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A STUDY ON INTERNATIONAL COMMUNICATION STANDARDS AND PERFORMANCE STANDARDS FOR SMART WATER QUALITY SENSORS

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Abstract

The world is now building an artificial intelligence (AI) water quality management system to detect water quality accidents at an early stage and predict water quality vulnerable areas in advance beyond measuring the water quality. In other words, by applying big data analysis and artificial intelligence technology to the conventional water quality measurement system that monitors water quality in real time, an artificial intelligence-based water quality measurement and water quality prediction system is built at the same time, and drones and unmanned ships are also introduced. It means implementing water quality management. Water quality accident prediction based on artificial intelligence measures water quality throughout the site of use through intelligent spatial analysis based on the integrated water quality database. On the other hand, the location of the site detected through artificial intelligence is displayed on the comprehensive monitoring screen, and special management such as on-site monitoring, replacement of consumables, and maintenance is carried out to prevent water quality accidents. In particular, the prediction accuracy of artificial intelligence is to create an algorithm for predicting future values by learning the characteristics and patterns of accumulated data. It depends on the function of the smart sensor itself. However, until now, there has been no international standard for smart sensors, so it was difficult to establish system interlocking or modularization for each manufacturer and site. Therefore, we present the most important standard communication standards for smart water quality sensors in the field and international standard performance specifications for smart sensors, and this research data is provided to all organizations engaged in water quality around the world for water quality measurement and prediction system data system for AI application.

Keywords*:* *water quality sensor, smart water quality sensor, artificial intelligence water quality monitoring, remote water quality detection, water quality management system, communication standard.*

Smart Water Quality Sensor Communication Standard

The standard protocol of smart water quality sensor is RS-485 communication based on MODBUS-RTU. There are several reasons for using MODBUS in water quality sensors. First, even if the sensor changes, the protocol does not change. That is, the MODBUS memory map is configured according to the sensor. According to the second number zone, it is divided into coils and resistors [1,2]. This is because MODBUS is made for PLC, and the coil can be thought of as a value of 1 bit and the register as a word value of 2 bytes. That is, the coil is a switch that turns on/off, and the register is an input/output value of 16 bits. Third, in serial communication, MODBUS can be implemented in two ways. MODBUS-ASCII and MODBUS-RTU, MODBUS-ASCII, as the name suggests, is ASCII communication with line feed characters (0x0d 0x0a) mixed. In contrast, MODBUS-RTU used in water quality sensor is binary communication. There

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is length data in the Modbus protocol, so it has the advantage of simple coding because it only needs to be received that much. Next, let's take a brief look at MODBUS.

MODBUS Command Structure

- Binary Number – shown with suffix B. For example: 10001B
- Decimal Number – without nay suffix. For example: 256
- Hexadecimal Number—shown with prefix 0x. For example: 0x2A
- ASCII Character or String – shown with quotation marks. For example:" YL1014010022"

Command Structure

MODBUS defines a simple protocol data unit (PDU), which is transparent to communication layer (Fig. 1).

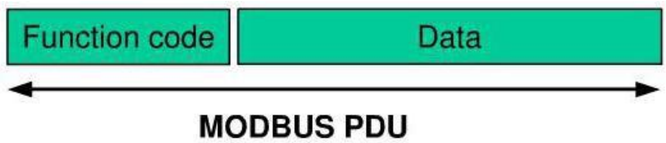

Fig. 1. MODBUS Protocol Data Unit

The mapping of MODBUS protocol on a specific bus or network introduces some additional fields on the Protocol Data Unit. The client that initiates a MODBUS transaction builds the MODBUS PDU, and then adds fields to build the appropriate communication PDU (Fig. 2).

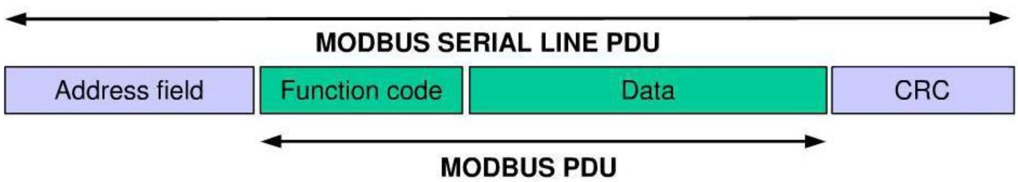

Fig. 2. MODBUS Structure for Serial Communication

Note(s):

- Slave address range for smart sensor is 1…247
- Master device sends a "request frame" with a targeted slave address. When slave device responses, it must put its own address in the "response frame", so that master device knows where the response comes from.
- Function code indicates type of operations
- CRC is the result of redundancy check.

