THE CHALLENGE:

Low-Cost Chlorine Monitoring for Rural Piped Water Systems

Award: **$20,000 USD** | Deadline: **6/30/21** |
Revision 1.3: **6/30/21**
Source: InnoCentive | **Challenge ID:** 9934302 | **Type: RTP**

THE SOLUTION TITLE:

Low-Cost Chlorine Monitoring System

employing Digital Residual Chlorine Sensor

and Real-Time Data Transfer over LoRaWAN network.

Abstract

A fully automated system, controlled by a custom-designed Arduino-compatible PCB is proposed for free residual chlorine monitoring using a certified, low-cost commercially available, amperometric FCL sensor using a three-electrode potentiostatic method in combination with a dedicated flow cell, real-time data transmission through LoRaWAN, semi-flexible solar panel, and local storage on a microSD card. The flow cell provides an adjustable/controlled constant flow rate of 0.25 L/min to the sensor with a drain to “waste”, thus making the system independent of pipe network flow or pressure. The water “loss” is 0.5L per measurement session with a duration of 130 seconds and can be collected in a water canister with a tap and used even as drinking water since the measurement does not affect its quality. So if the seeker requests 4 measurements daily, 2 Litres will be collected in the water canister per 24hours.

The selected digital free residual chlorine sensor (CS5530D) was preferred due to its reliable operation and infrequent, easy to perform maintenance (no buffer solutions, no membrane, etc.) without the need for service contracts thus allowing long unattended operation at low operating cost. The fully automated system is powered from a reliable Li-Ion Battery (NCR18650, 3.7V, 2.9Ah), which is charged by a semi-flexible solar panel (5V, 1W) through a dedicated solar panel manager (DFR0559) module employing high-end MPPT (Maximum Power Point Tracking) technology. The last ensures that the photovoltaic cells always output the maximum power when the light intensity changes, to make full use of solar energy. However, due to fact that the system mainly stays in Sleep (low-power) Mode (0.4mA) and wakes up only for a short interval of time (130sec) to perform the measurements, it could run only on battery for about 6 months before recharging is needed, thus allowing also its implementation without solar panel.

The system samples the water every 5 seconds (user-defined) and an average value of 21 measurements (105sec) is sent as a message over LoRaWAN network with a spread factor SF11, and locally stored on an SD card with a timestamp. The selected SF provides increased time on-air, with reduced data rate, but improved communication range. The complete system (Main PCB, Flow Cell, and Sensor) is housed in a waterproof IP67 aluminum enclosure, where the solar panel is externally attached to its front panel. All the components (hardware and software) are readily available off the shelf and are of economic cost. Additionally, the system allows for simple in-field calibration (ZERO and SLOPE) without the use of a Laptop, where only a water sample with a known free residual chlorine content is required.

1 Introduction

The dynamic measurement of residual free chlorine, as described by Seeker, may be approached by mainly two ways: optical and conductivity-based. Thus, there are two types of chlorine analyzers; those that use a colorimeter to measure the chlorine level optically and those based on amperometry. The colorimetric units require chromogenic reagents that must be disposed of and employ a waste stream of roughly 200 mL per minute. They require frequent maintenance and generally perform poorly in an application subject to biofouling.

When chlorine is added to water it hydrolyzes to form:

$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$

$HOCl\ (aq) \rightleftharpoons OCl^-\ (aq) + H^+ (aq)$

In an amperometric sensor, application of a fixed voltage occurs between two electrodes and a reaction takes place at the working electrode (cathode) where reduction of chlorine (HOCl) back to chloride (Cl-) takes place (Fig. 1).

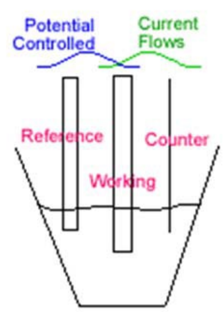

Figure 1: Three electrode amperometric cell

In an amperometric sensor, the current that flows because of this reduction is proportional to the chlorine presented to the sensor. The figure above shows the “three-electrode” configuration. Most membrane sensors use the “two-electrode” method. In general, the two electrode method readings are not as stable and electrodes will not last as long as the three-electrode method.

Virtually all of the “reagentless” amperometric chlorine sensors use a Johnson style membrane and electrolyte to control the reactions at these electrodes. These systems usually require elaborate pressure and flow control. In addition, recalibration of the membrane sensor is necessary if stretching or pressure spikes occur in the system. Membrane sensors also require frequent calibration, in some cases weekly or even daily due to changing conditions. They are also subject to the loss of electrolyte as it diffuses through the membrane. Membranes must also be frequently replaced, often quarterly.

A recent development in sensor technology is the use of screen-printed membranes. This eliminates the electrolyte replenishment but introduces another limitation in its lifetime due to membrane degradation. These sensors have a short life (approximately 6 months). Additionally, Membrane sensors (screen-printed or electrolyte style) generally will not work reliably at higher pH levels (7.5 to 8.5). There is also a complex temperature correlation and must be recalibrated if the temperature changes significantly.

The membrane in an amperometric chlorine sensor restricts the electrode to the measurement of only HOCl. In free chlorine applications, a pH of 5.0 to 7.0 is the ideal operating range for a membrane sensor, due to the high percentage of hypochlorous acid (HOCl) (>80%) in the sample and the steepness of the Free Chlorine Dissociation Curve in this range (Fig. 2).

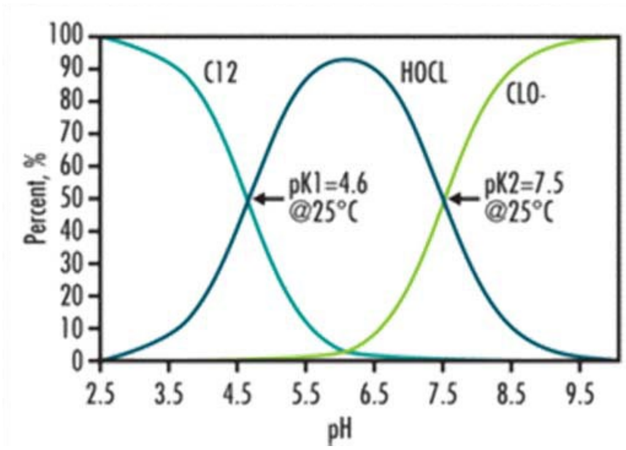

Figure 2: Chlorine dissociation curve

The pH can move within this range and the chlorine concentration can drift without significantly diminishing the accuracy of the instrument. This pH range, however, is not naturally present in drinking water facilities and a pH of 7.0 to 8.0 is typically the normal operating range for most drinking water facilities. The HOCl concentration is much lower versus the OCl- (hypochlorite ion) in this range. Another type of amperometric sensor uses bare electrodes for chlorine measurement. Depending upon the measurement potential selected, the bare-electrode sensor can measure both species (HOCl and OCl-). Although the signal response is not equal for both species, this type of sensor can operate at a higher pH than a membrane sensor and is less pH-dependent as seen in Table 1 (before pH compensation is applied).

Method	pH 7.0	pH 7.5	pH 8.0
Uncompensated HSI (Bare)	1.0 ppm	0.95 ppm	0.85 ppm
Uncompensated Membrane Sensor	1.0 ppm	~0.6 ppm	~0.2 ppm
DPD	1.0 ppm	1.0 ppm	1.0 ppm

Table 1: Compares the uncompensated chlorine signal with the HSI sensor, a typical membrane chlorine sensor versus the DPD method.

Conventional bare electrode amperometric sensors have some disadvantages though. These sensors operate with the application of a fixed potential. If used without a reagent feed to waste (with a buffered solution), as the electrode is polarized, the measurement current (chlorine signal) drops significantly during the first 24 hours. This requires additional effort by a technician to calibrate the unit the following day. Frequent inspections are necessary since these units do not have an electrode cleaning system. A common problem encountered with online measurement of water chemistry in the field is fouled electrodes in the sensor system. When the working electrode is covered with either inorganic layers (salts such as calcium carbonate) or organic layers (biofouling) that inhibit electrode processes, the system will under-report the chlorine level. Many sensor systems require a reagent feed of either an iodine solution or a buffer to lower the pH to 4.0. Other “reagentless” systems are dependent on flow or pressure and require controlled flow with a drain to waste to provide a constant flow rate to the sensor. This requirement further complicates the installation, maintenance, and logistical requirements and results in excessive water loss and unnecessary consumption.

Another problem with certain sensors is the lack of a flow-independent measurement method that can be installed in a process flow without adverse effects from changing flow rates on the sensor signal. Changing flow rates severely affect amperometric sensors. Preferably, a sensor system should provide accurate measurements with flow rates ranging from 0 to more than 7 feet per second without an appreciable change in the sensor output signal. Direct insertion into a pipe is impossible with most sensors without severely compromising accuracy. Frequent recalibration is necessary with most commercially available sensors due to changing electrode surface, fouling, electrolyte depletion, and membrane fouling or stretching. Maintenance costs often exceed the initial cost of the system.

Recently new Chlorine Sensor Platforms were developed that uses a different approach to residual measurement that eliminates many of the problems described above. Their objective is to eliminate the many factors that require recalibration in conventional amperometric sensors, allowing much longer unattended operation, up to a year or longer. These sensor platforms enable the measurement of five parameters with only four bare electrodes and a temperature sensor. This lowers the cost, improves the reliability and accuracy of the sensor by using the same electrodes and much of the same circuitry for multiple sequential measurements. With flow independent operation, onboard pH compensation, self-cleaning electrodes, and membrane-less chlorine measurement, the sensor can function for very long periods without calibration. However, they have a much higher cost and power consumption due to the dedicated electrode cleaning system (internal pumps, motors, etc.).

2 Materials and Methods

2.1 Free residual chlorine sensor

Alternatively, we propose a novel sensor (chromogenic reagents free colorimeter) that employs full-spectrum spectroscopy from UV to near IR to measure the chlorine level optically, thus avoiding the wastewater stream and electrode fouling. It uses reagent free spectrophotometric method with a spectral range from UV to NIR band. The proposed block diagram of the sensor is shown in Fig. 3.

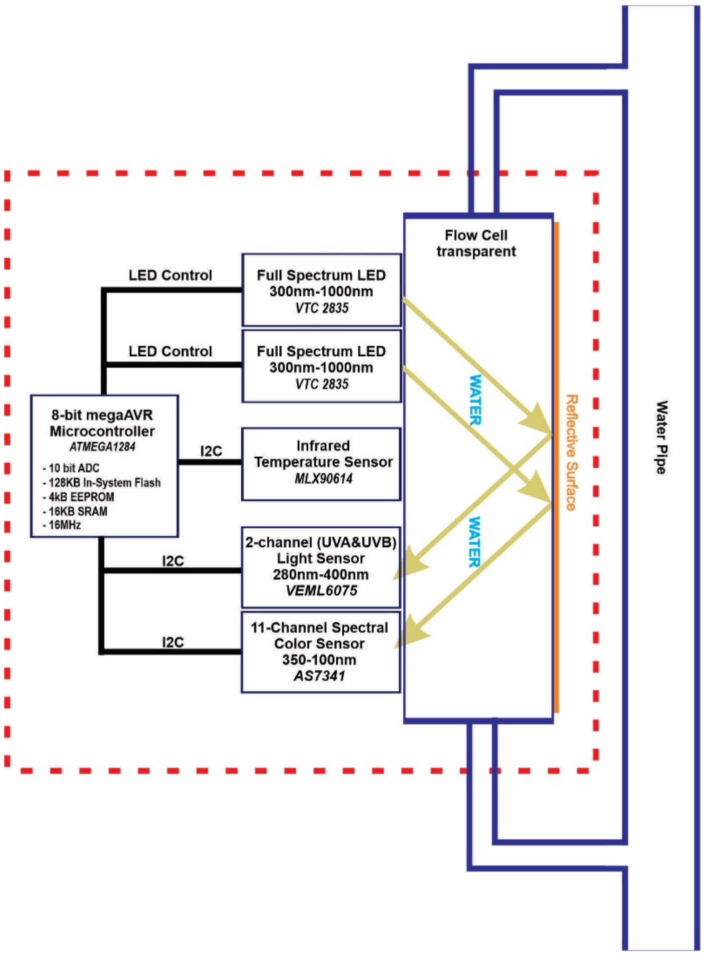

Figure 3: Simplified block diagram of the proposed free chlorine sensor employing machine learning

The novel idea is to measure as many as possible related parameters (absorptions at many different wavelengths, temperature, etc.) thus having enough data to allow the use of machine learning to compute the free chlorine level in the water. So in this case the systems can be trained using real data collected from the field of application. Our team built a pre-prototype and performed proof-of-concept testing with a simplified setup (without the UVA & UVB band) using the proposed spectrophotometric method with 11-Channel Spectral Sensor (AS7341) and true full spectrum LED (VTC 2835) with ultra-high CRI using violet die technology. This setup allows spectral response covering approximately 350nm to 1000nm with 8 channels centered in the visible spectrum (VIS), plus one near-infrared (NIR) and a clear channel.

