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A water pumping control system with a programmable logic controller (PLC) and industrial wireless modules for industrial plants—An experimental setup

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ABSTRACT

This paper describes a water pumping control system that is designed for production plants and implemented in an experimental setup in a laboratory. These plants contain harsh environments in which chemicals, vibrations or moving parts exist that could potentially damage the cabling or wires that are part of the control system. Furthermore, the data has to be transferred over paths that are accessible to the public. The control systems that it uses are a programmable logic controller (PLC) and industrial wireless local area network (IWLAN) technologies. It is implemented by a PLC, an communication processor (CP), two IWLAN modules, and a distributed input/output (I/O) module, as well as the water pump and sensors. Our system communication is based on an Industrial Ethernet and uses the standard Transport Control Protocol/Internet Protocol for parameterisation, configuration and diagnostics. The main function of the PLC is to send a digital signal to the water pump to turn it on or off, based on the tank level, using a pressure transmitter and inputs from limit switches that indicate the level of the water in the tank. This paper aims to provide a convenient solution in process plants where cabling is not possible. It also has lower installation and maintenance cost, provides reliable operation, and robust and flexible construction, suitable for industrial applications.

1. Introduction

Modern production processes use industrial automation systems. The automation of these processes is inevitable, and results in high efficiency and high-quality production. Day to day production tasks have rapidly progressed toward this level of automation. Automatic control systems enable a process to be operated in a safe and profitable manner. This can be achieved by continually measuring process operating parameters, such as temperatures, pressures, levels, flows and concentrations. These parameters can be used to automatically make process decisions, for example, actuating valves or pumps, and controlling heaters, so that selected process measurements are maintained at desired values.

Pumping equipment in modern manufacturing systems may be in the primary equipment for many industrial production activities, especially in chemical or food industries [1]. Pumping systems usually exist in the outer parts of the production plants. They are located in harsh environments that can damage any sort of cabling. Recent developments in communication technology have provided appropriate solutions for this problem.

Data communication plays an important role in the rapid development of industrial automation systems. Industrial automation systems enable peripheral production units to operate properly. By making data communication between all product systems possible, they also provide information from all systems to the top-level management. Distributed production plants or services require the use of heterogeneous networks, consisting of local and wide-area networks, and wired and wireless communication systems operated by different organisations, such as CAN (Control Area Network), Interbus, DeviceNet, Hart, Modbus, AS-I (AS-Interface), Profibus and FOUNDATION Fieldbus [2,3]. Wireless LAN technology is widespread in office environments, especially small office or home office settings. As previously stated, traditional networking offers many advantages, but requires cables to interconnect devices. This leads to high installation and maintenance costs, due to low scalability and the high failure rate of connectors. One of the most promising innovations in manufacturing plants is the introduction of wireless technology. The opportunity to replace the large number of cables that currently wire the plants with a wireless system will allow for reduced deployment and maintenance costs. Wireless systems also enable new applications because of the enhanced mobility and more flexible communication paradigms [4,5]. For this reason, wireless technologies have had enormous success in the consumer goods industry in the last few years. Wireless solutions are becoming more and more attractive for the communication systems of manufacturing plants. In addition, the adoption of wireless solutions at the sensor level offers

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other advantages: continuous, high-resolution, ubiquitous sensing; support for mobility; redundancy; and compactness [6].

To be able to use wireless communication technology in an industrial area, it is advisable to use products specially designed for such an environment. Wireless solutions are being used increasingly in process plants to meet the needs of modern work practices.

Wireless technologies may have considerable savings installation cost and a degree of flexibility not possible in wired systems. Wired control systems require trenching to lay new wire; repairing old wire or replacing stolen copper wire can be extremely expensive. Lower installation and maintenance costs, less interference from physical barrier problems, incongruity between standards being minimised and the transmission bit rate being increased to 54 Mbps are some of the specific profitable features of wireless networking [7].

There are several restrictions when using wireless systems that should be carefully taken into consideration, for instance, security issues, reliability, coverage area and fault tolerance. Insufficient information about these problems and their solutions can use away, despite the advantages of wireless networks [7].

Several parameters must be considered for industrial wireless communication. In [8], all relevant parameters which might influence the timing behaviour and failure modes of industrial wireless communication systems were defined and described, as well as a model approach for industrial wireless transfer tests.