MODBUS RTU Transmission Mode

When devices communicate on a MODBUS using RTU (remote terminal unit) mode, each 8-bit byte message contains two 4-bit hexadecimal characters. The main advantage of the RTU mode is that it has higher character density, which enables better throughput compared to ASCII mode at same baud rate [3,4]. Each RTU message must be transmitted in a continuous string of characters (see Table 1 and Table 2).

RTU Mode Format for Each Byte (11 bits):

- Encoding system → 8 bits binary

→ Each 8-bit packet contains 4-bit hexadecimal characters (0-9, A-F)

- Bit per byte → 1 start bit
  → 8 data bits, least significant bit
  → first No parity check
  → 2 stop bits
- Baud rate → 9600bps

Serial transmission of characters:
Every character or byte is sent under this sequence (left to right):
- Least Significant Bit (LSB)
- Most Significant Bit(MSB)

Table 1. RTU Mode Bit Sequence

Start	1	2	3	4	5	6	7	8	Stop	Stop

CRC Field Structure
Redundancy check (CRC16)

Table 2. RTU Message Frame Structure Maximum size of MODBUS frame is 256 bytes

Slave Address	**Function Code**	**Data**	**CRC**	
1 byte	1 byte	0…252 bytes	2 bytes CRC Low	CRC High

MODBUS RTU Message Frame
In RTU mode, message frames need to be separated by an idle interval of at least 3.5-character lengths. For the rest of this document, this idle interval is called t3.5 (Fig. 3).

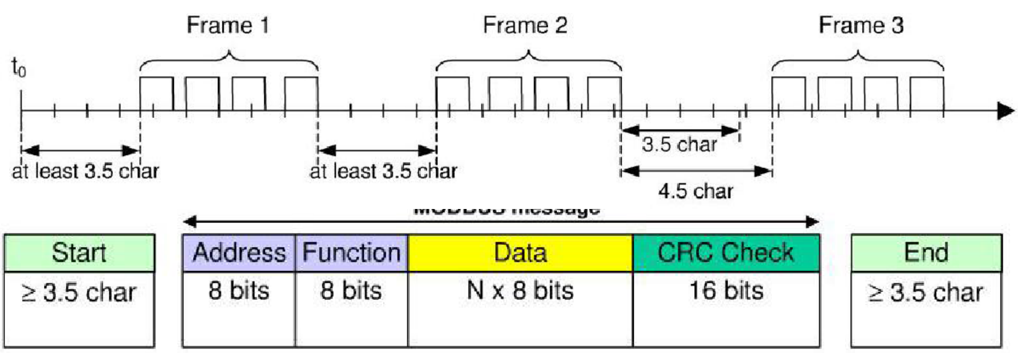

Fig. 3. RTU Message Frame

Entire message frame must be sent as continuous stream of characters. If idle time between two characters is longer than 1.5 characters, the message frame will be considered incomplete, and it will be discarded by the receiving side (Fig. 4).

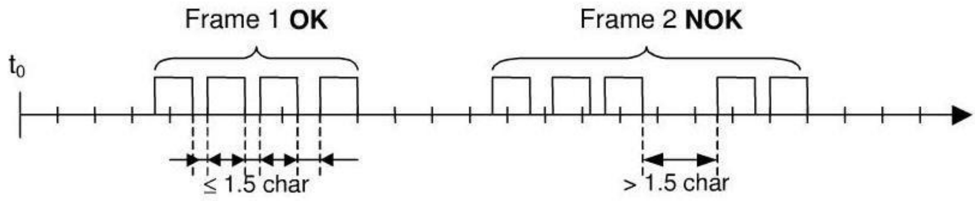

Fig. 4. Frame transmission

MODBUS RTU CRC Check

In RTU mode, the error checking field is based on a cyclical redundant checking (CRC) method. The CRC field checks entire content of MODBUS message, regardless of the existence of parity check bit. CRC16 checking method is utilized. CRC result is a 16-bit value with two 8-bit bytes, low order 8-bit byte first followed by high order 8-bit byte.

