX18.001.0010




REVISION CONTROL
CONNECTION TO SENSOR BOARD
TEENSY 3.5-3.6
DEBUG
3.5" TFT SHIELD
BATTERY2032
Universidad Carlos III
Robotics Lab
Project: INDIRES
HF Transceiver module
Full Circuit
N°: EX18.001.0010

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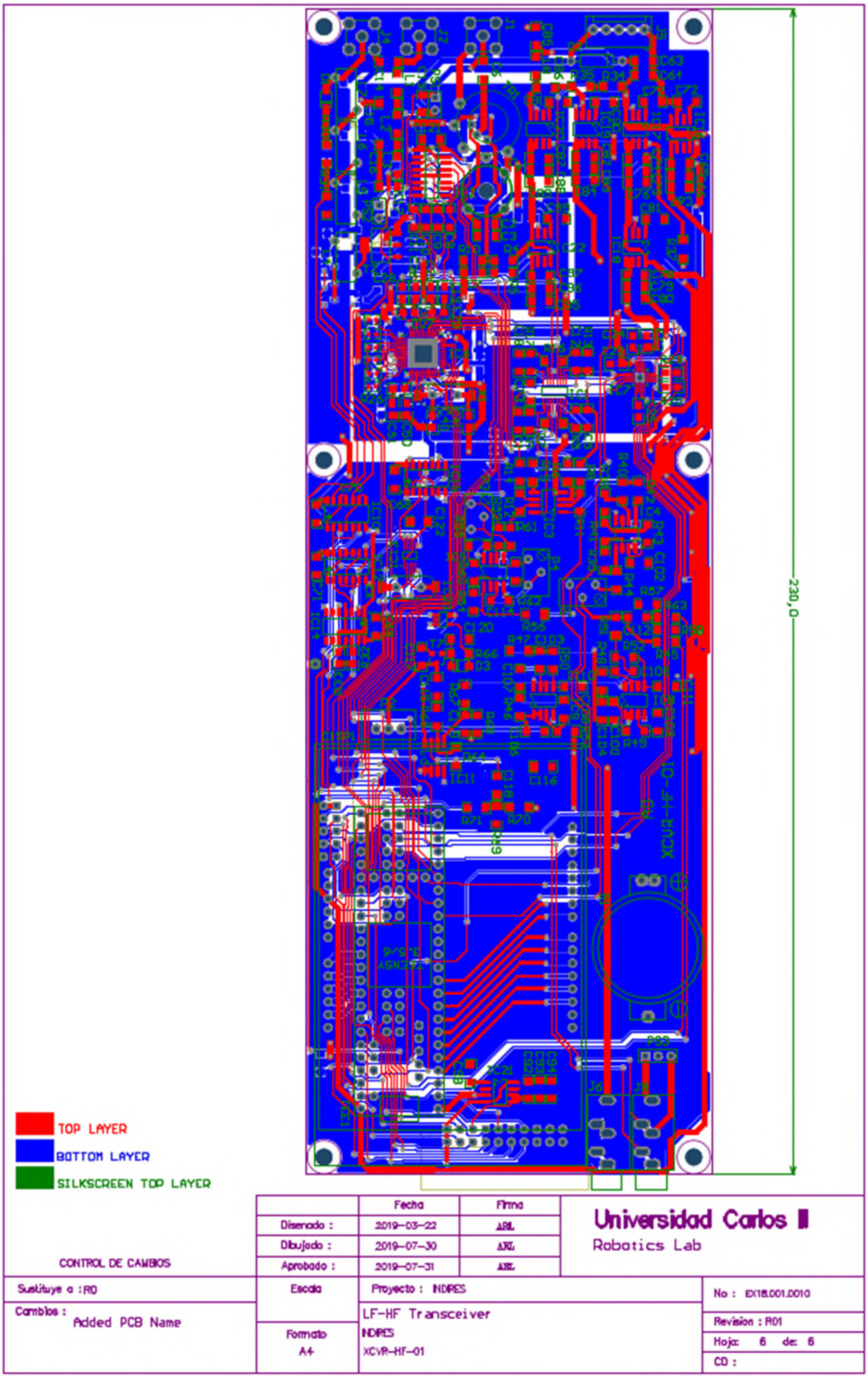
12 APPENDIX C – XCVR-HF-01A WMN PCB LAYOUT