Several studies have already been published on the use of wireless communication in industrial plants: in [7], one of the most notable analyses was carried out. In that work, a thorough survey of all industrial requirements was presented: scalability, cost-effectiveness, reliability, flexibility, high availability, immunity to interference, security, and many other factors. These issues are critical in hazardous and noisy environments. The existing wireless solution was reviewed, and the work explored potential matches between industry needs and existing wireless standards. A remote Automatic Meter Reading (AMR) system was developed for water supply organisations in [9]. In that work, for implementing the system, an MR (magnetic resistance) sensor, Reed switch and CYBLE sensor type modules were used, and for installing for system communication, RF and Zigbee modules were used. In [10], the authors surveyed issues and appropriate solutions for wireless communication in industrial applications: fundamental problems, the usage of existing wireless technologies for this specific field of applications, and the creation of hybrid systems. In [4], wireless sensor networks are described in detail. In [11], the implementation of a multi-interface module (I2M) for drilling and ratifying processes was described. The work simulated a system with an Industrial Hydraulic Module (MHI-01), based on the IEEE1451 standard. Wireless industrial sensors have been studied in a number of other works [12–16]. In the studies reported in [17–20], wireless sensor modules were used for home automation.

A servomotor remote control was carried out with a personal digital assistant (PDA), a PLC, a wireless device server and its driver in [21]. The system communication was established by the wireless network card of the PDA, wireless device server, and RS-232 port of the PLC. In [1], a small-capacity water pumping system was designed, constructed and tested using a PLC and frequency control. In that work, the system communication was established by cables. In other works, some examples of process control using a PLC and traditional cabling systems at the field level were carried out [1,22–30].

PLCs are usually a main part of automatic control systems in industry. They are used for the internal storage of instructions to implement control functions, such as logic, sequencing, timing, counting and arithmetic. They control various types of machines and processes through digital or analogue input/output modules. PLCs are also used to monitor and control plants or equipment in

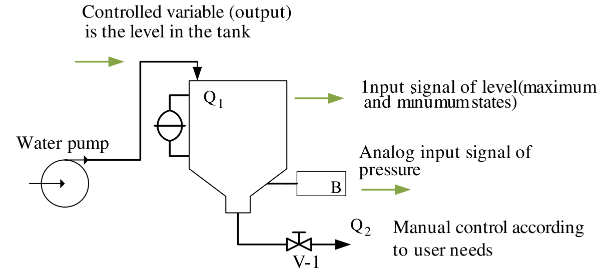

Fig. 1. Block diagram of controlled process.

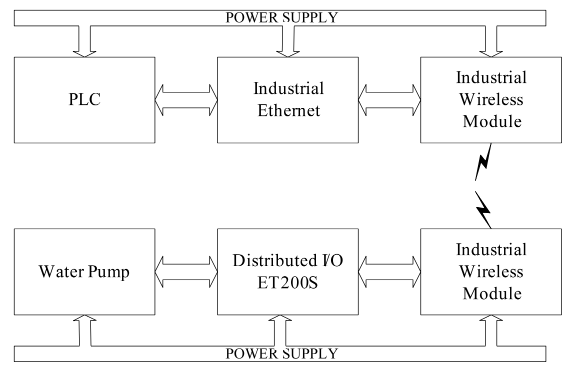

Fig. 2. Block diagram of water pump control system.

industries such as telecommunications, water and waste control, energy, oil and gas refining, and transportation [23].

This paper aims to provide a convenient solution in process plants where cabling is not possible. The proposed solution should lower the installation and maintenance costs, provide reliable operation, and be of robust and flexible construction for industrial applications. In this study, we used Siemens SCALANCE W IWLAN modules, which are different from the wireless sensor network (WSN) and WLAN systems used in previous reported studies.

2. System design

System design was carried out with consideration of environmental conditions and process details. Fig. 1 is an illustration of the controlled process. In this process, the Process Variable (PV) [31,32] is the water level in a tank. It is measured by a pressure transmitter and two limit switches (maximum and minimum water level) on the tank, and these values are the input into an automatic controller that actuates a pump based on the water levels. As shown in Fig. 1, an open tank is supplied with an inflow of water, $Q1$, from a water pump that can be controlled. The outflow from the tank, $Q2$, is controlled by a manual valve according to the user's needs. The level of water in the tank is controlled according to the pressure and inputs to the controller from the two limit switches. Thus, the process control mode is on–off control. This is a discontinuous form of control action and is also referred to as two-position control. In this process, the on–off controller turns 'on' when the water level is measured at its minimum value. The controller turns 'off' when the water level reaches its maximum. The system block diagram, designed according to environmental conditions and the desired process control, is shown in Fig. 2.