Although the preliminary results are promising (Fig 4 & 5), such a solution would require a longer time for development, training the system, proof of concept testing, validation, calibration, and reliability testing until suitable for use in real field applications. However, if the seeker is interested in such an approach, then a working prototype based on this approach can be developed and delivered upon request.

	F1 (410nm)	F2 (440nm)	F3 (470nm)	F4 (510nm)	F5 (550nm)	F6 (583nm)	F7 (620nm)	F8 (670nm)	CLEAR	NIR
Raw:	270	673	788	1014	1169	1293	1470	1666	4823	359
Basic:	0.002898	0.007222	0.008456	0.010882	0.012545	0.013876	0.015775	0.017879	0.051758	0.003853
Corr:	0.002805	0.006995	0.008190	0.010540	0.012152	0.013440	0.015281	0.017319	0.050143	0.003732

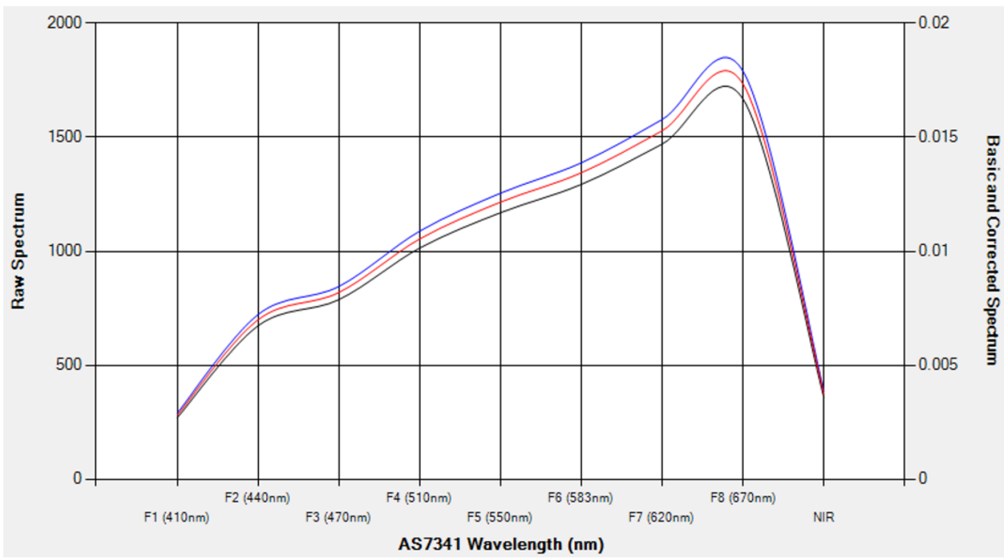

Figure 4: Preliminary results from water sample with 1mg/L free residual chlorine

	F1 (410nm)	F2 (440nm)	F3 (470nm)	F4 (510nm)	F5 (550nm)	F6 (583nm)	F7 (620nm)	F8 (670nm)	CLEAR	NIR
Raw:	273	681	797	1030	1181	1308	1499	1703	4879	364
Basic:	0.002930	0.007308	0.008553	0.011054	0.012674	0.014037	0.016087	0.018276	0.052359	0.003906
Corr:	0.002836	0.007078	0.008284	0.010706	0.012277	0.013596	0.015582	0.017704	0.050726	0.003784

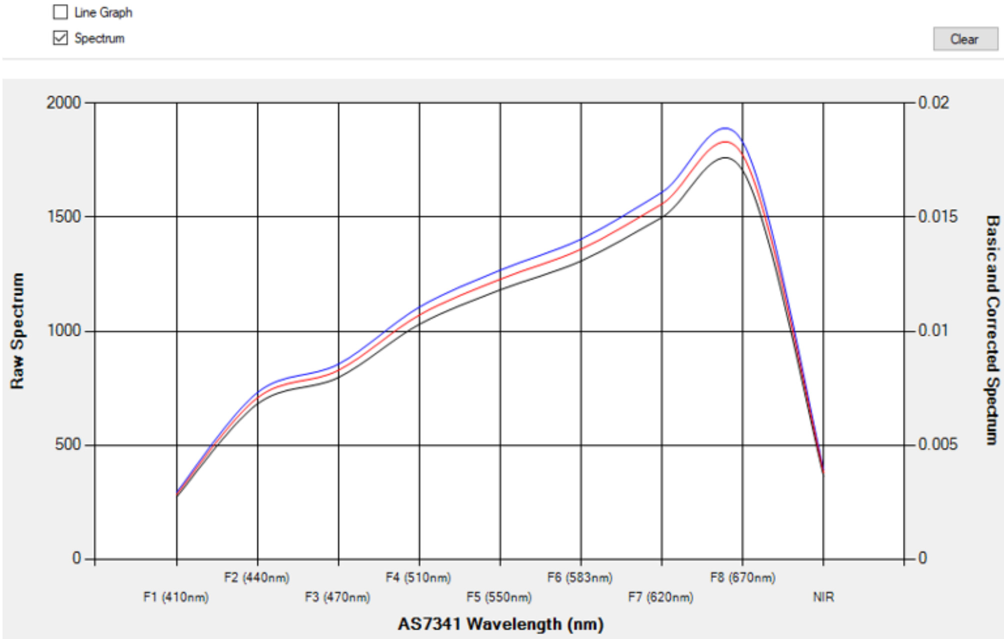

Figure 5: Preliminary results from water sample 0mg/L free residual chlorine

Based on the technology analysis performed, our team has concluded that the optimal straightforward solution to measure free chlorine for the specific challenge, that offers the shortest design, development, and validation times, is to use a certified, low cost commercially available, amperometric sensor, providing the required or higher measuring range and accuracy. Preferably the selected sensor should have infrequent, easy to perform maintenance (no buffer solutions or expendable membranes, etc.) without the need for service contracts thus allowing longer unattended operation at lower operating costs. Although that kind of sensors/probes could be simply submerged into a tank, wet well, or pipe, it is better to be used in combination with a flow cell in which pressure and flow rate are controlled and consistent.

After extensive market research, aiming optimal trade-off between quality and cost, our choice for residual chlorine sensor that will allow fast prototyping and minimal manufacturing time is the bare electrode (no membrane & buffer solutions) Digital Free Chlorine Sensor - CS5530D (Fig. 6), commercially available from Clean Instruments Corporation with a price range 160$ (for 200pcs) to 210$ (for 1pcs) according to the order quantity. It is a new generation of intelligent water quality detection sensors, independently developed by the company.

*Figure 6: Main specifications and dimensions of the selected sensor (*offered only with range 0-20mg/L and opt. flow rate 10-30L/h).*

During measurement the chlorine and chlorine dioxide will be consumed from the water sample, therefore continuous water flow must be maintained. This is easily implemented by a dedicated flow cell which is also offered by the company with a cost range from 50$ to 70$. A good alternative choice is the use of the analog version of the sensor (CS5530) which is offered with a price range from 100$ (for 200pcs) to 140$ (for 1pcs). However in this case an additional analog circuitry is needed as shown in Fig. 7 (circuit designed by our team). The main advantage, in this case, is that the potential in the galvanostatic mode can be set by the user and additionally allows for bipolar operation or variable bipolar waveforms rather than a fixed potential, thus minimizing the electrode polarization and therefore less frequent calibrations. Another advantage is that that the front-end amplifiers (U13) can be implemented with pico-Ampere (pA) input bias current operational amplifiers, allowing operation with very low potential/voltage, hence current, thus minimizing further the electrode polarization effects and the electrode “fouling”. However, such a solution will also require a longer developing time until the interface circuit is properly tuned, and temperature compensated (use of extra temperature sensor is required) for valid and reliable measurements. Nevertheless, if the seeker is interested in such an approach, then we can develop and deliver a working prototype based on an analog sensor upon request.

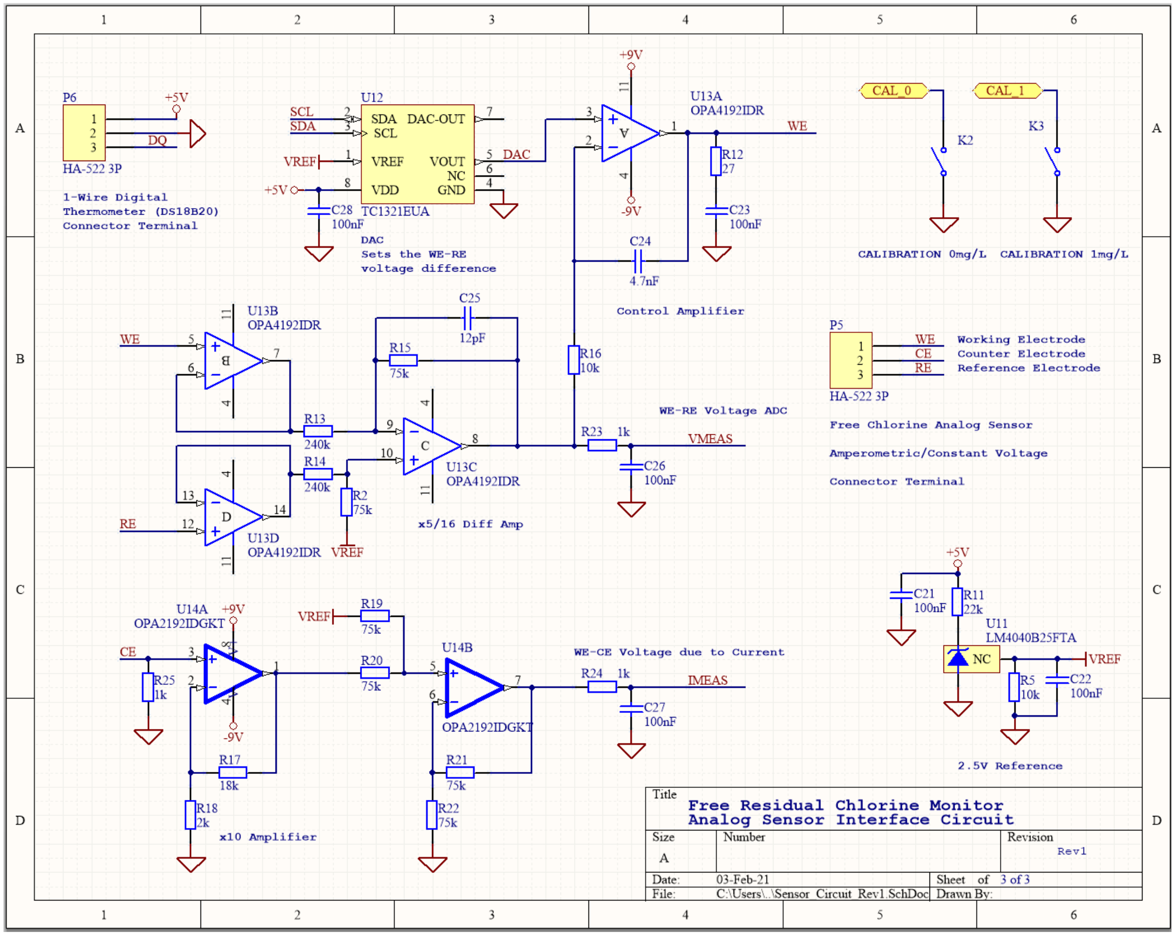

Figure 7: Schematic of the interface circuit for analog amperometric sensor

The selected digital sensor (CS5530D) adopts advanced non-membrane constant voltage residual chlorine measurement, thus having no need to change diaphragm/membrane or fill solution and providing stable performance and simple maintenance. Constant voltage measurement maintains a stable electric potential at the measurement side of the electrode, different components produce different current intensities, thus electric potential when measured. The micro-current measurement system consists of two platinum electrodes and a reference electrode. The sensor is temperature compensated, easy to maintain, and provides stable and accurate measurements with an operational range and accuracy higher than the requested by the seeker, which makes it highly suitable for drinking water distribution networks. However, it should be noted that operating in poorer quality water may be possible but will require much more frequent cleaning, which can defeat the low maintenance purpose of this technology. Additionally, elevated levels of iron will prevent the 3-electrode sensor from producing a reliable output signal. The sensor features high precision, good stability, long lifetime, rapid response, and low maintenance cost. The main features and technical specifications of the selected digital free chlorine sensor are as follow:

- Isolatated power and output signal to ensure electrical safety
- Built-in protection circuit of power supply & communication chip
- Good environmental resistance and easier installation and operation
- Platinum sensor, three-electrode method
- Body Material: Glass
- Working pressure: 0-6 bar
- Dimensions: length 110mm, 12mm diameter
- Suitable for pipe installation (PG13.5 thread)
- 4 line electrical interface (2 power lines, 2 RS-485 signal lines)
- Power Supply: 9-24 VDC
- Current consumption: <30mA
- Output: isolated current output RS485 (RS485 Modbus RTU)
- Chlorine Measurement range: 0 – 20 mg/L
- Resolution: 0.01 mg/L
- Accuracy: ±1%
- Stability: ±0.01 mg/L/24h
- Automatic real-time temperature compensation: 0 - 70 ℃, resolution 0.1 ℃
- Optimum Flow Rate: 10-30L/h (0.16-0.5 L/min)
- Low maintenance cost
- IP68 Protection

2.2 Main System Board

The main system electronic board was also designed and implemented by readily available Arduino boards and a set of different breakout boards (Fig. 31). However, such a solution is far from optimal due to the increased number of different breakout boards required, featuring excessive functionality (non-useful for the purpose) which leads to excessive wiring and component count resulting in increased power consumption and dimensions. The cost also proved to be higher and the work effort was significant. Furthermore, using this approach does not allow to reduce significantly the power consumption during sleep mode which is essential for the power autonomy of the system, so this design & implementation solution was abounded and will not be described further but may be provided on request. Therefore we propose an Arduino-compatible custom-designed PCB fully optimized design according to the specific project aims, as shown in Fig. 8. All system modules and components are well denoted in the two schematic sheets, the PCB design, and the provided BOM (Fig. 25, 26, 27, 28).

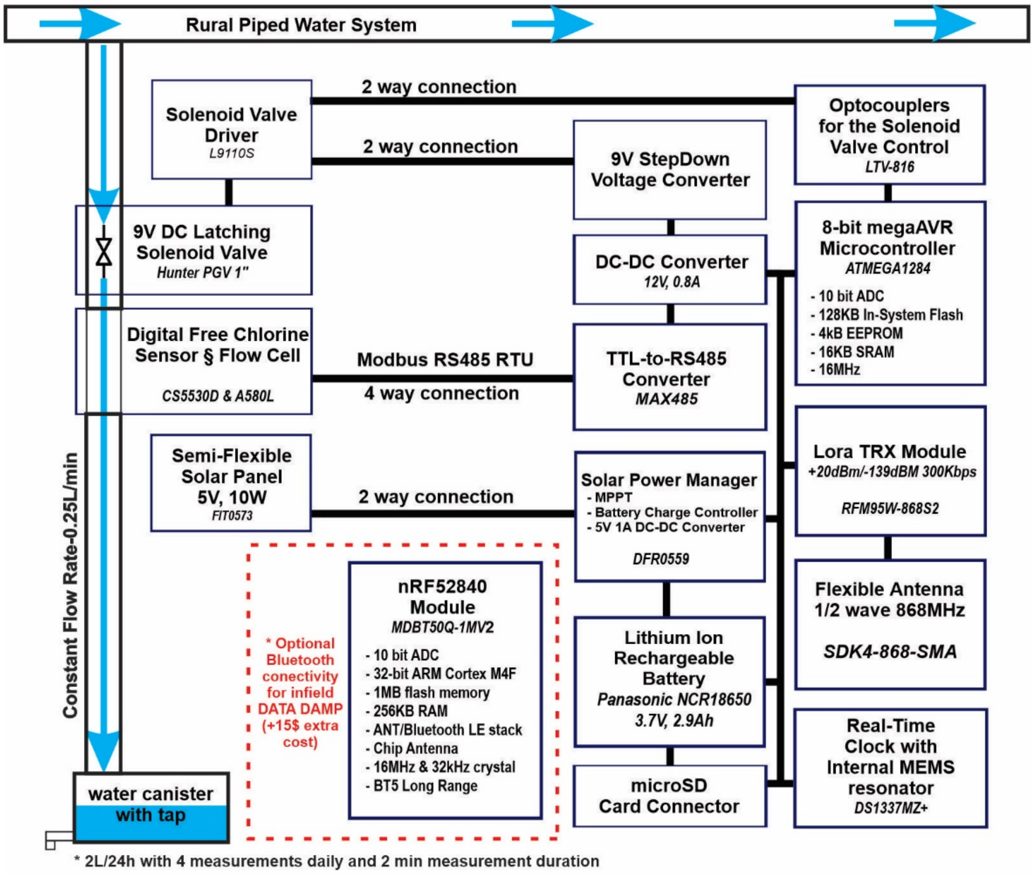

Figure 8: Block diagram of the proposed free chlorine monitoring system

2.2.1 Microcontroller

The system operates at 5V, 3.3V, and 12V and is controlled by an Arduino compatible high-performance Microchip 8-bit AVR® RISC-based microcontroller ATmega1284-AU (Fig. 9), which offers 128 KB ISP flash memory with read-while-write capabilities, 4 KB EEPROM, 16 KB SRAM, 32 general-purpose I/O lines, 32 general purpose working registers, a real-time counter, three flexible timer/counters with compare modes and PWM, two USARTs, a byte-oriented

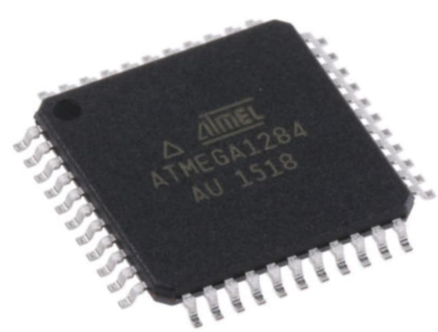

Figure 9: Photo of the ATmega1284-AU microcontroller

Two-Wire serial interface, an 8-channel 10-bit A/D converter with optional differential input stage with programmable gain, programmable watchdog timer with internal oscillator, SPI serial port, a JTAG (IEEE® 1149.1 compliant) test interface for on-chip debugging and programming, and six software selectable power saving modes. By executing powerful instructions in a single clock cycle, the device achieves throughputs approaching one MIPS per MHz, balancing power consumption and processing speed.

2.2.2 **Power Supply** (Solar Panel, Solar Power Manager, Battery Charge Controller, and DC-DC Converter)

The power supply is implemented by a commercially available Solar Power Manager (DFRobot DFR0559), a Semi-Flexible Solar Panel (5V 2A), and a Lithium-Ion Rechargeable Battery (NCR18650), which were selected due to their proven high reliability and high conversion efficiency.

2.2.2.1 Solar Panel

The selected powerful semi-flexible Solar Panel (5V, 2A, 10W) features an A-class monocrystalline silicon panel (Fig. 10). Due to up to 21% conversion efficiency and waterproof design, we don't have to worry about rains. It can supply plenty of power in various environments to prevent the system from shutting down, even on rainy days. The energy of the solar panel is particularly efficient when paired with the selected solar power management board. The ultra-thin, lightweight design weighs just 142g. It's much lighter than a solar panel in a traditional glass package. It is recommended when installing this panel, to make sure it is facing the sun and there is no shade covering it. https://www.dfrobot.com/product-1751.html

Figure 10: Photo of the selected semi-flexible Solar Panel

2.2.2.2 Solar Power Manager, Battery Charge Controller, and DC-DC converter

The Solar Power Manager, the Battery Charge Controller, and the DC-DC converter are implemented by a single commercially available Solar Power Manager Module (DFRobot DFR0559), selected due to its proven high reliability and safety (Fig. 11 & 12). The Solar Power Manager features an MPPT (Maximum Power Point Tracking) function, maximizing the efficiency of the solar panel. The module can provide up to 900mA charging current to 3.7V Li battery with USB charger or solar panel. The ON/OFF controllable DC-DC converters with 5V 1A output satisfy the needs of various solar power projects and low-power applications. The module also employs various protection functions for battery, solar panel, and output, which greatly improves the stability and safety of the project. https://www.dfrobot.com/product-1712.html

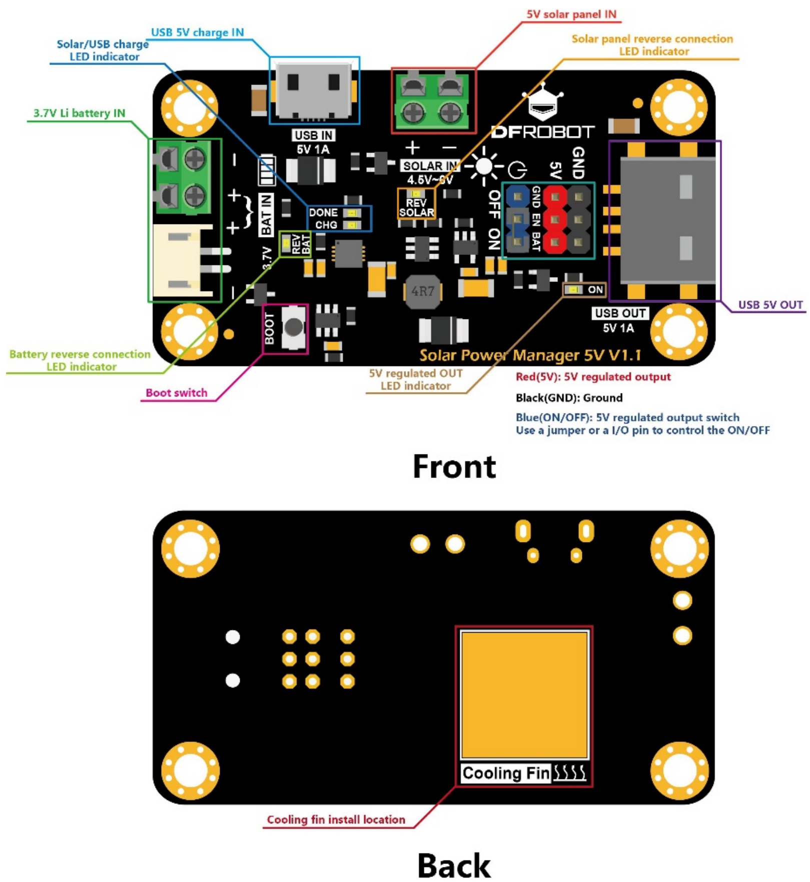

Figure 11: Model of the selected Solar Power Manager

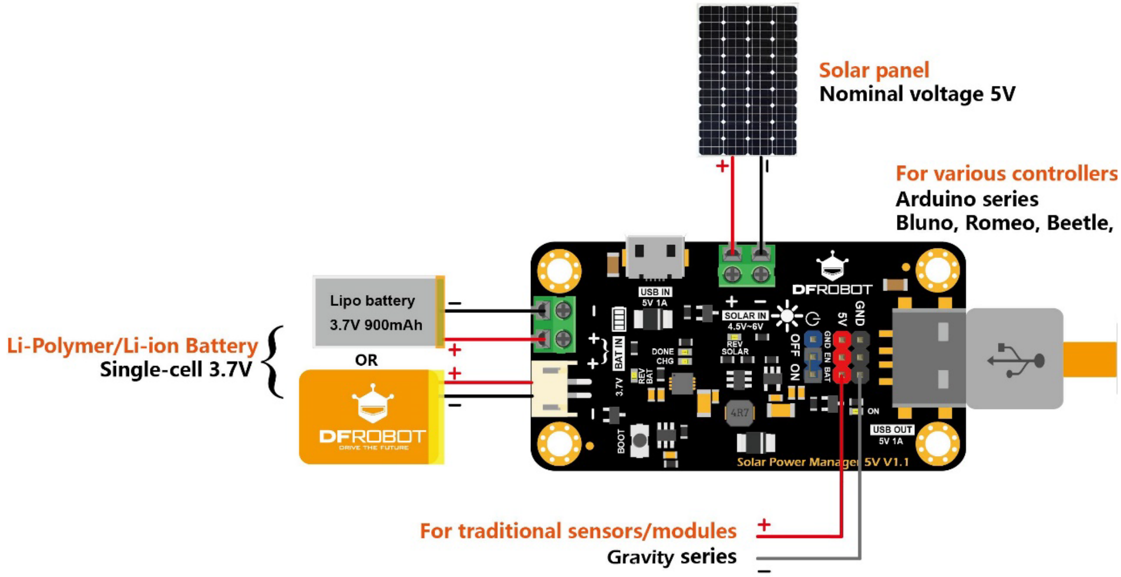

Figure 12: Typical setup using the selected Solar Power Manager

2.2.2.3 Lithium-Ion Rechargeable Battery

The selected battery is the extremely powerful Panasonic NCR18650, 2900mAh, 12A, 3.6V, Grade A Lithium-Ion battery, intended for use in high capacity 18650 battery packs (Fig. 13). Thanks to the new NNP, and HRL technology Panasonic 18650 NCR18650 li-ion battery cell is one of the top 18650 performers. Despite the increased power, which normally gives rise to an increased safety risk, Panasonic batteries remain particularly safe thanks to the patented Heat Resistant Layer (HRL) technology. This solution consists of an insulated metal oxide film between the electrodes, which prevents overheating even in the case of an internal short-circuit. Tested, and confirmed, Panasonic 18650 batteries are highly regarded for performance and safety. Theoretically, based on the low system's consumption, the system could run only on battery for about 6-7 months before recharging is needed. Thus allowing long period operation without dedicated solar panel.