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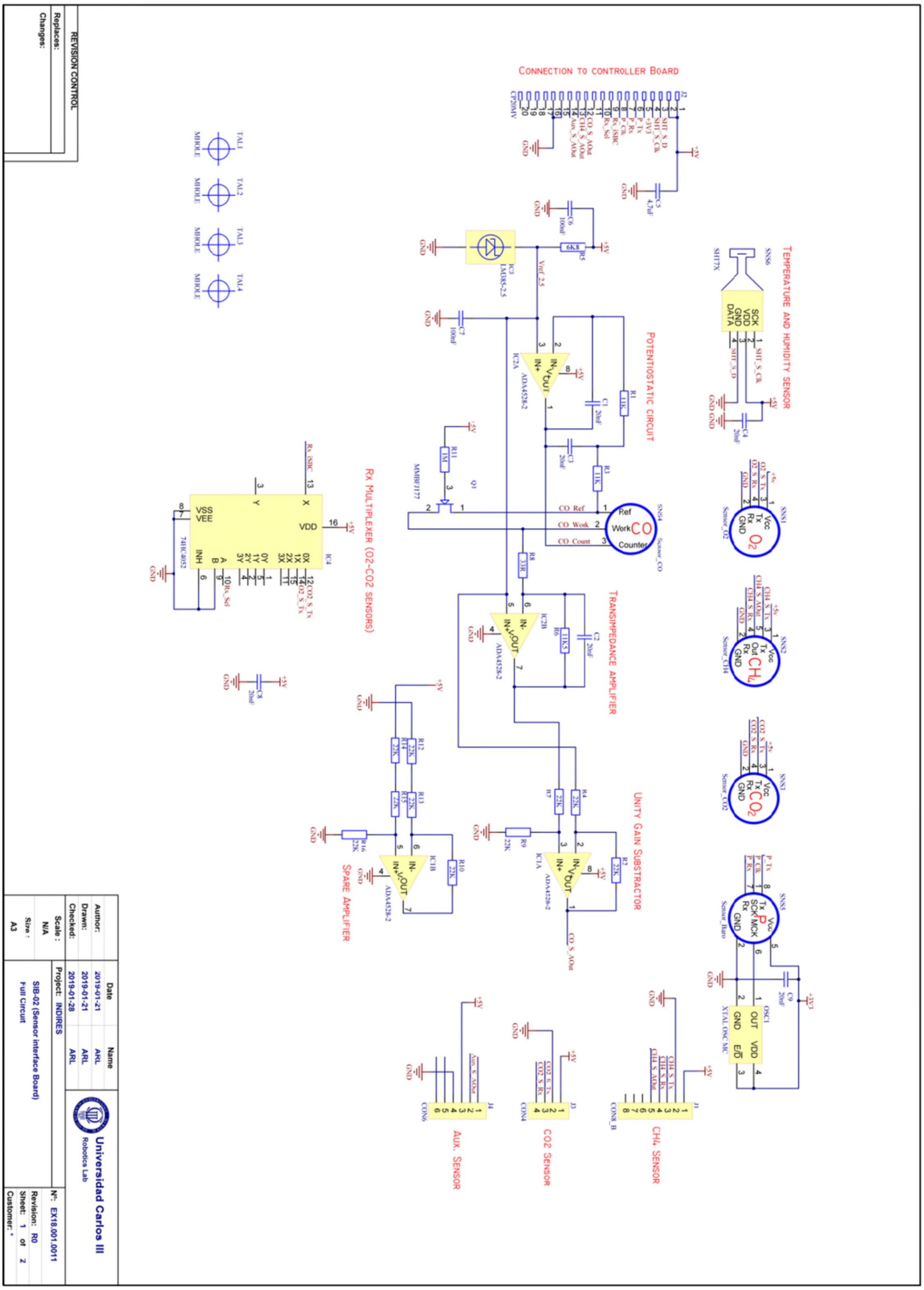
13 APPENDIX D – SIB-02 CIRCUIT DIAGRAM