2.1. Hardware structure

As shown in Fig. 3, the whole system consists of three different units. The first unit is the PC. The PC runs a program called SIMATIC MANAGER, which is used to configure the hardware, the software package (STEP 7) as shown in Fig. 5, and write a control program for the PLC. This control program is downloaded to the PLC through the MPI (Multi Point Interface) PC Adapter communication cable.

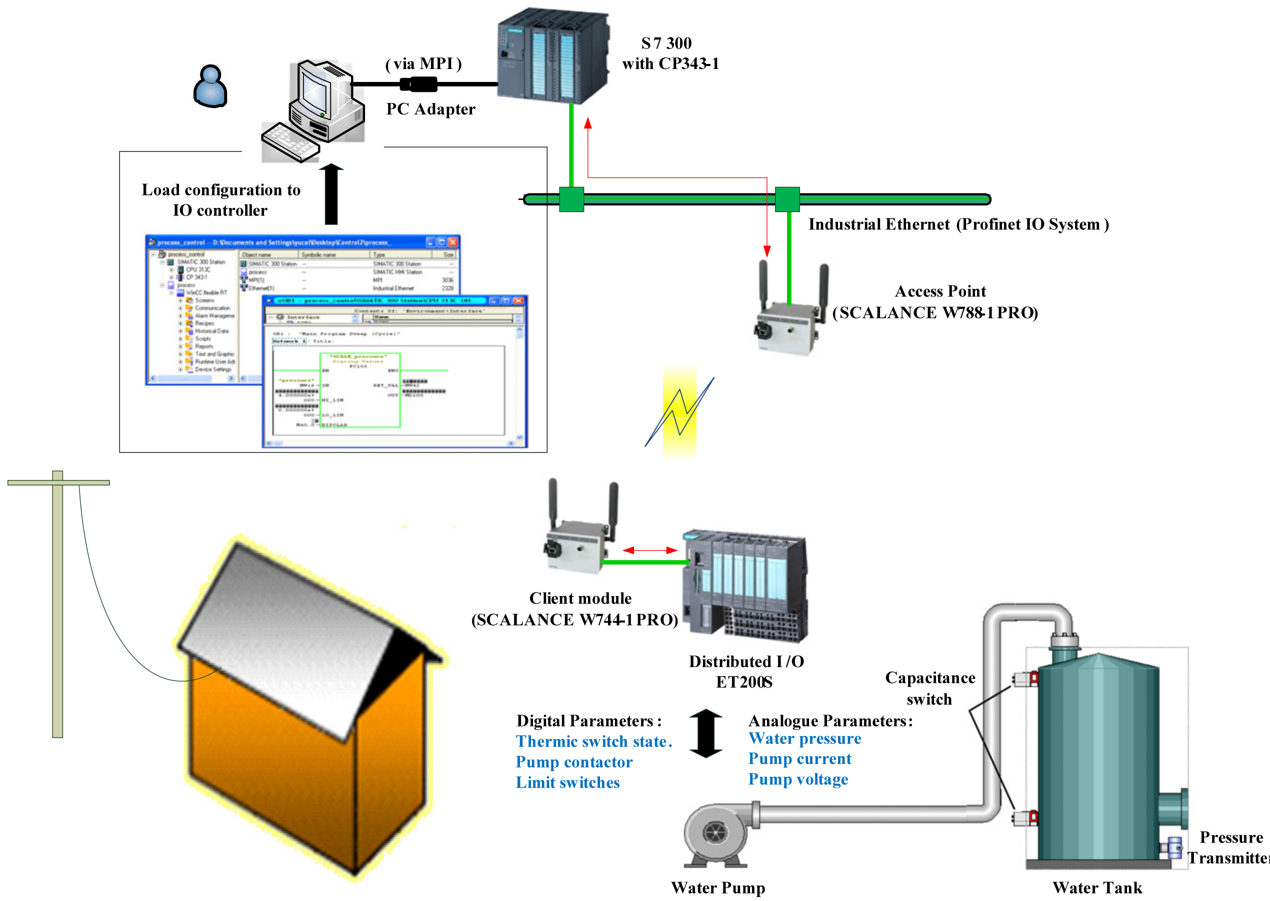

Fig. 3. System configuration diagram.