Figure 13: Photo of the Lithium-Ion Rechargeable Battery Panasonic NCR18650

2.2.3 Step-up DC-DC Converter

The DC-DC Step-Up Converter used for generating the 12V for the digital chlorine sensor is implemented by the AM1SS-0512SJZ from AIMTEC Inc (Fig. 14). It is an isolated (1500VDC) 1W; Single Step-Up Converter with a conversion efficiency of 83%. The 12V isolated power is used for the supply of the digital free chlorine sensor, and the solenoid valve after stepping it down to 9V. Thus the chlorine sensor and the solenoid valve are galvanically isolated (floating) from the rest of the control circuit, thus providing enhanced safety, noise immunity, and reliability.

Figure 14: Photo of the selected DC-DC -5V to 12V Step-Up Converter

The 9V power supply for the Solenoid Valve is obtained from the 12V simply by using 4 diodes and one super Capacitor which charges till 9V and stores the energy needed for opening & closing the valve.

2.2.4 LoraWAN Module and Antenna

The selected LoRa Module is the RFM95W-868S2 transceiver from HOPE Inc., which features the LoRa^{TM} long-range modem that provides ultra-long range spread spectrum communication and high interference immunity whilst minimizing current consumption (Fig. 15). Using Hope RF's patented LoRaTM modulation technique RFM95W can achieve a sensitivity of over -148dBm using a low-cost crystal and bill of materials. The high sensitivity combined with the integrated +20 dBm power amplifier yields an industry-leading link budget making it optimal for any application requiring range or robustness. LoRa^{TM} also provides significant advantages in both blocking and selectivity over conventional modulation techniques, solving the traditional design compromise between range, interference immunity, and energy consumption.

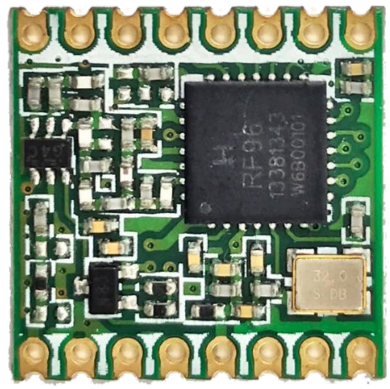

Figure 15: Photo of the LoRa Module, the RFM95W-868S2 transceiver

These devices also support high performance (G) FSK modes for systems including WMBus, IEEE802.15.4g. The RFM95W delivers exceptional phase noise, selectivity, receiver linearity, and IIP3 for significantly lower current consumption than competing devices. The selected antenna (SDK4-868-SMA) is the best in its class. It is a flexible end-fed 1/2 wave antenna for the 868 MHz frequency band with a length of 17 cm (Fig. 16). It features SMA connection, no ground plane needed, and 3dB more gain than a 1/4 wave antenna. The antenna is connected to the mainboard through an Interface Cable SMA Female to U.FL - 20cm.

Figure 16: Photos of the selected Antenna and Interface Cable

2.2.5 TTL-to-RS485 Converter

The TTL-to-RS485 Converter is used to communicate with the Digital Free Chlorine Sensor - CS5530D and is implemented with the MAX485 IC, a low-power transceiver for RS-485 and RS-422 communication (Fig. 17). Each part contains one driver and one receiver. These transceivers draw between 300µA and 500µA of supply current when unloaded or fully loaded with a disabled driver and operate from a single 5V supply. The Driver is short-circuit current limited and is protected against excessive power dissipation by thermal shutdown circuitry that places the driver outputs into a high-impedance state. The receiver input has a fail-safe feature that guarantees a logic-high output if the input is an open circuit. The chip is designed for half-duplex applications.

Figure 17: Photo of the selected TTL-to-RS485 Converter

2.2.6 Real-Time Clock

The Real-Time Clock (RTC) is used to generate an alarm for waking up the device and performing measurements every 6 hours (or user-defined) and the timestamp for the data when written to the SD card (Fig. 18). It is implemented with a low-cost, extremely accurate, and industry's first temperature-compensated RTC with an internal MEMS resonator that reduces crystal mechanical failure susceptibility (DS3231MZ+). The device incorporates a battery input and maintains accurate timekeeping. The integrated oscillator improves the long-term accuracy of the device and reduces the number of components of the production line. The RTC maintains seconds, minutes, hours, day, date, month, and year information. The date at the end of the month is automatically adjusted for months with fewer than 31 days, including corrections for leap year. The clock operates in either the 24-hour or 12-hour format with an AM/PM indicator. Two programmable time-of-day alarms and a 1Hz output are provided. Address and data are transferred serially through an I2C bidirectional bus.

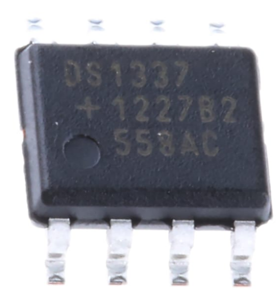

Figure 18: Photo of the selected Real-Time Clock DS1337MZ+ in 8-Pin SOIC package

2.2.7 microSD Card Connector

The microSD Card Connector is implemented with 8 Pin Surfacemount Card Connector with gold contact plating from 3M Electronic Solutions (Fig. 19). It is very durable and reliable and features a low profile, card polarization, metal-shielded cover, and smooth push-push eject mechanism thus providing long-lasting performance.

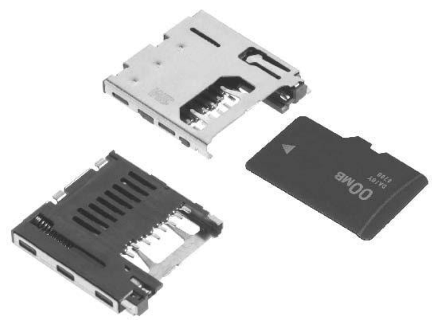

Figure 19: Photo of the selected microSD Card Connector

2.2.8 Solenoid Valve & Driver

The solenoid valve is implemented with the top-of-the-line 9V DC latching Solenoid Valve Hunter PGV 1" Female Threaded, selected for its high reliability, durability, low power consumption, hassle-free maintenance, and long-lasting performance (Fig. 20). This valve features high-grade construction and a rugged diaphragm with support to prevent stress failure. It has proven its superior leak-free performance due to the double-beaded diaphragm, where the DC latching enables battery-powered controllers. The 1" Female Threaded interface provides an easy and trouble-free connection to a pipe network. https://www.waterirrigation.co.uk/hunter-pgv-1-female-threaded-9v-solenoid-valve-with-flow-control.html

Figure 20: Photo of the selected 9V DC latching Solenoid Valve Hunter PGV 1"

The solenoid driver is implemented with the H-Bridge Motor Driver chip L9110S (Fig. 21). The chip was selected for its low cost and proven reliability in many Arduino-based projects. It is an ASIC device, with a two-channel push-pull power amplifier integrated into a monolithic IC, thus reducing the cost and improving the reliability. This chip has two TTL/CMOS compatible inputs, and one output with large current driving capability (750-800mA of continuous current and up to 1.5-2A peak current), low output saturation voltage, and a built-in clamp diode.

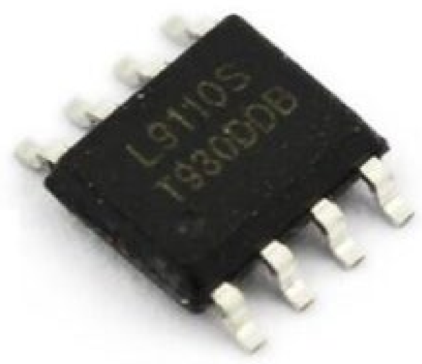

Figure 21: Photo of the selected Solenoid Valve Driver

2.3 Data Transfer

The digital transmission of logged data is implemented by a LoRaWAN network with star-of-stars typology (Fig. 22), with uni-directional data transfer, in which a so-called transparent bridge is used as a gateway. LoRaWAN solutions provide cost-efficient and reliable data transfer and are particularly suitable for the sending and receiving of small amounts of data across distances of potentially tens of kilometers, depending on the terrain.
(https://www.thethingsnetwork.org/docs/lorawan/).

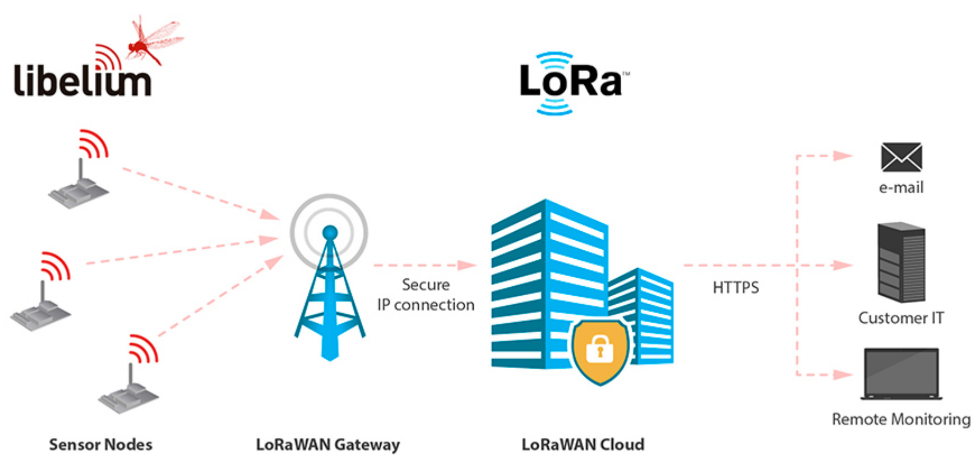

Figure 22: Typical LoRaWAN network with star-of-stars typology

Moreover, the required LoRaWAN Gateway can be easily build based on Raspberry Pi C880A-SPI concentrator board as described in an open-source project available in GitHub. (https://github.com/ttn-zh/ic880a-gateway/wiki). We have also developed a custom-tailored IMST iC880a LoRaWAN backplane, shown in Fig. 23, which can be provided on request as well.

