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Industrial measurement system with LoRa interface

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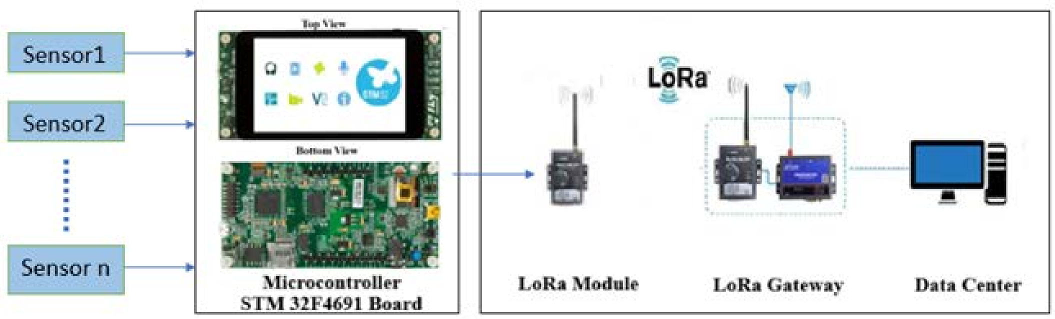
Article

ABSTRACT



Measurement, monitoring, and controlling various process parameters is a practice that has been prevalent in the manufacturing industry for the past few decades. Numerous measurement instruments which are available in the industry suit only a particular application requirement. Thus, multiplexing of a measurement device has many advantages over a single parameter measurement device. Wireless connectivity with the application infrastructure has always been desirable since the advent of IoT. This paper showcases the design process for the development of such a multiplexed measurement system, that will be compatible with a wide range of applications, with minimal installation space and cost, and which can communicate with the IoT network with the help of a LoRa module. LoRa, a wireless modulation method, enables low-power devices to communicate across long distances and low bit rates. The design of industrial measurement with LoRA interface aims to be a portable stand-alone embedded system, with an attractive and easily interpretable Graphical User Interface (GUI).

Keywords: Metrology, GUI, STM32, Sensor interface, Data logging, IoT

INTRODUCTION

Industrial metrology has evolved significantly over the past few decades, with the use of embedded systems in measuring instruments being increasingly effective. Compact and portable instruments with wireless connectivity are highly desirable in manufacturing plants for monitoring quality. Metrology was considered a domain in engineering during the first industrial revolution and is now crucial in various fields such as energy, communications, food science, medical, military, environment, trade, and transportation. The core of metrology is the measurement of various parameters and their conversion into measured values with a specific unit. Measured quantities on industrial sites need to be communicated to data servers for analysis. Techniques are being implemented to make almost every electronic device part of the Internet of Things (IoT) network.[1]

The increasing application of digital technology has fueled the industry, resulting in the fourth industrial revolution, term ‘Industry 4.0’. It is a trending topic these days and has a huge impact on the way the industry is viewed.[2,3] Traditional manufacturing instruments that are being used are installed on the manufacturing floor and are permanently connected to the process equipment. Such instruments are highly expensive and measure single parameter. Such independent units need to be installed at all points where monitoring a certain process parameter is necessary. A configurable measurement tool that can accept all compatible sensor inputs and display the result in a clear graphical format can take the place of this setup. This facility can save time and installation costs. Such units, being portable, can be connected at any suitable measurement point on a shop floor to measure certain parameters such as water flow, gas flow,[4] displacement, air pressure, and so on.