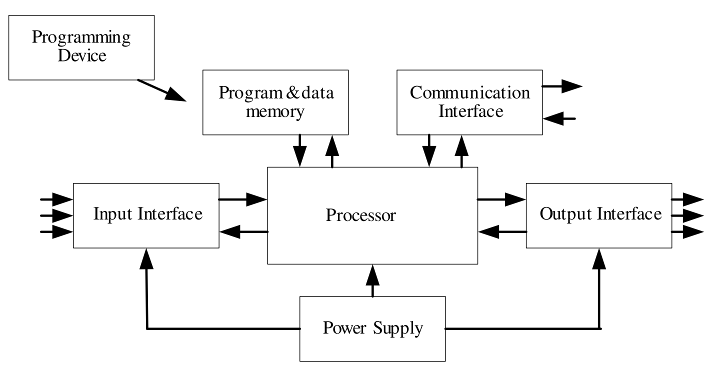

Fig. 4. Basic structure of a PLC.

The second unit is the master node, and it consists of three parts: a PLC with digital and analogue modules, a CP (Communication Processor), and a Wireless Access Point. The last unit is on the client node side. This unit is located on the outer part of the control centre and is connected directly to the device to be controlled. The Wireless Client module, Distributed I/O Interface module and motor protection package (MPP) constitute the client node.

- The Programmable Logic Controller (PLC). Typically, the basic functional components of a PLC system [33] are a processor unit, memory, power supply unit, input/output interface section, communications interface, and programming device. Fig. 4 shows the basic arrangement.
- The processor unit or central processing unit (CPU) is the unit containing the microprocessor. This interprets the input signals and carries out the control actions, according to the program stored in its memory, communicating the decisions as action signals to the outputs.
- The power supply unit is needed to convert the mains AC voltage to the low DC voltage necessary for the processor and the circuits in the input and output interface modules.
- The programming device is used to enter the required program into the memory of the processor. The program is developed in the device and then transferred to the memory unit of the PLC.
- The memory unit is where the program for the microprocessor is stored. The memory unit also stores input data from for processing and buffers data for output.
- The input and output sections are where the processor receives information from external devices and communicates information to external devices. The inputs might be from switches or sensors such as photo-electric cells, temperature sensors, or flow sensors. The outputs might be connected to motor starter coils, solenoid valves, or other actuators. Input and output devices can be classified by signal type, such as digital or analogue.

- The communications interface is used to receive and transmit data on communication networks. It manages device verification, data acquisition, synchronisation between user applications, and connection management.

In this study we used a Siemens S7 313C Compact PLC which has 24 DIs (Digital Inputs), 16 DOs (Digital Outputs), 5 AIs (Analogue Inputs), 2 AOs (Analogue Outputs), and a power supply (120/230 V AC, 24 V DC, 5 A).

- Communication Processor (CP). The PLC system Ethernet module is a communication processor for the S7 family that connects the PLC to the network [29]. An additional communication processor is used to allow communication between the PLC and IWLAN over TCP/IP. The CP343-1 communications processor in our work is designed for operation in an S7-300 programmable logic controller. It allows the S7-300 to be attached to the Industrial Ethernet and supports PROFINET IO.
- IWLAN modules. Wireless networking solves the physical barrier problems that are inherent to wiring, decreases installation costs, improves flexibility when reconfiguring systems, and speeds up the deployment of the network [7]. Industrial Wireless LAN is a generic term covering functions and mechanisms that represent an enhancement of the IEEE 802.11 standard. Even the standard mechanisms of 802.11 provide a good degree of ruggedness for use in industrial applications. IWLAN, however, also supports demanding applications and provides a particularly high degree of real-time and deterministic scheduling, as required in PROFINET [34].
- In this study, an IWLAN network was created using the new SCALANCE W generation components from Siemens. The radio network was set up using a SCALANCE W788-1 PRO access point, and an Ethernet client module W744-1 PRO was used to connect a node to an IWLAN.
- Distributed I/O module. When a system is configured, the I/O to and from the process is often integrated centrally in the automation system. The ET 200S distributed I/O system is a discrete modular, highly flexible DP slave for connection to process signals on a central controller or a field bus. ET 200S supports field bus types PROFIBUS DP and PROFINET IO. This study used the ET200S-IM151-3PN standard with 4 DIs, 2 DOs, 4 AIs and two 24 V power modules for the PROFINET IO bus [35].
- Motor protection package. The motor protection package consists of a classical contactor, thermic switch, current measuring transducer (CMT), and voltage measuring transducer (VMT). The CMT is used for measuring sinusoidal and non-sinusoidal alternating currents, input current 0 to 100 A, and loop-powered output of 4 to 20 mA. The VMT is used for alternating current voltages from 0.20 to 0.440 V, and output signal 0.10 V/0(4).20 mA.