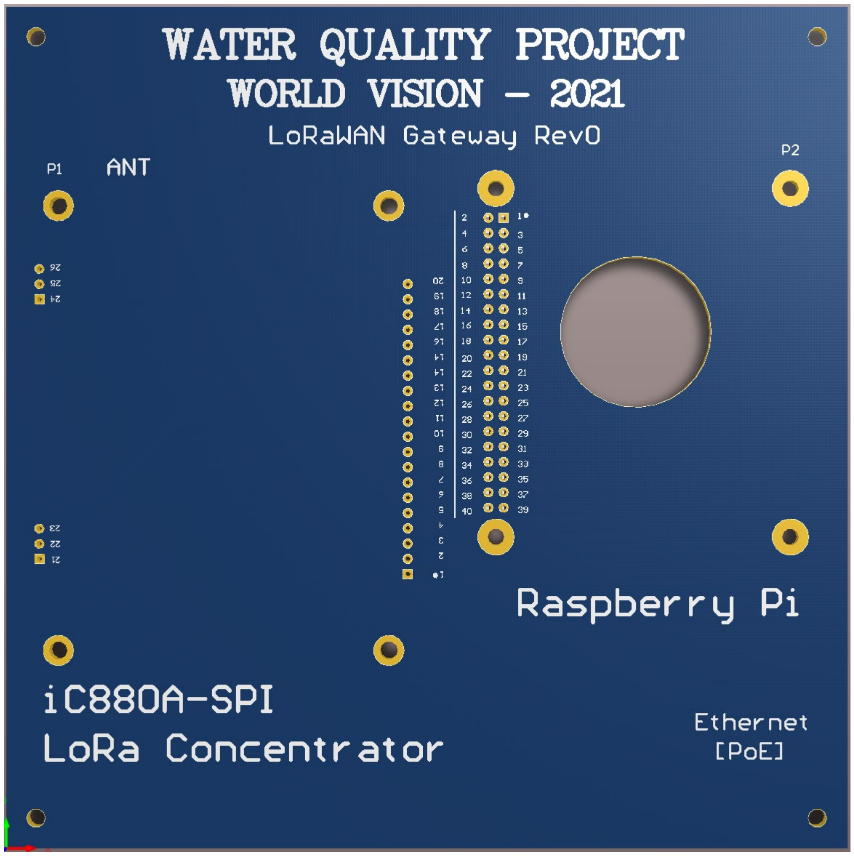

Figure 23: PCB of the IMST iC880a LoRaWAN backplane.

The advantage of LoRa technology compared to other modulation solutions is good radio coverage even at long distances while the power consumption remains at a minimum. LoRa is based on spread spectrum modulation, with a great tolerance for interference, and minor effect of reflections and diffraction on the signal. LoRaWAN data transfer can be uni-or bidirectional, and it is divided into various frequency channels and speeds. The selection of data transfer speed depends on data volumes and the distance between the sensor and central network server (gateway). Typically, the data transfer speed in LoRaWAN networks is 0.3–50 Kbps. Data volumes are typically a few dozen kilobytes. Batteries used in low power sensors employing Lora technology can last for even ten years, so these solutions are practically maintenance-free. LoRaWAN is also a very secure solution due to the encrypted data transfer that is implemented in three different network layers.

The proposed monitoring system samples the water every 5 seconds (user-defined) and an average value over a 3-minute period is sent as a message over LoRaWAN with a spread factor (SF) of 11ms and a message size of 2bytes. The selected SF provides increased time on-air, with reduced data rate, but improved communication range and has proven optimal in other LoraWAN devices developed by our team. The transmitted data is also locally stored on an SD card with a timestamp.

2.4 System Enclosure

The complete system (main PCB, flow cell, sensor etc.) is housed in a sealed aluminum enclosure, where the solar panel is externally attached to the box. The selected housing (APV 20 ILME) is 264x214x122mm and is waterproof with a rating of IP67 as shown in Fig. 24 (https://www.tme.eu/en/details/ilme-apv20/multipurpose-enclosures/ilme/apv-20/.). The housing can be also 3D printed using premium ASA Filament. It is a thermoplastic polymeric material in the form of a fiber, used for 3D printers in the method FFF. Intended for the manufacture of functional prototypes and finished products, which are expected to have great resistance to weather conditions and durability. Filament does not change color under the influence of UV radiation (https://grobotronics.com/3d-printer-filament-devil-asa-1.75mm-natural-1kg.html). A dedicated enclosure design for 3D printing can be also provided on request.

Figure 24: Photo of the selected system housing APV 20 ILME

3 Results

3.1 Hardware

A working prototype was developed according to the proposed solution and underwent 33 days trial where the experimental results are logged. The two main schematic sheets depicting the complete circuit of the system are shown in Fig. 25 & 26, where the PCB design is shown in Fig. 27 & 28.

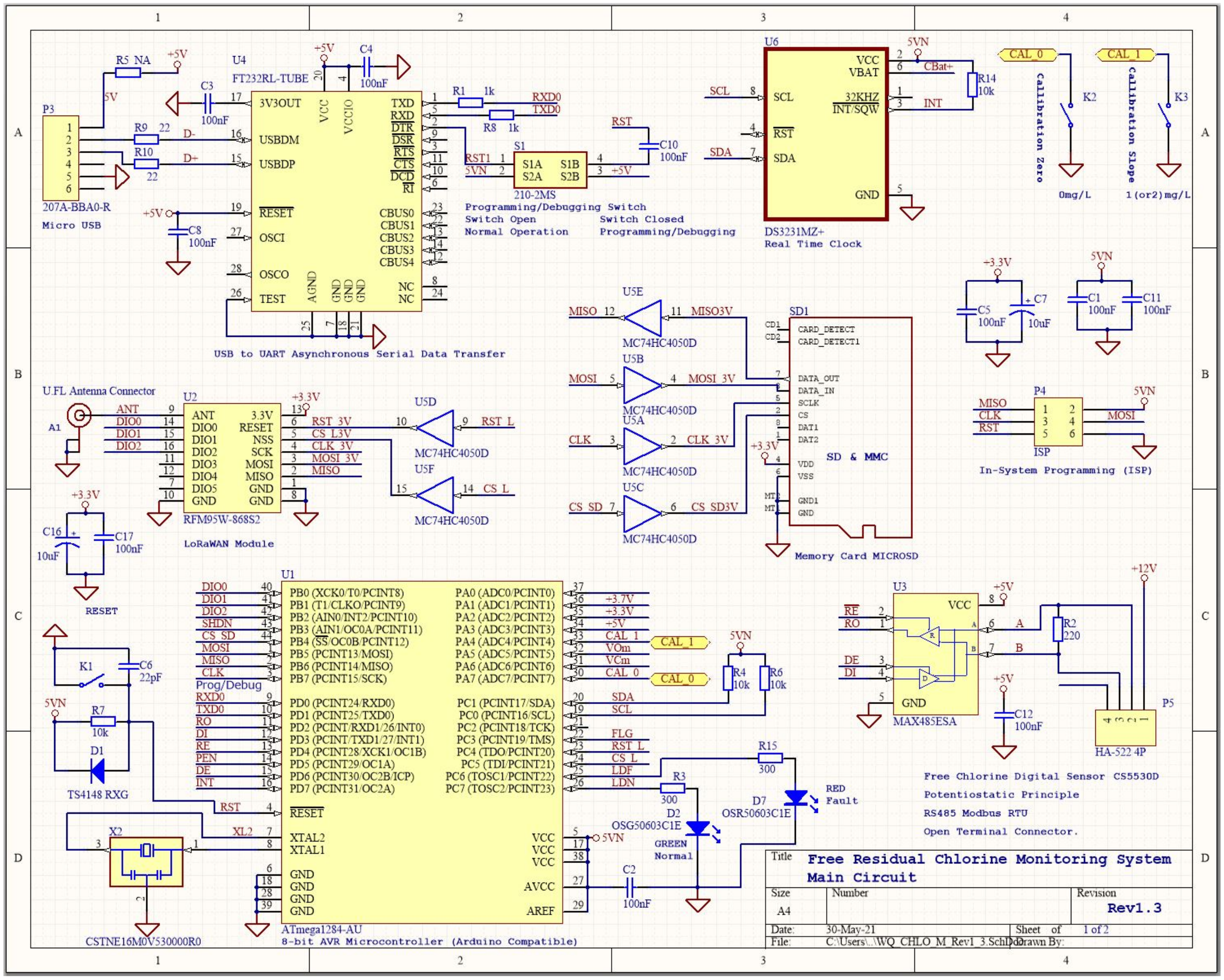

Figure 25: Main schematic of the proposed free chlorine monitoring system.

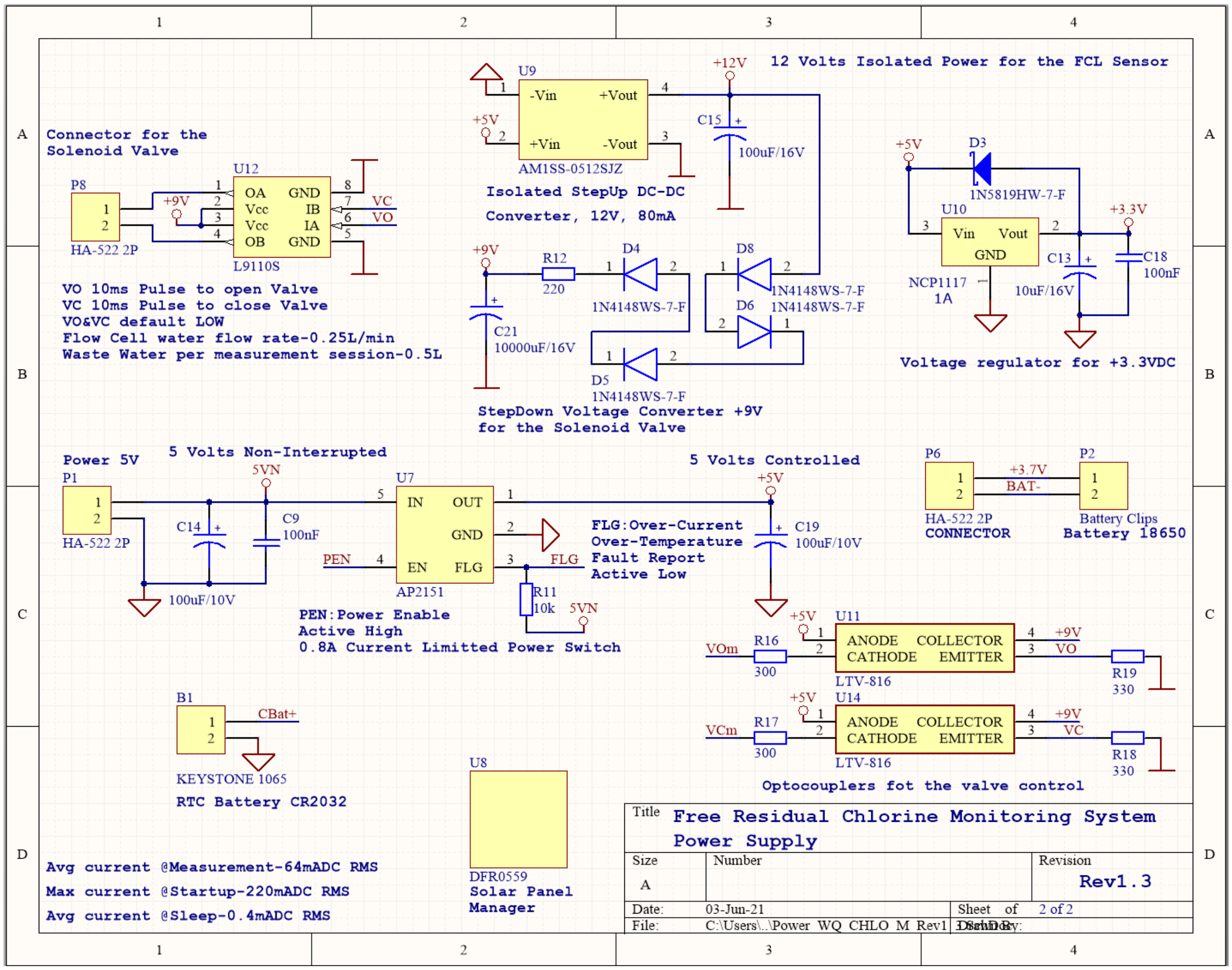

Figure 26: Schematic of the power supply of the proposed free chlorine monitoring system.

Being by years in R&D, with broad experience in design and development of different instrumentation, we are also capable of developing custom-tailored LoRaWAN Gateway and Software for collecting and analyzing the data send through LoRaWAN from the proposed measuring system.