Since the beginning of industrial measurement, scientific instrumentation has preferred to be digital rather than utilizing mechanical processes. Today, we can see that traditional benchtop

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instrumentation procedures are incapable of fulfilling the needs of new-age applications, which require portability, faster performance, modularity, networking abilities, and low costs.[5,6]

Industrial management systems integrate various systems, technology, and processes to improve efficiency, output, and profitability. One challenge is maintaining safety and efficiency while cutting costs. LoRa, a wireless modulation method, enables low-power devices to communicate across long distances at low bit rates. LoRaWAN is a network protocol that allows low-power end devices to communicate with base stations or gateways, offering connectivity to the internet or cloud.[7] By using the LoRa interface, industries can remotely monitor and control machinery, equipment, assets, and environmental conditions, increasing efficiency, reducing operational costs, and improving safety.[8,9] Advantages of LoRa include its long-range capability, small power consumption, and flexibility. However, issues include interference and distance restrictions. Despite these limitations, LoRa offers numerous benefits through remote monitoring and control of processes, sensors, and systems.[10–12]

If the instrument is equipped with a graphical display, it becomes easier to read and understand the readings quickly. Thus, GUI (graphic user interface) arrangement facilitates faster, easier, and more convenient operation of any instrument. Such two instruments namely PI 500 and DS 400 are described below.

PI 500

The PI 500 is a portable industrial measurement tool by CS Instruments GmbH. It features a graphical display with a touch screen and a keypad interface to select the appropriate sensor interface. The device has a configurable sensor input. Various types of sensors can be connected to this port. For instance, pressure sensors, temperature sensors, flow sensors, dew point sensors, as well as any sensors compatible with 0/4...20 mA, 0.1/10 V, PT1000, pulse, and Modbus. The measured parameters can be stored on the computer with the help of a USB drive. The data can be easily evaluated with the help of CS Basic software.[13]

DS 400

A mobile chart recorder system is the type of instrument that CS Instruments GmbH developed, the DS 400. This portable chart recorder instrument comes with options for additional accessories such as an integrated Ethernet and RS485 interface, an integrated web server, etc. It comes with an integrated data logger with configurable data logging intervals.

GUIs, are highly popular and can be observed in almost all HMIs (human-machine interfaces) in industry, personal computers and mobile phones. Almost all control actions can be carried out with the help of GUI elements such as buttons, widgets, icons, and windows.[14,15] A modular and vivid graphical interface that modifies according to the user's demands is important to make the interface more interactive. Research needs to be carried out for measurement instruments with an aesthetic GUI. The development of such an instrument has been meticulously guided by a thorough analysis of existing solutions with similar functionalities. This comprehensive research provided a clear idea about what is really required by the industry, what features are needed, and how this product's functionality can be enhanced.

System Development

The term system development has been used here in a broad sense for numerous independent activities undertaken for the design process, and successful integration of such modules as a complete functional unit. Figure 1 shows the system block diagram. A multiple-input channel design has been proposed here. The benefit of using multiple channels can be seen while analyzing different materials. Multi-channel systems can improve the speed of operation as well, especially when measurements are to be acquired over a wider area.[16]

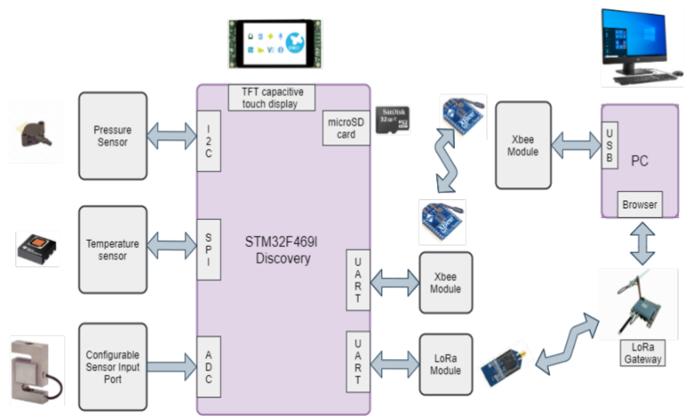

Figure 1. System Block Diagram.

I. Block Diagram

All the components and their interconnections have been showcased in Figure 1. Various protocols used for different components have also been displayed in this diagram.

STM32F469I Discovery board has been used as the central Microcontroller. The left side of the block diagram shows the sensor interface section and the protocols used for communication with the microcontroller. The right side of the diagram shows the data logging section which includes the PC interface as well. The LoRa Node AcSip S76S has been used to communicate with the LoRaWAN outdoor gateway.