2.2. Software structure

The software for the control system was developed in the SIMATIC Manager. This is the central window which becomes active when the software package (STEP 7) is started. The default setting starts the STEP 7 Wizard, which assists the programmer to create a STEP 7 project. Programmers can select the programming mode: ladder diagram (LAD), function block diagram (FBD), and instruction list (STL) [36]. The project structure is used to store and arrange all the data and programs in order.

The system software was completed in four steps. Step 1 designs the solution to the automation task. Step 2 configures the hardware and the network [37], as shown in Fig. 5. Step 3 creates the program in ladder diagram form. Step 4 transfers the program to the CPU. Finally, the software is tested for input status, program execution, and output status.

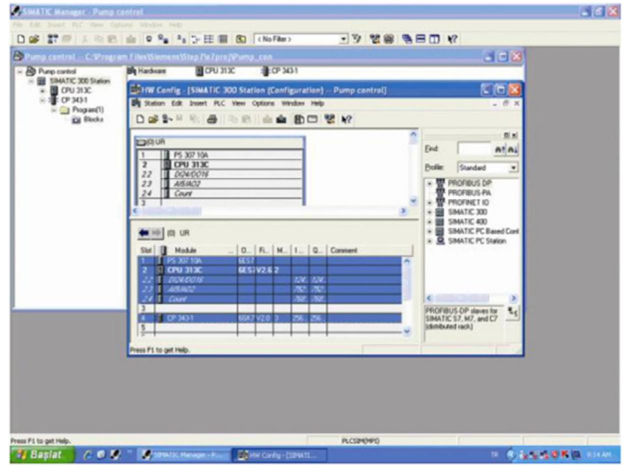

Fig. 5. Hardware configuration in SIMATIC Manager.

3. System implementation

This water pumping control system was designed as an on–off controller, operated by a stored program in the PLC. Data transmission to control the water pump was provided by the PLC and the Distributed I/O via IWLAN modules, as shown in Fig. 6. The distributed I/O was connected to a SIMATIC CPU over an IWLAN wireless network. A Scalance W788-1 PRO access point connected to the SIMATIC CPU via an Ethernet module over PROFINET services the cell. On the client side, a Scalance W744-1 PRO client module and distributed I/O ET 200 S are used. Downstream from each IWLAN is a distributed I/O ET 200 S with 4 DIs, 2 DOs, and 4 AIs, supplied with PROFINET. The cycle time (load caused by the program) is specified as 50 ms, which results in a typical reaction time of approximately 140 ms at an update time of 32 ms.

3.1. System communication

System communication is formed of three main parts: the PC side, the access node, and the client side. The PC is connected to the master node via an MPI interface. The communication between the access and client nodes is established through RF in IEEE 802.11 [6–8] standard for industrial applications. The RF communication is performed using IWLAN modules operating on the 802.11b/g and 802.11a standard with up to 54 Mbps speed and 2.5 GHz frequency [38,39].

Fig. 7 shows the minimal transaction times for 32 Byte data on the 802.11a/b/g standard. The minimal transaction time to be reached for small packets in Wireless LANs lies between 120 μs using 802.11a or 802.11g, each with 54 Mbit/s, and well over 1000 μs using 802.11b. The requirements of many industrial systems can be provided by these WLAN components [40].

The client nodes, as shown in Fig. 6, are connected directly to the device to be controlled via conventional command components.

The communication is established over a PROFINET field bus during the network configuration part of the software package (STEP 7). PROFINET enables distributed field devices (I/O devices such as signal modules) to be integrated directly in the Industrial Ethernet. During configuration with STEP 7, these field devices are assigned to a central controller (I/O Controller). Existing modules or devices can continue to be used with PROFINET-compatible interfaces or links. PROFINET provides new functions and applications for wireless communication with an Industrial Wireless LAN. The functions implemented here are based on a PROFINET network via a Wireless LAN [6]. The following functions are available for the data traffic between the user program of the S7-300 CPU and the PROFINET IO devices via a CP as a PROFINET IO controller, as shown in Fig. 8.