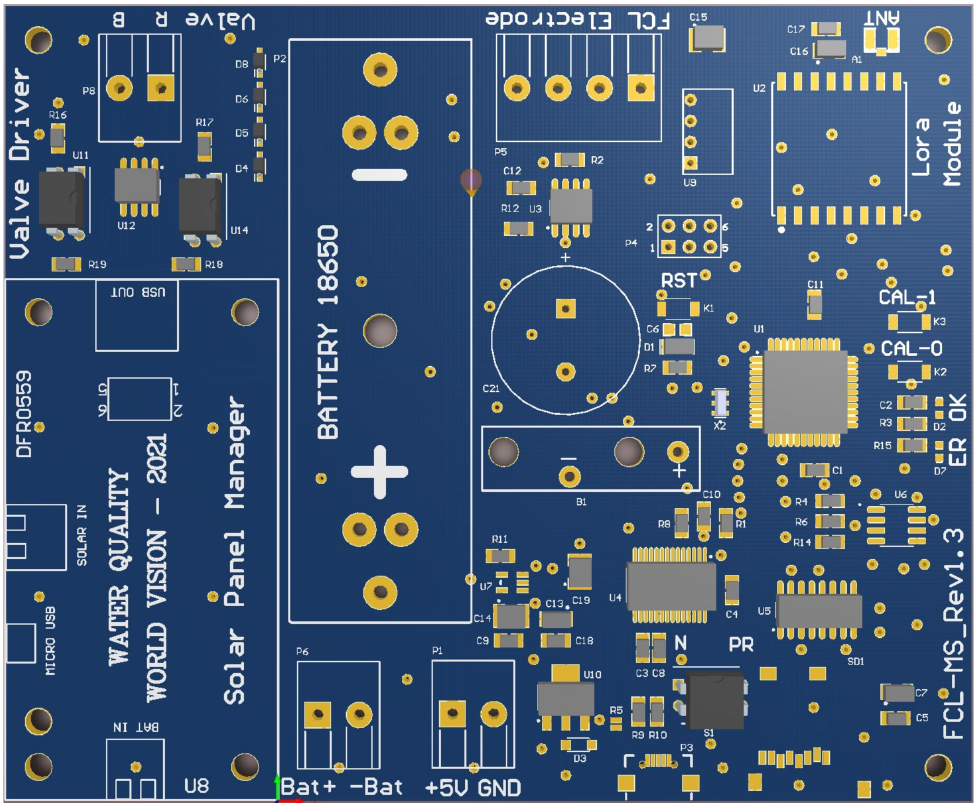

Figure 27: PCB design of the proposed free chlorine monitoring system.

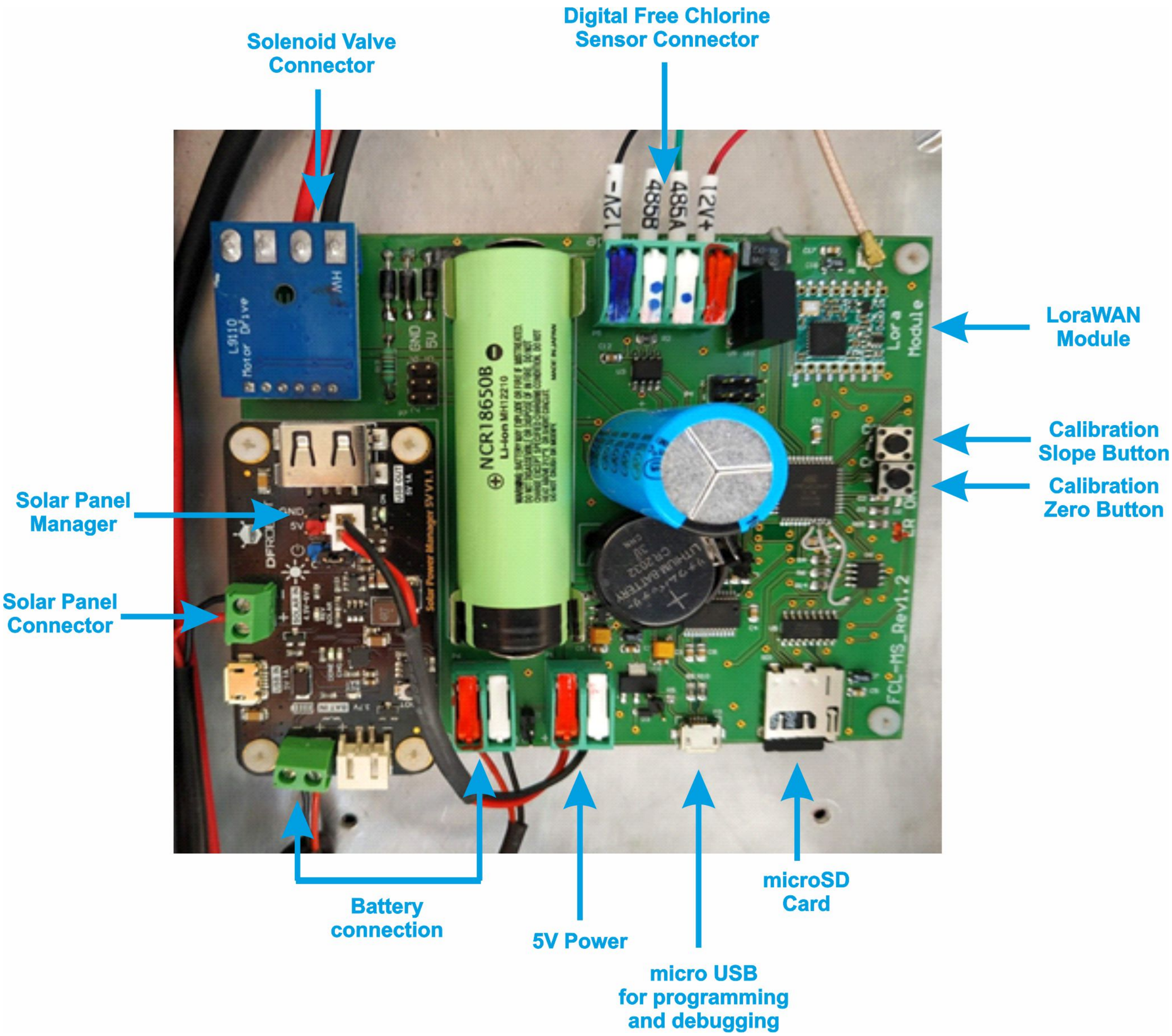

Figure 28: Photo of the final PCB prototype

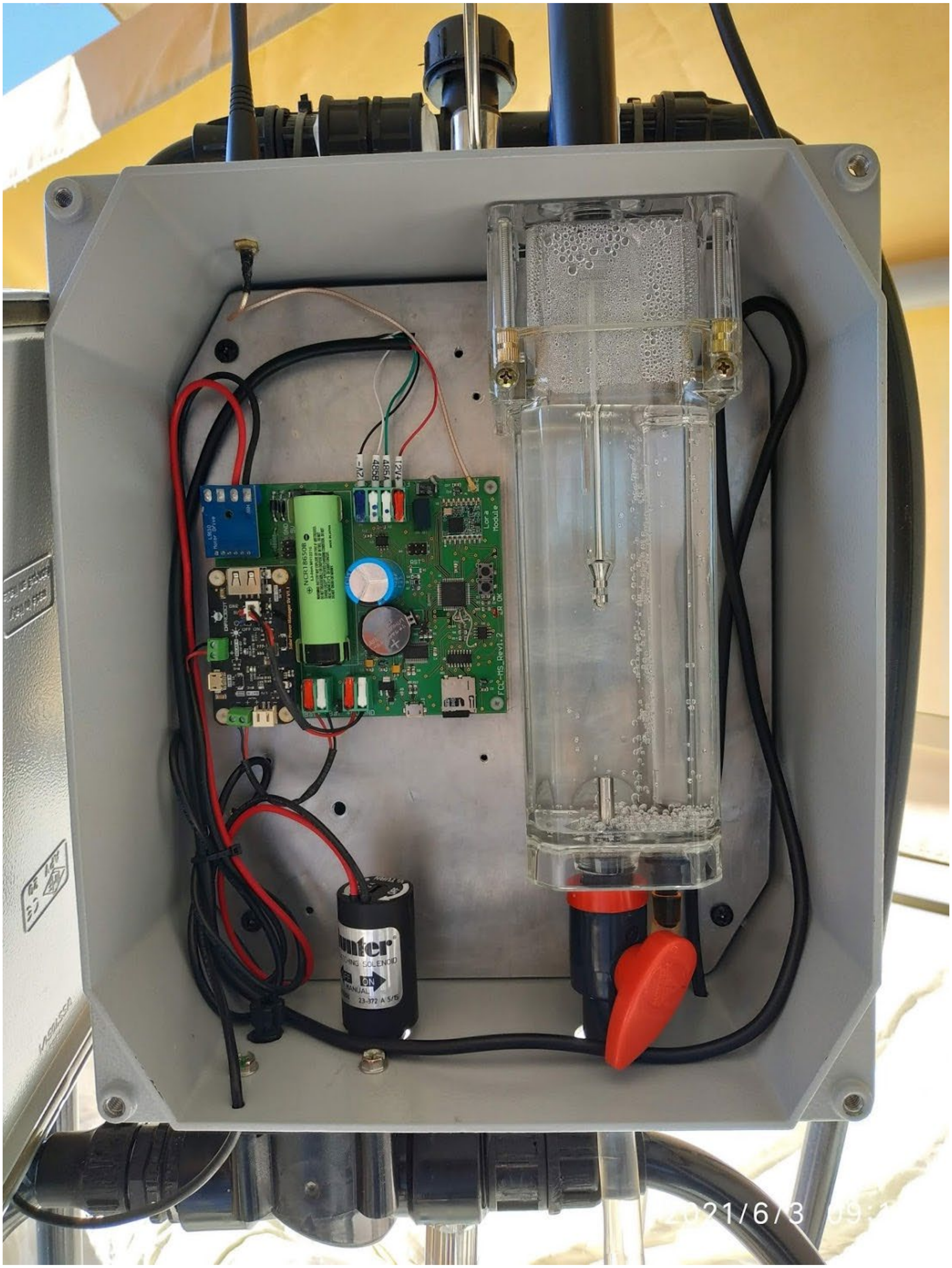

Figure 29: Photo of the final working system prototype (without front panel)

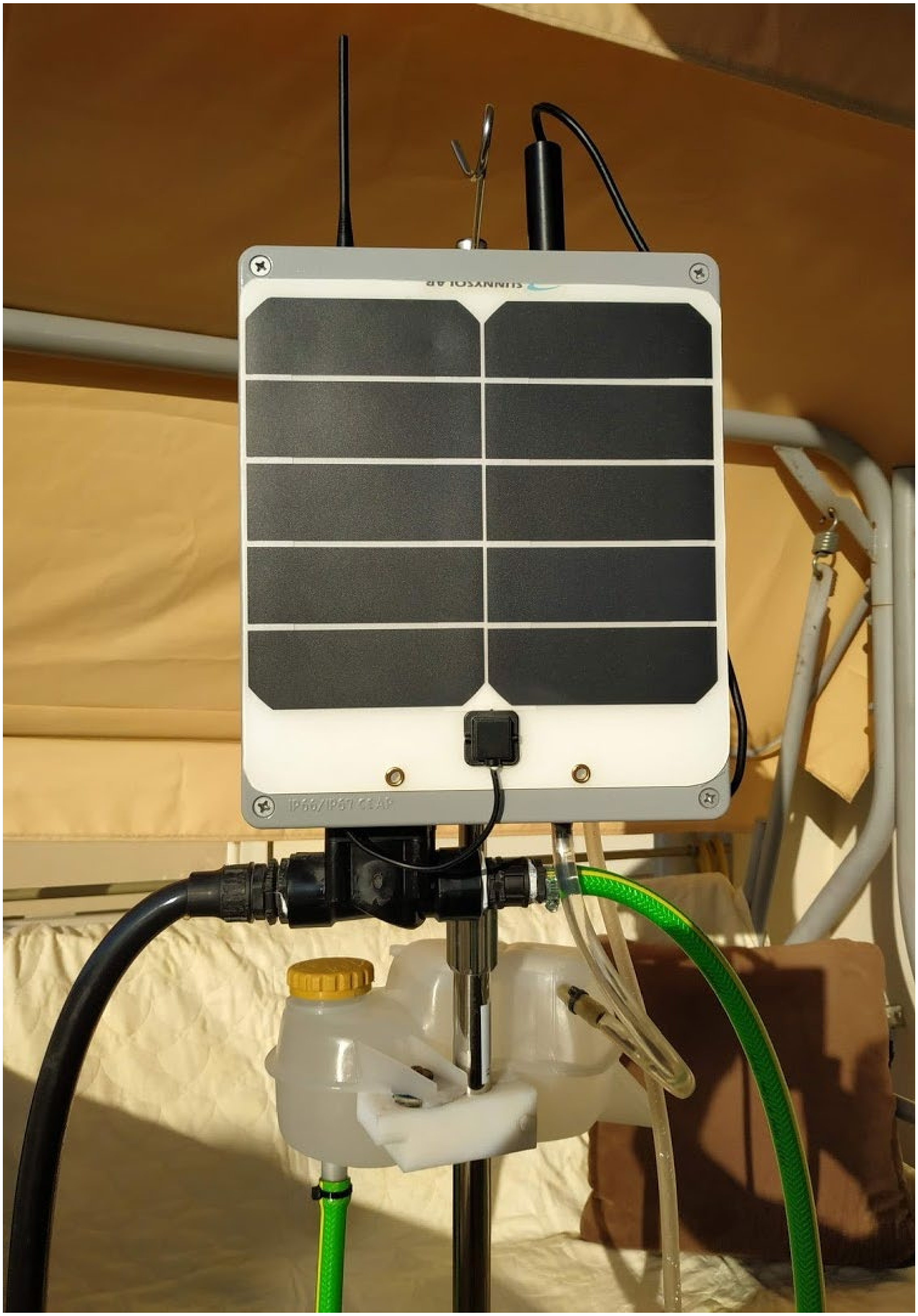

Figure 30: Photo of the final working system prototype & testing setup

The proposed system was implemented also from readily available Arduino and a set of different breakout boards as shown in Fig. 31.