II. System Flowchart

This flowchart shows the sequence of operations carried out by the system after power on. All the important tasks of this system have been covered in the flowchart shown in Figure 2.

On system power on, the first step is initialization of all the connected peripheral devices. The GUI then displays the main screen. The system starts scanning for sensor data sequentially. As soon as input from the user is received, the selected sensor data is displayed on the screen. If the data logging option is selected, the data is logged on the appropriate interface.

Hardware Design

The hardware assembly required for this design has been completed with the help of the following components.

I. STM32F469I Discovery board:

The STM32F469I-DISCO Discovery kit (32F469I DISCOVERY) is a demonstration and development platform for STMicroelectronics Arm® Cortex®-M4 core-based

STM32F469NIH6 microcontroller.9. The board consists of a wide range of peripherals, which are accessible to the developer through different on-board connectors. Various modules on the discovery board have been utilized in this design. DSI LCD, ADC, I2C interface, SPI interface, USART port for communication with data transmission devices, microSD card for data storage, etc. are some of the on-board components used.

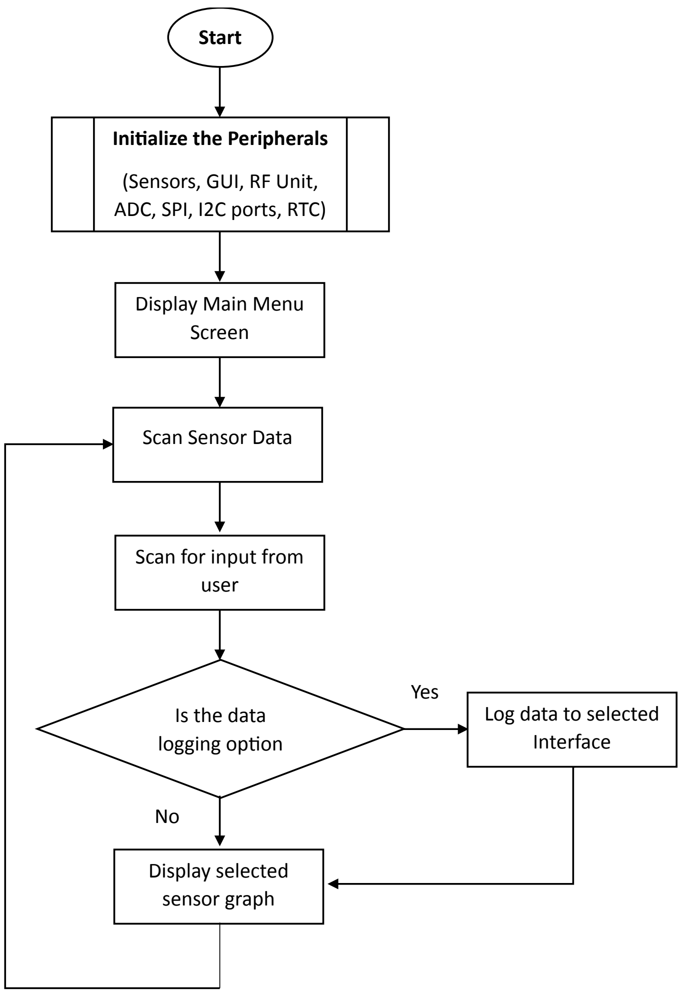

Figure 2. System Flow Chart

II. Sensor Interface:

The sensor interface is the most critical part of this design. The following sensors have been used here.

a) Load cell: The Sensortronics S-type load cell Model 60001 sensor has been interfaced with one of the ADC channels of the Microcontroller board. M60001 is a tension-compression load cell with a humidity-resistant coating. It has shielded cables, which make it possible to use in harsh environments while maintaining ideal operating specifications. Additional sense wires make up for changes in lead resistance due to temperature changes and cable extension.12 It gives voltage output proportional to the weight of the load cell. The analog output provided by this load cell is processed by the controller, and the current reading is displayed on the LCD GUI.