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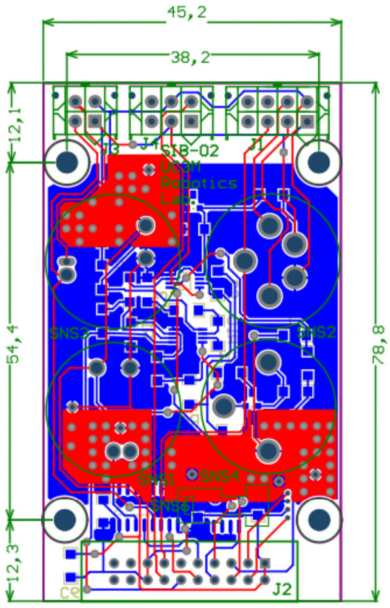
14 APPENDIX E – SIB-02 PCB LAYOUT



TOP LAYER
BOTTOM LAYER
SILKSCREEN TOP LAYER

		Fecha	Firma	
	Disenado :	2019–01–28	ARL	Universidad Carlos III
	Dibujado :	2019–02–28	ARL	Robotics Lab
CONTROL DE CAMBIOS	Aprobado :	2019–03–07	ARL	
Sustituye a : R0	Escala	Proyecto : INDIRES		No : EX18.001.0011
Cambios : Added PCB Name	Formato A4	SENSOR INTERFACE BOARD INDIRES SIB–02		Revision : R01 Hoja: 2 de: 2 CD :

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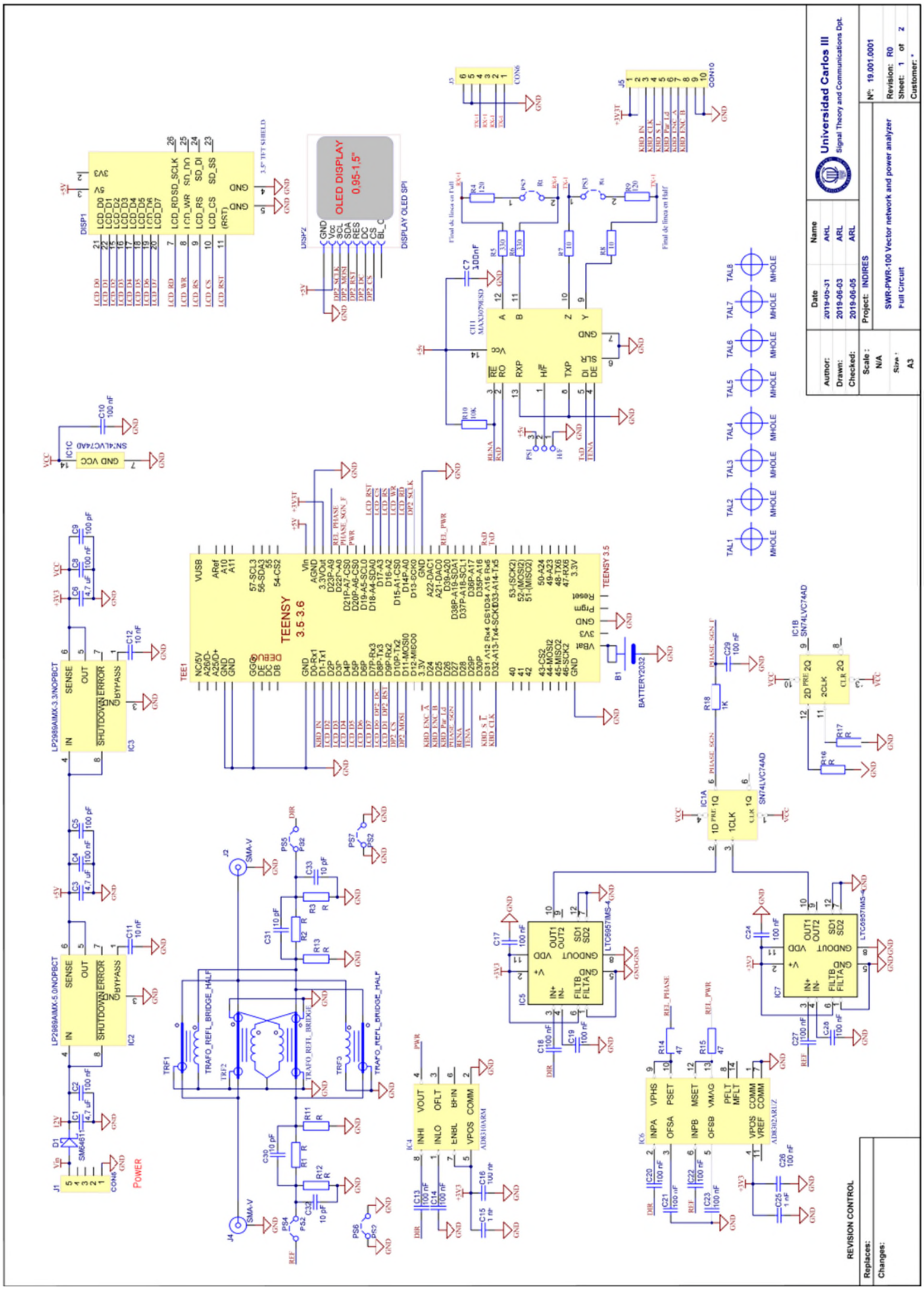
15 APPENDIX F – SWR-PWR-100 CIRCUIT DIAGRAM