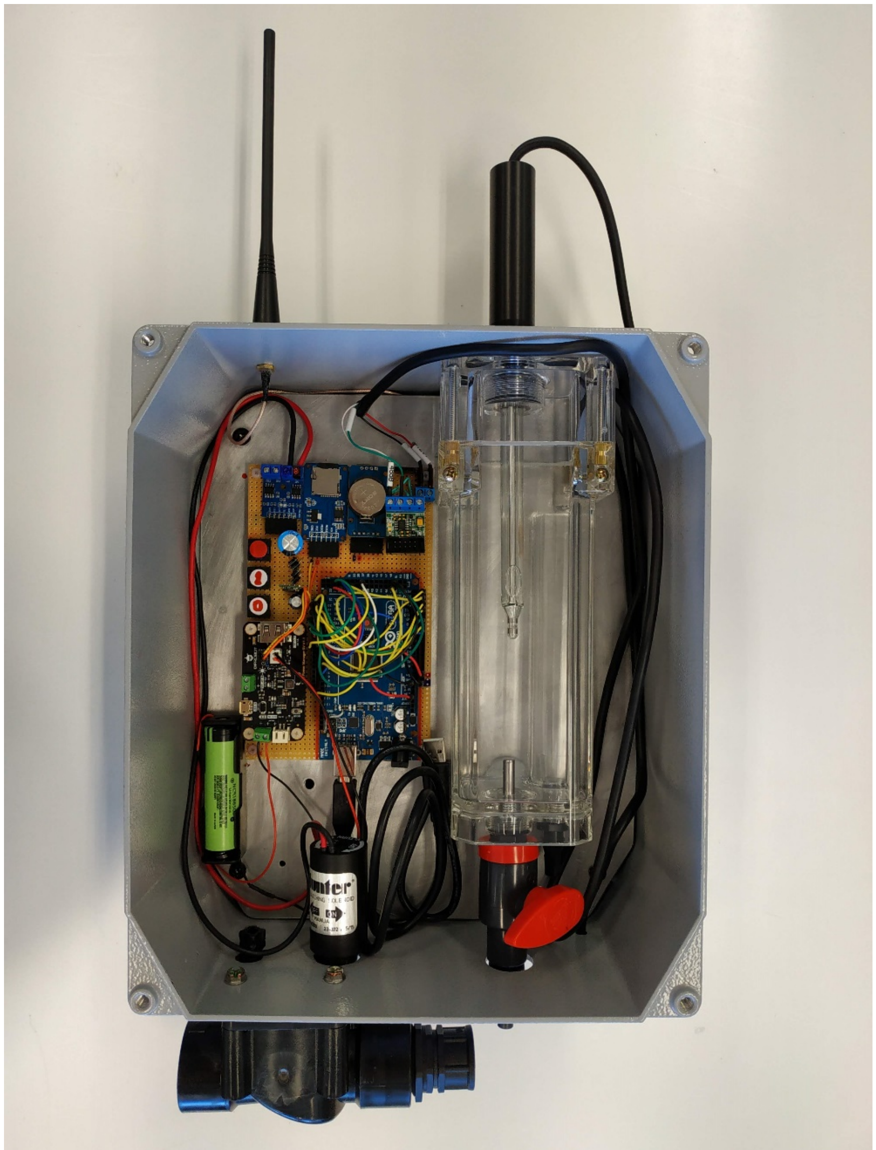

Figure 31: Photo of working system prototype based on Arduino & breakout boards

3.2 Application Firmware

The Application Firmware is written as Arduino “Sketch”, using standard Arduino syntax and within the Arduino GUI. The general term "sketch" is a synonym for Arduino program regardless of the host compile environment. First, a bootloader is programmed/burned through ICSP using also Arduino GUI and a compatible programmer (AVRISP mkII in our case). After the programming is done via USART (serial programming) and the programmer is not needed.

A simplified flowchart of the system’s firmware is shown in Fig. 32. After Power On/Reset or WakeUp, the system configures I/O ports, closes preventively the Solenoid Valve and starts initializing the peripherals (USB, SD card, Lora Transceiver, FCL sensor, RTC, etc.), and sends the related debug messages. After Power On/Reset and if the initialization is successful, the system enables the RTC alarm wakeup interrupts and sets the RTC alarm according to the selected time interval between readings, based on the selected number of automated readings per 24 hours. After the SD card is stopped to prevent eventual file corruption, the firmware closes again preventively the Solenoid Valve and goes into Sleep (low-power) Mode until woken Up by RTC Alarm or manually by short or long-pressing any of the pushbuttons (K2, K3). A short press of either K2 or K3 will wake up the system and start an FCL measurement session. After wakeUp, the system is initializing again all the peripherals, and if all is OK and the battery level is high enough, the system opens the solenoid valve, waits 15 seconds for Flow Cell conditioning, and starts reading the FCL values. The flow cell provides a controlled constant flow rate of 0.25 L/min to the sensor with a drain to "waste", thus making the system almost independent of pipe network flow or pressure. The water "loss" is 0.5L per measurement session with a duration of 2 minutes and can be collected in a water canister with a tap and used even as drinking water since the measurement does not affect its quality. So if 4 measurements are needed daily, 2 Litres of water will be collected in the canister for 24 hours. When 21 measurements (user-defined) are obtained, an average value is calculated, sent over the LoraWAN network, and written to the SD card. Subsequently, the system goes again into Sleep (low-power) Mode. In this mode, it consumes only 0.43mA and if up to 6-7 measurements per day are selected, it may work only on battery (suppose no daylight at all) up to 6 months before recharging is needed.

The main PCB employs three pushbuttons, K1 for system Reset, and K2 and K3 for the Calibration of the Digital Free Chlorine Sensor (CS5530D) when long-pressed and for starting a measurement session if short pressed. Inserting the sensor tip in a chlorine-free water sample and pressing K2 (CAL-0) button for more than 3 seconds will initiate a dedicated Calibration Procedure for calibrating the Zero point (Calibration Zero), where the measured value will be referred to as ZERO (0mg/L). Similarly, inserting the sensor in a water sample with known free chlorine concentration ("S") and pressing K3 (CAL-1) button for more than 3 seconds, will initiate another Calibration Procedure for calibrating the Slope point (Calibration Slope). The value of "S" should be preferably between 1 and 2.5mg/L FCL as recommended by the manufacturer of Sensor (CS5530D). The selected "S" value must be declared in the Arduino sketch, compiled, and programmed before the actual calibration, where a water solution with an "S"mg/L free chlorine should be prepared and used for calibrating the slope. The two Calibration Modes are properly indicated by specific different LED lighting patterns as shown below.

LED Patterns:

1. GREEN & RED LEDs are OFF: the system is in Sleep (low-power) Mode
2. GREEN LED flashing SLOW: the system is Initializing after PowerOn/Reset/WakeUp
3. GREEN LED stable ON: the system is reading Free Chlorine (FCL) values (measurement session)
4. GREEN LED flashes 3 times: the average Free Chlorine (FCL) value is sent over Lora and written to the SD card.
5. GREEN LED flashing FAST: the system is in Calibration Mode and is setting new Slope Point of the Digital Free Chlorine Sensor.
6. RED LED flashing FAST: the system is in Calibration Mode and is setting new Zero Point

of the Digital Free Chlorine Sensor.

7. RED LED flashing SLOW: a fault condition is found during initialization or Battery level is LOW.

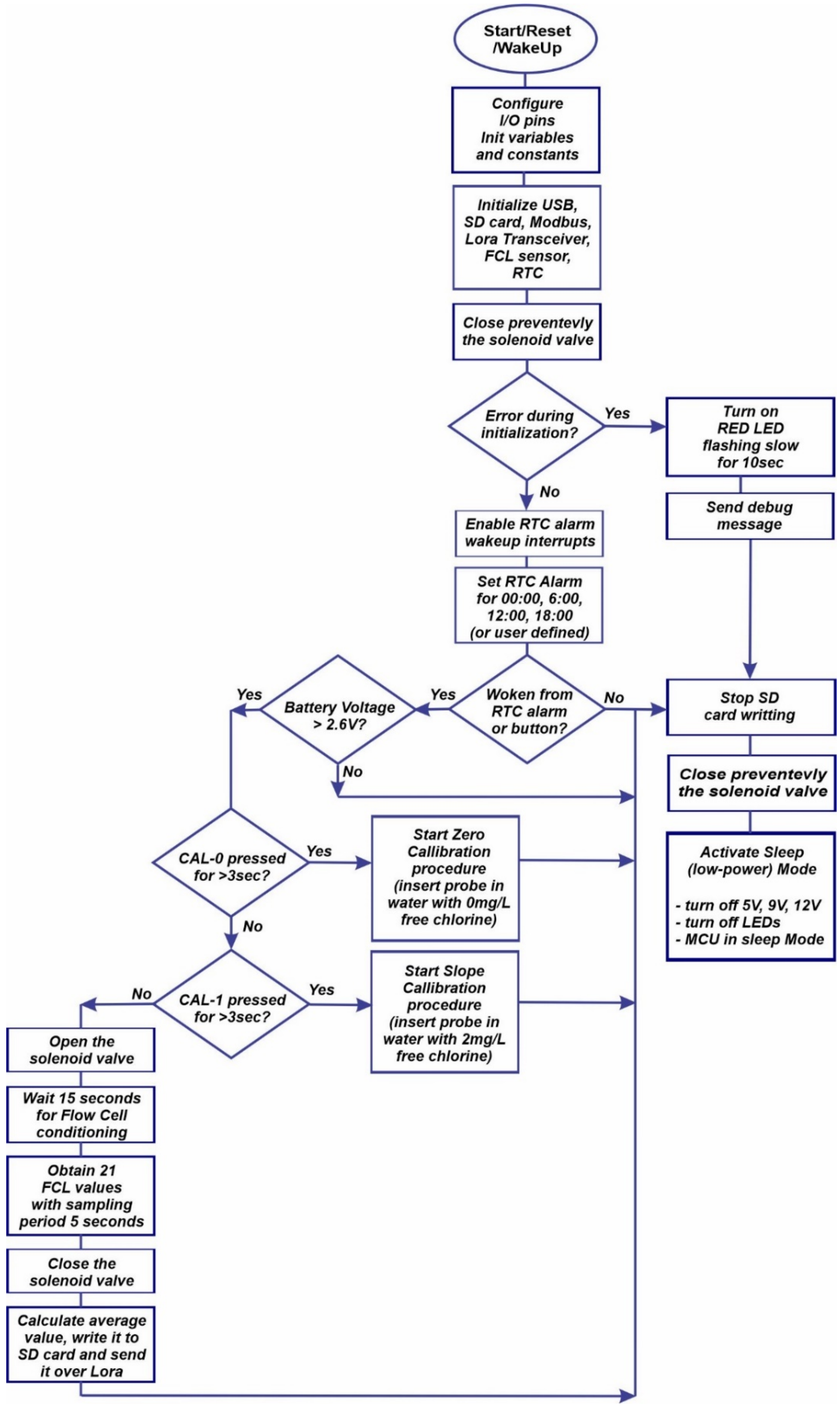

Figure 32: Simplified Flowchart of the System's Firmware

3.3 Experimental Test Setup

Different experimental setups for testing and validating the developed system prototype were designed and built. The first test setup to test the system with the local piped water system is shown in Figure 34, where an automotive cooling expansion tank was inserted between the solenoid valve and the Flow Cell to allow for altering the FCL content of the water coming from the local piped system by adding chlorine tablets. The tablets used for the purpose were from LifeSystems company.
(https://www.lifesystemsoutdoor.com/en-gr/products/water-purification/chlorine-tablets)