b) Temperature and Humidity Sensor: Honeywell HumidIcon™ Digital Humidity and Temperature Sensors, HIH8000 Series, are digital output-type relative humidity (RH) and temperature sensors included in the same package. These sensors provide an accuracy level of ±2.0 %RH and a temperature accuracy level of ±0.5 °C.12. This sensor has been interfaced with the SPI port of the STM32 Discovery Board.

c) Pressure sensor: The MPX5500 piezoresistive transducer is a monolithic silicon pressure sensor that has been designed for a wide range of applications, particularly those utilizing a microcontroller or microprocessor with A/D inputs. This single-element transducer combines advanced micromachining techniques, thin-film metallization, and bipolar processing to provide an accurate, high-level analog output signal that is proportional to the applied pressure. [11]
This pressure sensor provides an analog output proportional to the pressure input port of the sensor. It can be connected to the ADC channel of the microcontroller board.

d) Configurable Sensor Input Port: A standard 4-20 mA port is to be designed as many sensors and industrial measurement devices provide outputs in a 4-20 mA range, such as water flow meters, gas flow meters, LVDT, power, and energy measurement systems, etc. This utility is extremely useful, as it can provide an instantaneous graphical view of readings for practically any sensor with a supported output format.

III. Data logging interface

All the data that is collected by the sensors needs to be saved for record purposes. This function is called data logging. Two types of data logging interfaces have been designed in this work, which are Local data logging and Remote Data Logging.

The local Data logging interface includes dumping data on an SD card after such a request from the user is received. Remote logging has been implemented by an RF module i.e., an XBEE trans-receiver and a LoRa module.

a) XBee: Digi XBee® and Digi XBee-PRO Zigbee RF modules provide wireless connectivity to electronic devices at a low cost. Digi XBee and Digi XBee PRO Zigbee modules can prove ideal for applications in the energy and system control markets where manufacturing efficiencies are critical.[13]
Remote data logging is another unique feature of this work. In most industrial plants, cabling between sensors and functional units is not desirable because of the chances of accidents. RF transmission over short distances is the optimum solution to this problem. In this case, the PC which is used for processing sensor data has been interfaced by the measurement system wirelessly. This function is performed with the help of XBee trans-receiver modules, one at the System end, and one at the PC end.

b) LoRa Interface: The LoRa Interface is typically implemented using a LoRa transceiver chip, which handles the modulation and demodulation process for the microcontroller or other device controlling the LoRa device. The LoRa Interface offers a long range of up to 15 kilometers in rural and 5 kilometers in cities, low power usage, resistance to interference, scalability for thousands of devices, and secure end-to-end encryption for IoT applications. It provides a perfect balance for various applications. AcSip S76S module has been used to enable the remote data logging feature. This module has been interfaced to the central controller board using the USART module. It sends data to a centralized gateway, which further relays the data to a centralized LoRa data server.

c) microSD card: In some situations, the data collected at the site must be required for analysis. So local data logging is to be made available with an SD card interface. An 8 GB microSD card is made available with the system. The user has an option of dumping data on the SD card on the graphical touch screen. As soon as such a command is received, data is logged onto the SD card in CSV format. The option of continuous periodic data logging can also be made available.

IV. Software Design

Free RTOS has been used to achieve multitasking of all the required processes.

Free RTOS can be considered as a library that provides multi-tasking abilities for tasks that would otherwise have been a bare metal application. Free RTOS is supplied as a collection of C source files. Some of the source files are common to all ports, while others are specific to a port.

Free RTOS is included in the STM32CubeF4 MCU package, which is the software package supported by the STM32F469 Discovery board. The use of free RTOS ensures that the GUI runs smoothly while efficiently processing all the data received from the sensors, effectively communicating it to the remote system, and logging data on an SD card parallelly.