The protocol of the smart water quality sensor must support the following three commands, and the configuration example is as follows:

- Read the floating data register → For example, Function code 04
  - Upper computer command format: Address, Function code, starting register address, Read the number of registers N
  - Lower computer normal response: Address, Function code, Data for N registers, CRC
  - Lower computer error response: Address, Function code+80H, Error code, CRC
- Read the internal parameter register → For example, Function code 03
  - Upper computer command format: Address, Function code, starting register address, Read the number of registers N
  - Lower computer normal response: Address, Function code, Data for N registers, CRC
  - Lower computer error response: Address, Function code+80H, Error code, CRC
- Modify the internal parameter register → For example, Function code 06
  - Upper computer command format: Address, Function code, the register address to modify, the register data to modify, CRC
  - Lower computer normal response: Address, Function code, Modified register address, Modified register data, CRC
  - Lower computer error response: Address, Function code+80H, Error code, CRC

Register Types

Register types are largely composed of floating data (reading input register function) and internal parameter register (reading hold register function code, rewriting function code alone).

Functions for Each Metric

The smart water quality sensor must include the following functions according to the measurement items. Since all water quality measurement items cannot be covered in this research data, the most important items have been selected and organized [5,6].

pH / ORP

The function code basically consists of measurement data (reading input register function) and internal parameter register (reading hold register function code).

Measured Data

• Register Address: 0000H~000FH

• Register Name (and range): pH value (0.00~14.00pH), pH voltage value (±1000mV), ORP value (±1000mV), ORP voltage value (±1000mV), temperature value (-10.0℃~110.0℃), decimal and units should be included.

• High Byte: Decimal digits 2, 0, 1 (for example, 2 is two decimal places)

• Low Byte: Indicates the unit and is pH, mV, ℃.

• Read and Write: R

• Other Functions: 0X7FFF Over / 0X8000 Under

Internal Parameter Register

• Register Address: 0010H~0043H

• Register name and (range): pH calibration (0: no calibration, 1: already calibrated), pH offset (±60mV), pH slope (70.0%~130.0%), ORP calibration (0: no calibration, 1: already calibrated), ORP offset (±100mV), ORP slope (70.0%~130.0%), decimal and unit (decimal number 0), local address (1~255), baud rate (0: 1200, 1: 2400, 2: 4800, 3: 9600), temperature compensation type (0: manual, 1: auto), automatic temperature compensation (-10.0℃~110.0℃ / default 0.0℃), manual temperature compensation (-10.0℃~110.0℃ / default) 25.0℃), measurement type (0: pH, 1: ORP), sensor type (0: glass electrode, 1: antimony electrode, buffer solution type (0: NIST, 1: USA) must be included.

• High and Low Bytes: 10 times the value for temperature (for example, if you read 250, the actual value is 25.0

• Read and write: R/W

• Remarks: In the case of manual temperature compensation, the next register is the set temperature value / In the case of automatic temperature compensation, the next register is the set offset value.

EC (conductivity)

The function code basically consists of measurement data (reading input register function) and internal parameter register (reading hold register function code).

▪ Measured Data

• Register Address: 0000H~000FH

• Register Name (and range): EC value (0~20.00uS, 0~200.0uS, 0~2000uS ~20.00mS), TDS value (0~10.00ppm, 0~100.0ppm, 0~1000ppm, 0~10.00ppt) , 0~100.0ppt), salinity value (no unit, user-defined), temperature value (-10.0℃~110.0℃), decimal number and unit should be included.

• High Byte: Decimal digits 2, 0, 1 (for example, 2 is two decimal places)

• Low Byte: Indicates the unit and is uS, mS, S, ppm, ppt, ℃.

• Read and Write: R

• Other functions: 0X7FFF Over / 0X8000 Under

Internal Parameter Register

• Register Address: 0010H~0043H

• Register Name (and range): EC calibration (0: no calibration, 1: already calibrated), EC slope (70.0%~130.0%), local address (1~255), baud rate (0: 1200, 1: 2400, 2: 4800, 3: 9600), temperature compensation type (0: manual, 1: auto), automatic temperature compensation (-10.0°C~110.0°C / default 0.0°C), manual temperature compensation (-10.0°C~110.0°C) / Default 25.0°C), cell constant setting (0: 0.01, 1: 0.10, 2: 1.00, 3: 10.0), range (1: Low, 2: Middle, 3: High), reference temperature (15.0°C~35.0°C) / Default 25.0°C), temperature coefficient (0.00%~10.00% / default 2.00%), TDS factor (0.40~1.00 / default 0.50), salinity factor (0.20~0.80 / default 0.60) must be included.