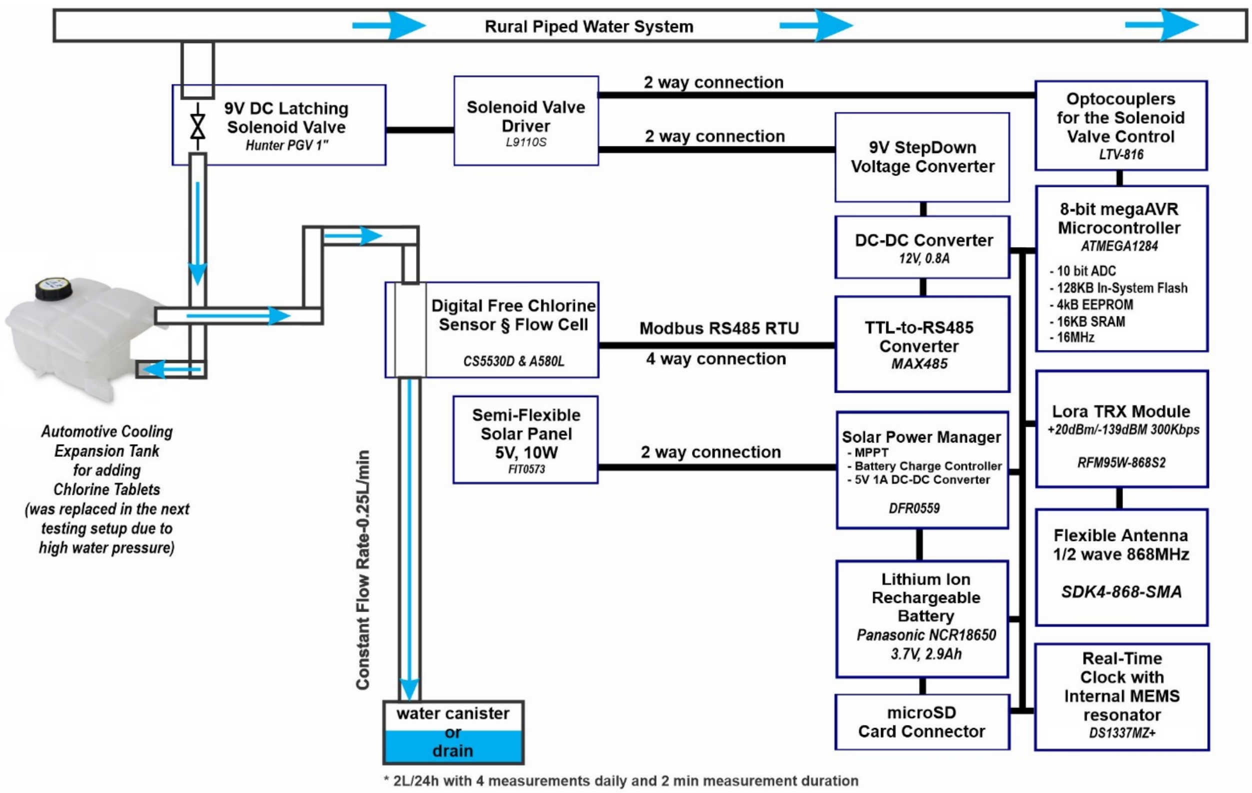

Figure 34: Simplified Test Setup with an expansion tank (setup 1)

However, this test setup was used only for several days due to the automotive cooling expansion tank not able to withstand the water pressure of the local piped system (about 3-4 bars). After, the expansion tank was replaced by extra pipings to provide a water volume needed for the chlorine tablets to alter the FCL content in combination with a plastic screw cap as shown in Fig. 35. This setup proved more reliable than the previous one and worked flawlessly during the 33 days trial.

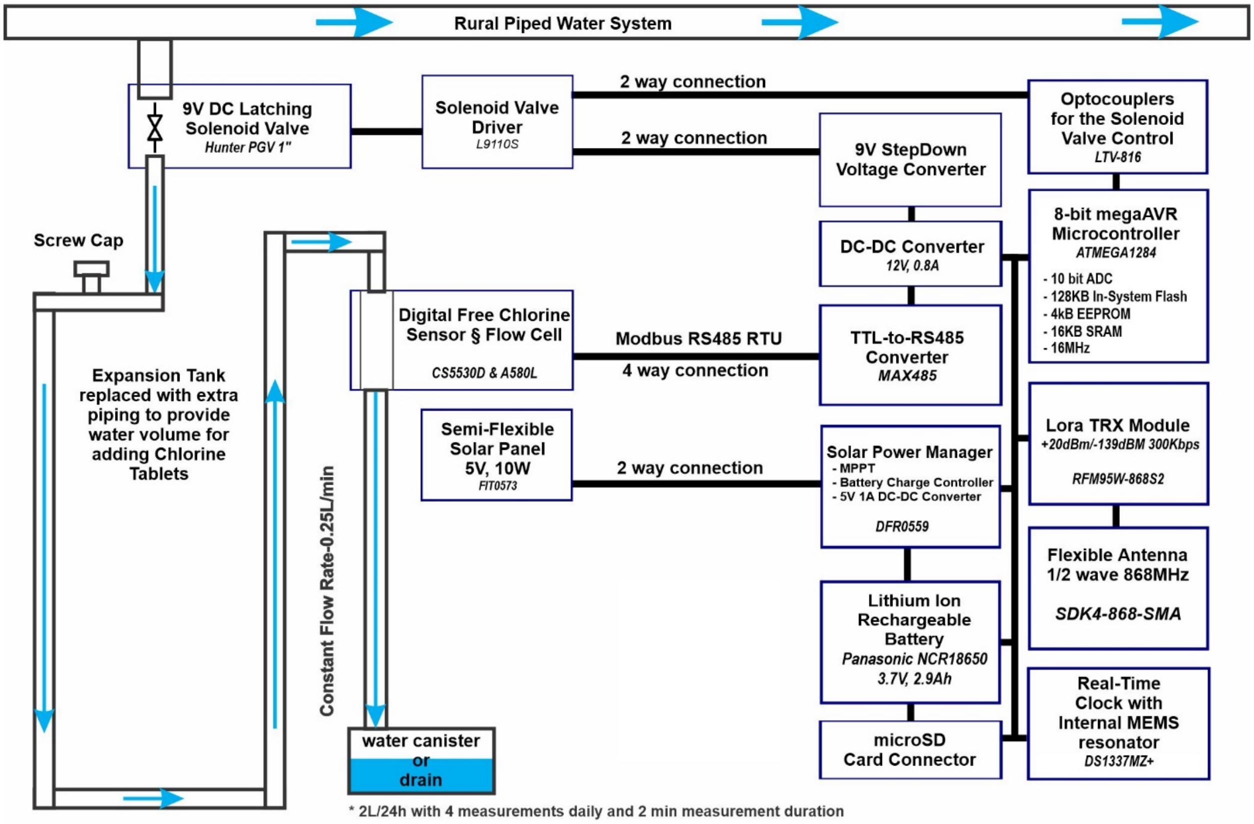

Figure 35: Simplified Test Setup with extra piping for additional water volume (setup 2)

However, the main challenge was the calibration procedure since the sensor is designed to work within constant water flow from 10 to 30L/hour (0.16 – 0.5L/min) provided by the water pressure within the piped network and the Flow Cell. Though, it is a bit of a challenge to provide a constant water flow with a constant known FCL concentration for a certain time duration needed for the sensor's calibration procedure. Thus a separate dedicated calibration setup was designed and built for the purpose as shown in Fig. 36. The setup features a high-pressure water pump (0142YA-24-80 130PSI DC24V 80W) which provides almost the same water pressure as the local water piped system and allows water with altered and known FCL content to circulate in a closed loop through the Flow Cell, thus providing almost ideal conditions for the calibration procedure. This calibration setup worked perfectly fine but would be a bit troublesome to be implemented outdoor in the real field of application of the system. So we also successfully tested a simplified method where during the calibration procedure, the "constant" flow was simulated/created simply by moving fast the sensor probe within the calibration solution in a circular manner. An alternative approach is to use a magnetic or hand stirrer, but this was not tested. The main advantage of the method is the ease of use and the possibility of the system being calibrated in the place where it is installed or in the real field of application.

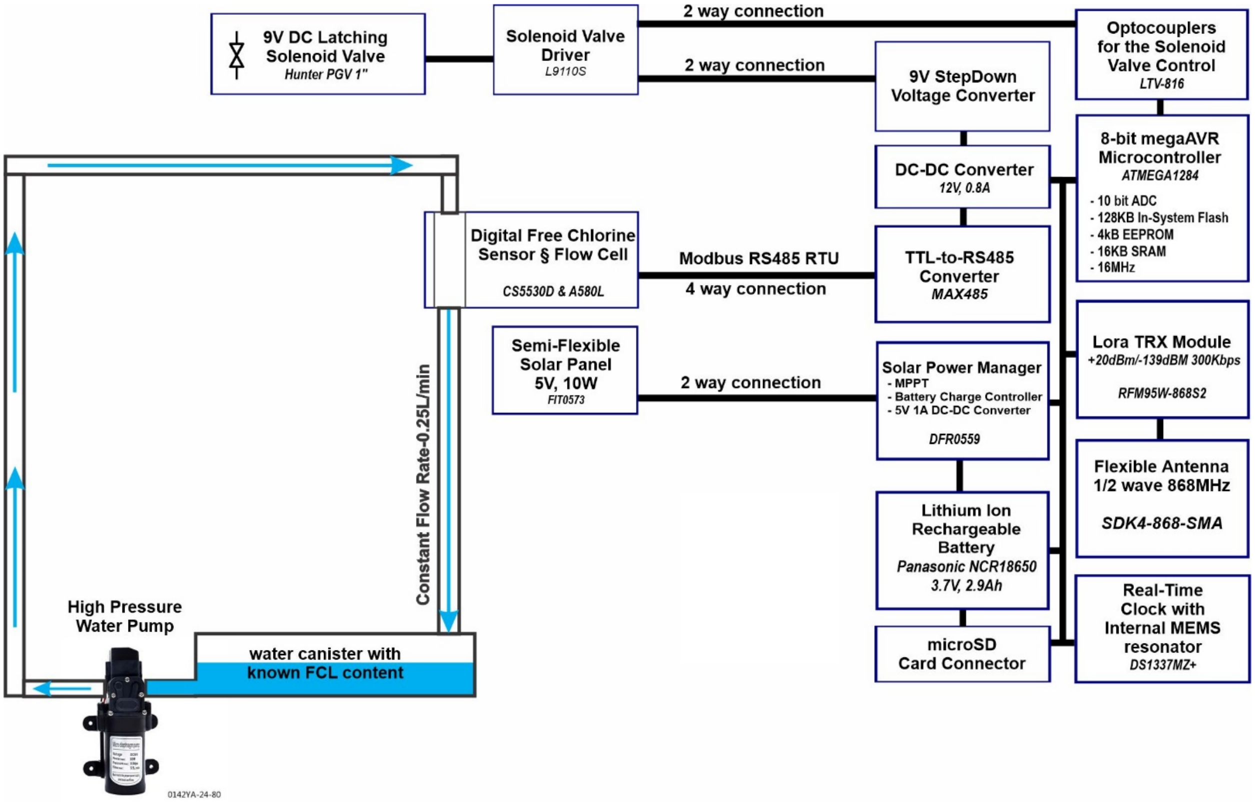

Figure 36: Calibration Setup with high-pressure water pump

3.4 Conclusion

Based on the obtained results from the 33 days trial, we can conclude that the proposed system is highly suitable for monitoring free residual chlorine of rural piped water systems as requested by the seeker providing highly reliable autonomous operation with an infrequent, easy to perform maintenance, without the need for service contracts thus allowing long unattended operation at lower operating cost. All the components are readily available off the shelf and are of economic cost. Furthermore, the system allows for simple in-field calibration (both ZERO and SLOPE) without the use of a computer or other dedicated equipment, where only a water sample with a known free residual chlorine content is required.