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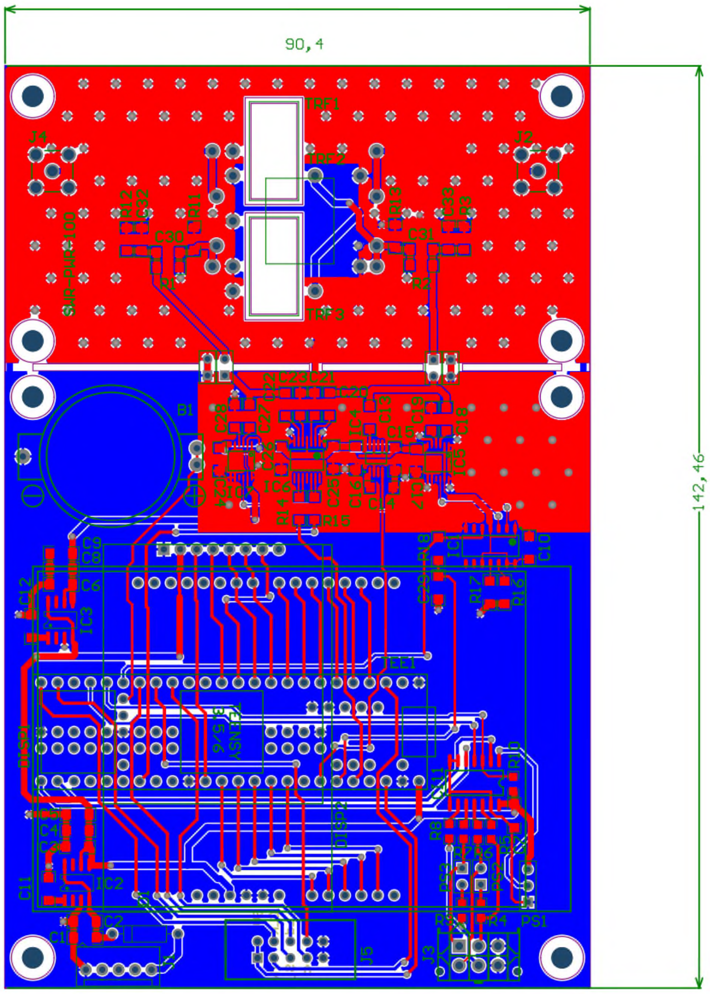
16 APPENDIX G – SWR-PWR-100 PCB LAYOUT



TOP LAYER
BOTTOM LAYER
SILKSCREEN TOP LAYER

	Fecha	Firma	Universidad Carlos III Robotics Lab
Disenado :	2019-03-22	ARL	
Dibujado :	2019-'3-28	ARL	
Aprobado :	2019-03-31	ARL	

CONTROL DE CAMBIOS

Sustituye a : R0	Escala	Proyecto : INDIRES	No : EX18.001.0001
Cambios : Added PCB Name	Formato A4	SENSOR MOTHERBOARD INDIRES ESI-01	Revision : R01
			Hoja: 2 de: 2
			CD :