• Upper and lower bytes: reference temperature (10 times, if 250 is read, the actual value is 25.0°C), temperature coefficient (100 times the % value, if 200 is read, the actual value is 2.00%), TDS factor (100 times As a value, if you read 50, the actual value is 0.50), salinity factor (if you read 60 with a value of 100, the actual value is 0.60)

• Read and write: R/W

• Remarks: When setting the value, it should be based on Shaping. (For example, to set the temperature to 25°C, you would set it to 250. As another example, to set the salinity to 0.6, you would set it to 60)

DO (Dissolved Oxygen)

The function code basically consists of measurement data (reading input register function) and internal parameter register (reading hold register function code).

▪ *Measured Data*

• Register Address: 0000H~000FH

• Register Name (and range): DO value (0.00mg/L~20.00mg/L), oxygen saturation (0.0%~200.0%), DO sensor current value (0~1000nA), temperature value (-10.0°C~110.0) °C), decimal and units should be included.

• High Byte: Decimal digits 2, 0, 1 (for example, 2 is two decimal places)

• Low byte: Indicates the unit and is mg/L, °C.

• Read and Write: R

• Other functions: 0X7FFF Over / 0X8000 Under

▪ *Internal Parameter Register*

• Register Address: 0010H~0043H

• Register Name (and range): DO calibration (0: no calibration, 1: already calibrated), DO offset (0~40 user defined), DO slope (70.0%~130.0%), local address (1~255) , communication speed (0: 1200, 1: 2400, 2: 4800, 3: 9600), temperature compensation type (0: manual, 1: automatic), automatic temperature compensation (-10.0°C~110.0°C / default 0.0°C), Manual temperature compensation (-10.0°C~110.0°C / default 25.0°C), sensor type (0: 400nA, 1: 80nA), atmospheric pressure compensation (600mbar~2000mbar / default 1013mbar), process pressure compensation (600mbar~2000mbar / default 1013mbar) , salinity compensation (0.0ppt~40.0ppt / default 0.0ppt) must be included.

• Upper and lower bytes: For example, if the temperature reads 250 as a tenfold value, the actual value is 25°C. As another example, if you read 200 as a tenfold value for salinity, the actual value is 20.0 ppt.

• Read and write: R/W

• Remarks: When setting the value, it should be based on Shaping. (For example, if you want to set the temperature to 20.0ppt, you must set it to 200.) / In case of manual temperature compensation, the next register is the set temperature value / In the case of automatic temperature compensation, the next register is the set offset value.

Residual Chlorine

The function code basically consists of measurement data (reading input register function) and internal parameter register (reading hold register function code).

▪ *Measured Data*

• Register Address: 0000H~000FH

• Register Name (and range): FCL value (0.00mg/L~20.00mg/L), HCLO value (0.00mg/L~20.00mg/L), FCL voltage value (-10mV~40mV) Temperature value (-10.0) °C~110.0°C), decimal number and unit should be included.

• High Byte: Decimal digits 2, 0, 1 (for example, 2 is two decimal places)

• Low byte: Indicates the unit and is mg/L, °C.

• Read and Write: R

• Other functions: 0X7FFF Over / 0X8000 Under

▪ *Internal Parameter Register*

• Register Address: 0010H~0043H

• Register Name (and range): FCL calibration (0: no calibration, 1: already calibrated), FCL offset (16bit Shaping), FCL slope (30.0%~300.0%), local address (1~255), baud rate (0: 1200, 1: 2400, 2: 4800, 3: 9600), temperature compensation type (0: manual, 1: automatic), automatic temperature compensation (-10.0°C~110.0°C / default 0.0°C), manual temperature compensation (-10.0°C~110.0°C / default 25.0°C), pH compensation (0: close, 1: open), and pH compensation value (0..00pH~14.00pH) must be included.

• Upper and lower bytes: For example, if the temperature reads 250 as a tenfold value, the actual value is 25°C. As another example, if you read 200 as a tenfold value for salinity, the actual value is 20.0 ppt.

• 16bit Shaping is 700~1300. But 0 is zero and 1 is slope

• Read and write: R and R/W

• Remark: When setting the value, it should be based on Shaping. (For example, to set a pH compensation of 6.8 pH, you need to set it to 686). / In case of manual temperature compensation, the next register is the set temperature value / In case of automatic temperature compensation, the next register is the set offset value.

ISE (Common)

Here, ISE refers to all ion-selective electrode methods and applies only to smart ISE. The function code basically consists of measurement data (reading input register function) and internal parameter register (reading hold register function code).