The RTOS tasks have been implemented as follows.

a) Sensor Interface task: A task with high priority has been created for accepting data from sensors. This task is periodic, with an interval of less than 100 ms. This runs continuously parallel to the main loop.

b) Data Logging task: This task takes a priority lower than the Sensor Interface task. It is called whenever the user selects the data logging option. It includes the interfaces to the microSD card and XBee module.

c) GUI task: This task has the highest priority. It consists of inputs regarding sensor selection from the user, and displays live data reading on the screen. The GUI has been designed with the help of TouchGFX Designer.10

d) LoRa Server Communication: The Things Network® LoRa Server was used to interface the LoRa Module. An application was added to the server. The device was configured to communicate in ABP mode. The device is programmed to send data whenever requested by the user through the GUI.

RESULTS AND DISCUSSIONS

After the successful completion of the development of individual hardware and software modules, the system was integrated and tested as a whole. These results include data obtained from testing sensor modules, communication modules, and an overview of the GUI.

I. Sensor Interface

a) Load Cell: A circuit attached to the S type Load cell provides output in the form of 4-20mA to the ADC channel of the microcontroller circuit. A 150Ω resistance was used to convert the current output to the appropriate voltage.

From the specifications of the load cell, it was found that a weight of 22 kg load corresponds to 20 mA, and 0kg corresponds to 4 mA. Hence the total usable range is spread linearly for 16mA. The internal 12-bit ADC uses a reference voltage of 3.3V. The calculation of load values from ADC counts aligns with the equation (1). The system thus gives load output as

$$Load = ((Cout\_ADC * 3.3/4096 * 1000/150) - 4) * 22/16 \quad (1)$$

Calibrated test weights were used to obtain the following results that ensure accuracy and traceability. Multiple data points across the load range provide a good representation of the load cell's behavior.

Table 1 Load Cell Results

Sr. No.	Test Load (Kg)	Theoretical ADC Count	Obtained ADC Count	Calculated Load (Kg)	% Error
1	0	745	744	-0.01	-0.01
2	5	1422	1419	4.98	-0.41
3	10	2098	2095	9.97	-0.28
4	15	2775	2774	14.99	-0.09
5	20	3452	3448	19.96	-0.18

We can thus comment that this sensor is accurate within ±0.5% of the full scale.

The overall impression about the calibration process:

- The process appears to be well-structured and executed.
- The results demonstrate a good level of accuracy, with errors within a reasonable range.
- The observed errors are relatively small (within -0.41% to -0.01%), indicating a good level of accuracy.
- Potential sources of error include:
    - Load cell non-linearity
    - ADC quantization error
    - Noise in the measurement system

b) Pressure Sensor: The pressure sensor[17,18] provides an analog output of 4 volts corresponding to 72 PSI. It needed to be converted to 3.3 volts to make the input compatible with the ADC. Hence a resistor divider with 10KΩ on the top arm and 20KΩ on the bottom arm was connected to the output of the pressure sensor. Using a resistor divider to adapt the sensor's 4V output to the ADC's 3.3V input range is a simple and effective approach. The chosen resistor values (10kΩ and 20kΩ) provide a voltage division ratio of 0.333, accurately scaling the pressure sensor's output. The pressure was calculated with the help of the equation (2). The pressure calculation equation utilizes the voltage scaling factor and ADC resolution, demonstrating a clear understanding of the system.

$$Pressure = Count\_ADC * 3.3/4096 * 72/3 \quad (2)$$

Table 2. Pressure Sensor Results

Sr. No.	Actual Pressure (PSI)	Theoretical ADC Count	Obtained ADC Count	Calculated Pressure (PSI)	Error
1	0	8	1	0.02	.02
2	12.4	641	640	12.38	.20
3	20.2	1045	1036	20.03	.83
4	29.7	1536	1551	29.99	.98
5	41.6	2151	2148	41.53	.16
6	49.3	2550	2561	49.52	.44
7	61.5	3181	3175	61.39	.18
8	72.3	3739	3745	72.41	.16

We can thus comment that this sensor is accurate within ±1% of the full scale.