▪ *Measured Data*

• Register Address: 0000H~000FH

• Register Name (and range): Ion value (0.000ppm~19999ppm), ion sensor voltage value (±500mV), temperature value (-10.0°C~110.0°C), decimal number and unit should be included.

• High Byte: Decimal digits 0, 1 (eg 1 is one decimal place)

• Low byte: Indicates the unit and is ppm, °C.

• Read and Write: R

• Other functions: 0X7FFF Over / 0X8000 Under

▪ *Internal Parameter Register*

• Register address: 0010H~0043H

• Register Name (and range): Ion calibration (0: no calibration, 1: already calibrated), ion slope (30.0%~300.0%), local address (1~255), baud rate (0: 1200, 1: 2400, 2: 4800, 3: 9600), temperature compensation type (0: manual, 1: auto), automatic temperature compensation (-10.0℃~110.0℃ / default 0.0℃), manual temperature compensation (-10.0℃~110.0℃) / Default 25.0℃), Electrovalence (1: Monovalent ion, 2: Divalent ion) must be included.

• Upper and lower bytes: For example, if the temperature reads 250 as a tenfold value, the actual value is 25°C. 16bit Shaping is 700~1300.

• Read and write: R and R/W

• Remarks: Default unit % is the first decimal place / In case of manual temperature compensation, the next register is the set temperature value / In case of automatic temperature compensation, the next register is the set offset value.

Unit of Use

It should be possible to set and use the data in the unit used for the smart water quality sensor. (Example: 0X0E is mg/L / 0X0A is pH) Based on the water quality measurement items shown in this study, it is as follows.

• mV, nA, uA, mA, Ω, kΩ, MΩ, μS, mS, S, pH, ℃, ℉, μg/L, mg/L, g/L, ppb, ppm, ppt, %, mbar, bar, mmHg.

Register address basic configuration (read measurement data, input register function 04).

The address of this measurement data must match the basic configuration so that there is no confusion in using it.

• 0000H: It is the measurement value of the unconditional measurement item.

• 0001H: decimal number and units for measurement

• 0002H: pH and mV value of ORP electrode, TDS value, oxygen saturation, HCLO, ISE voltage value

• 0003H: decimal number and units for 0002H value

• 0004H: ORP relative value, pH value at FCL sensor

• 0005H: decimal number and units for the 0004H value

• 0006H: ORP relative value, pH electrode mV value at FCL sensor

• 0007H: decimal number and units for 0006H value

• 0008H: temperature value

• 0009H: decimal number and units for 0008H values

(In this study, the internal parameter register function code will not be mentioned.)

Performance Standard of Smart Water Quality Sensor

What is a smart water quality sensor?

In general, to perform water quality analysis, sensors and instruments are basically required. The sensor mainly uses an electrochemical formula and measures various water quality items such as temperature, pH, ORP, dissolved oxygen, electrical conductivity, residual chlorine, and various ions in water [7].

However, since the general electrochemical sensor cannot be used alone, it must be used in connection with the measuring instrument. So far, general water quality measuring instruments convert the analog signal input from the sensor into 4~20mA, 1~5V, which are international unified signals, and output it for communication with other external devices. The difference between the smart water quality sensor and the prior art is that it uses MODBUS-RTU for remote communication, and the biggest feature is that the sensor itself can communicate without a measuring instrument. Here, the performance standards of the international standard that the sensor should be equipped with are presented, and for additional performance, the contents of this research standard should be suitable [9-11].

Basic specifications of smart sensor

The signal of a general water quality analysis sensor is an electrical signal. To represent these electrical signals as numerical values and communicate with externally connected devices, the following four conditions must be satisfied in terms of configuration [12].

- Power
- Signal Conversion
- Display
- Output Signal

In addition to the basic sensor function, the smart sensor includes three functions of power, signal conversion, and output signal among the above four basic components that can communicate with external devices, and only the display is customized.

Power

A constant voltage DC12V (9V~24V must be available) should be used as standard.

Cable Type

The smart sensor should be able to be composed of a cable fixed type and a detachable type.

▪ Separable type: VP connector is adopted, and the sensor and cable can be separated freely, making it easy to replace during use. Therefore, it may be suitable for cases where replacement is not easy due to frequent replacement or cable burial after installation in the field. In addition, in the case of sampling method or distribution type, only the sensor can be removed and exchanged, so the work efficiency is good.

▪ Fixed type: A cable is combined with the smart water quality sensor body. It is used as a submersion type because it is advantageous for waterproofing or dustproofing rather than a separate type.