- Testing across the entire pressure range (0-72 PSI) provides a comprehensive picture of the sensor's performance.
- The small errors (±0.02 to ±0.98 PSI) throughout the range support the conclusion of high accuracy.

c) Temperature Sensor: Honeywell HumidIcon was interfaced with the SPI port of the microcontroller. The sensor provides a 14-bit ADC count, which can be converted into an appropriate temperature value with the help of the following equation from the datasheet.

$$Tempe = Temp\_SPIvalue)/(2^{14} - 2) * 165 - 4 \quad (3)$$

The functioning and accuracy of the temperature sensor are reflected in the readings listed in Table 3.

From the results, we can conclude that this sensor interface provides an accuracy of ±1% of full scale.

Table 3. Temperature Sensor Results

Sr. No.	Temperature (°C)	Received Value	Calculated Temperature (°C)	% Error
1	20.2	5996	20.39	0.95
2	25.6	6530	25.77	0.67
3	31.4	7109	31.60	0.64

d) Humidity Sensor: The same sensor that was used for temperature measurement also provides Relative Humidity (RH).[19,20] 14-bit ADC RH value is read from the sensor through SPI and converted to RH with the help of the following formula.

$$\%RH = (RH\_SPIvalue * 100)/(2^{14} - 2) \quad (4)$$

The functioning and accuracy of the humidity sensor are reflected in the readings listed in Table 4.

Table 4. Humidity Sensor Results

Sr. No	Relative Humidity * (%)	Received Value	Calculated Humidity (%)	% Error	Month
1	56	9174	56.00	0.00	March
2	46	7535	46.00	-0.01	April
3	36	5897	36.00	-0.01	May

*Results recorded in Pune City for 3 consecutive months

The accuracy of this parameter can be considered to be ±1% of full scale.

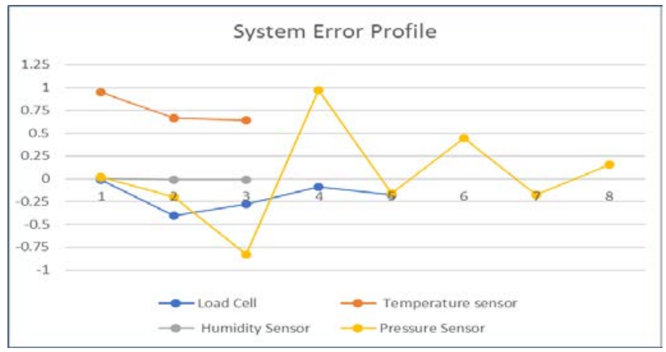

Figure 3. System Error Profile

Figure 3 shows the system error profile. The X-axis of this graph represents the number of readings captured for each sensor. It is not the same for all sensors. The blue line represents the Load Cell Error column. The orange line shows error values for the temperature sensor. The grey and yellow lines represent the humidity and pressure sensors respectively.

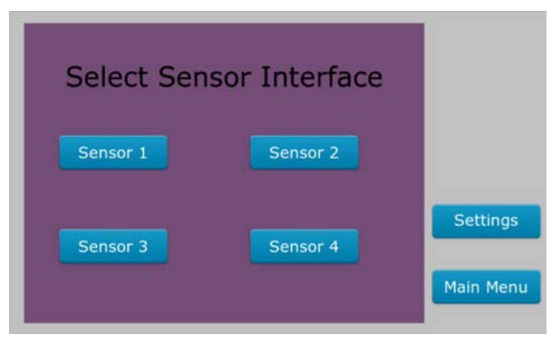

Figure 4. Sensor Selection Interface

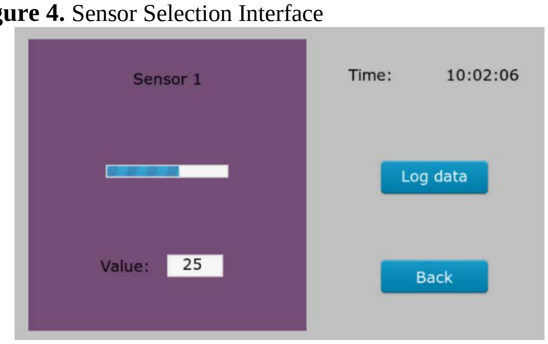

Figure 5. Sensor Interface

Figure 6. PC Interface

The motivation behind representing accurate data in a graphical format is to analyze the error profile of the system. The humidity sensor shows the best performance, with consistent readings, and errors close to zero. The temperature sensor error can be assumed to be drift on the positive side. The load cell error is on the negative side with minor variations over the full scale of measurement. The pressure sensor's performance can be considered to alternate on the positive and negative sides.

Here four sensor interfaces have been tested for various input values. The system can be thus considered to be accurate within a limit of ±1% of the full input range. This is generally considered an industry-acceptable standard of accuracy. In the case of applications where higher accuracy is required, appropriate sensors can be selected and easily interfaced with the existing system. Hence indirectly, the system's accuracy depends on the accuracy of the selected sensors.

II. GUI Snapshots

The key feature of this system is the Graphical User Interface (GUI). As soon as the system powers up, the home screen is displayed. The display interface consists of 8 screens in total, out of which 2 have been explained here.

a) Sensor Selection Interface: A total of 4 sensors are available for display. The screen shown in Figure 4 is the screen for sensor selection. It has 2 additional options for switching to the Settings screen and Main Menu. The sensor names are written on user buttons, which have a distinct color from the background for easy operability.

The screen shown in Figure 5 is the screen for Sensor 1 data display selection. It shows data in the form of a horizontal line chart. It has a button that causes the screen to switch to the Data Logging screen.

b) PC interface: VB.net has been used to develop the PC application for accessing the data. The data transmitted by the XBee trans-receiver is received by another trans-receiver, which is interfaced with the PC. This feature is helpful for remote processing of data acquired by the instrument.

Figure 6 shows the screenshot of the PC-based application. The GUI screenshots that have been showcased in Results give a clear idea of the ease of operation of this measurement system. The major motivation for the design of a GUI-based system was to provide the user with all the required data at a glance. Navigation through multiple screens also facilitates the display of only required data and avoids unnecessary clutter on each screen.

This design's GUI has been inspired by a variety of industrial systems. This will ensure that the Universal Industrial Measurement System can be accommodated readily in most industries.

COMPARISON OF PROPOSED WORK WITH EXISTING SYSTEMS

The two products developed by CS Instruments GmbH in the above sections have similar features to the LoRa-based industrial measurement system. The first system mentioned here differs from the second one primarily in terms of physical structure.

This paper showcases a design that is a handheld instrument like the PI 500, which is portable, with minimum space requirements. Chart recording feature from the DS 400 is convenient, and thus this system aims to achieve the implementation of such data logging and graph plotting capabilities. Both these mentioned devices lack remote connectivity. Hence addition of wireless connectivity with the help of two protocols i.e., XBee and LoRa enables this device to communicate with the Remote PC and centralized database server simultaneously.

Areas of Applications: The proposed design can be seamlessly integrated into most measurement industries.

The aim of acquiring information for calibration and verification can be thus achieved. A synchronized application with multiple sensors working at the same time can be achieved.[13]

Manufacturing, shipping, construction, and supply chain management areas are being highly influenced by Industry 4.0. This has direct impacts on everyday industrial processes.[21]

Conclusions

The paper presents a new multiplexed measurement system that offers versatility, portability, and efficient communication in a compact and cost-effective package. It uses LoRa technology for wireless connectivity in IoT, enabling diverse industrial applications like factory automation and environmental monitoring. Remote logging with IoT allows easy access to measured data anywhere. LoRa can form an infrastructure of multiple sensors connected to a single gateway, while XBee can be used for short-distance line-of-sight wireless communication. The system offers flexibility, low power, and long-range capability, making it a compelling solution for industrial applications. Further investigation and refinement are needed to optimize power consumption and ensure robust operation in varied environmental conditions.

Conflict of Interest

The authors declared no conflict of interest the for publication of this work.

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