Cable Terminal Block

There are 4 separate and fixed cable terminals, 2 for 8~24V power supply, and the other 2 for communication. U or I terminals can be used with 4 wires, or 4P waterproof plug-in terminal blocks can be used.

Temperature Compensation

Temperature compensation should be basic for each measurement item, and NTC10K is used. Temperature compensation measures the temperature of the water, but also has the purpose of automatic temperature compensation.

Thread Specification

The standard thread of the sensor body is applied, and 3/4”NPT, 1/2”PT, PG13.5 must be used. Whether single-item or multi-channel, it must be manufactured to one of the thread specifications presented. Should be less than 3/4”NPT maximum for non-standard threads.

Sensor Body Material

The body material of the smart water quality sensor is POM and PPS as standard, and it must be engineering plastic, and glass material like pH and ORP electrodes are possible. However, in the use of body materials except for threads, metal series can only be used for special purposes such as food, fermentation, and ultrapure water processes. This is because it is vulnerable to corrosion or noise.

Sensor Size

In general, in the case of glass, like pH and ORP, the electrode should be 12mm in diameter and 120mm in length. The maximum diameter of the body depends on the thread of the sensor (3/4"NPT, 1/2"PT, PG13.5) and must be smaller than the thread. The total length of all sensors should be within 230mm excluding the cable part.

Allowable Current

The smart water quality sensor basically does not require a measuring instrument and is a form of self-communication. Therefore, the allowable current should not exceed the maximum of 50mA.

How it Works

All smart water quality sensors must have the same measurement structure and the same operating principle as existing electrochemical sensors. The sensor body should not have a structure in which a separate signal converter (for example, RS485 communication module) is mounted on a general electrochemical water quality sensor but must have an integrated structure in which a communication module and a smart algorithm module are embedded in the upper part of the sensor body. The various standard ways of operation are shown below, one should apply.

• pH: composite glass electrode method / ORP: composite metal electrode method / EC: two-electrode method, four-electrode method, electromagnetic induction method / DO: polarography method, galvanic cell method, optical method / FCL: ion selective electrode method, galvanic cell method, polarography method / ISE: Ion selective electrode method / Turbidity: Optical (90˚ scattered light method-ISO 7027 method) / MLSS and SS: Optical method (transmitted light method and transmitted scattered light method) / Temperature: resistance displacement method

Conclusion

If we look at the origin of the smart sensor, it is first in the output signal system. To break it down, we must look back from the development of the instrument rather than the sensor. The first generation can be seen as the 1960s when a sensor signal was received and a current or voltage was remotely controlled from a measuring instrument as an output signal, and in fact, it still occupies a significant portion. The second generation can be seen in the 1990s as the point in time when the remote was achieved through RS-232C or RS-485 communication from the instrument. The 3rd generation managed water quality remotely by combining a separate communication module with the water quality sensor in the early 2000s. After various changes, it was necessary to further miniaturize the field. In the 2010s, when the fourth generation was announced, a water quality sensor was combined with a small communication module and marketed, but the algorithm for power and sensor functions was insufficient. Moreover, up to this point, to manufacture a multi-sensor, the size of the sensor increased, making it difficult to install in the field.

Years later, smart sensors were finally completed with the current 5th generation technology. In fact, the 4th generation, 2010s, can be seen as the beginning of the 1st generation. This is because the technology to miniaturize and mount the communication module or printed circuit board inside the smart sensor was also a problem, but above all, the technology to miniaturize the electrode part of each sensor was more difficult and started to be completed in 2010. In any case, the current smart sensor is the most suitable standard that has completely solved all these problems so far, and the communication module and the algorithms for all user functions are built-in within the sensor. All the functions necessary to measure and control water quality are built into the sensor, so users can build UI/UX based on the MODBUS-RTU protocol and measure easily with a computer, personal terminal, or mobile phone anywhere through various communication networks. Measurements and remote control are also possible with a mobile phone. Maintenance using a convenient user app (APP) is the most representative. On-site, for example, delivery date, maintenance, replacement time, remote control and calibration can be managed at any time.

If you use the APP, you can manage users around the world in real time, making all customer management convenient. Drinking water management, large aquaculture and fishery management, marine water quality management, river or lake management, hydroponics management, hot spring and bath management, swimming pool water quality management, various on-site water quality process management, etc. linked with the user APP can manage. I hope that this study will be utilized as basic data necessary for the international standardization of smart water quality sensors and that it will be of great help to all who are engaged in water quality related fields around the world.

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