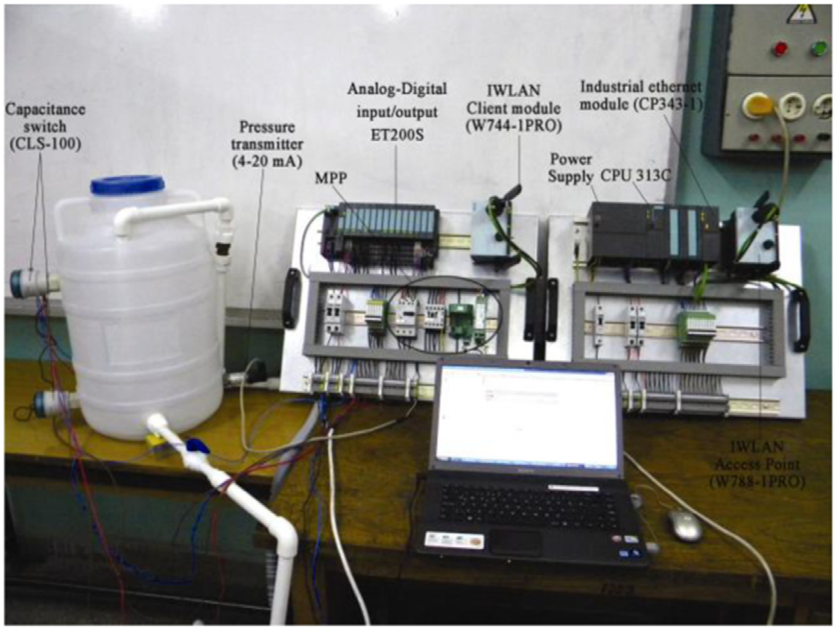

Fig. 6. A photograph of the designed system.

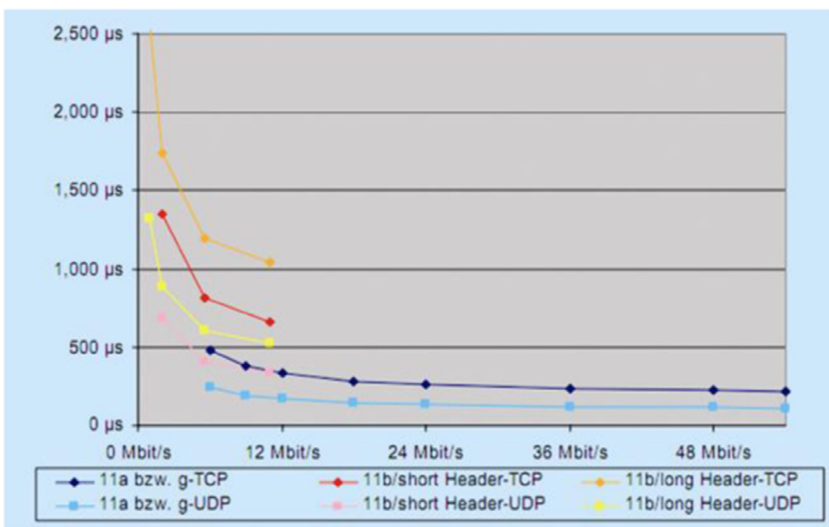

Fig. 7. Minimal transaction times for 32 Byte data [40].

- PNIO_SEND (FC 11)
- PNIO_RECV (FC 12).

In addition, the following function blocks are available for diagnostics:

- PNIO_RW_REC (FB 52) (not used in this application)
- PNIO_ALARM (FB 54) (not used in this application).

The blocks are included in the SIMATIC_NET_CP library.

Block FC 11 (PNIO_SEND) is used for transferring process data and is called cyclically in the user program. The process data are made available in memory, accessible as a data block. The FC11 transfers these process data (outputs) to the CP to forward them to the PROFINET IO devices. Block FC 12 (PNIO_RECIEVE) is used to accept the process data from PROFINET IO devices (inputs of the controller) and transfers the IO provider status (IOPS) from the PROFINET IO devices to the specified input areas [38].

3.2. System operation

Pumping equipment may be a major part of modern manufacturing and industrial production systems for chemical, food, and other industries [1]. Pumping systems usually exist in the outer parts of the production plants and are found in harsh environments that could damage any sort of cabling. Therefore, this system was designed to be wireless, using IWLAN modules for communication and a PLC for control.

Where a number of plants are supplied with water from one set of pumps, a very effective plan is through a ring-main, which supplies water to all the feeders. Control systems for these systems operate by monitoring the water level. In this study, the water level is measured by a pressure transmitter and for precaution by maximum and minimum limit switches.

Level measuring with the pressure method: the heights of liquids are directly proportional to their pressure on the base. If base pressure of the liquid formulation had been done

$$P = d \times g \times h. \quad (1)$$

$d_{\text{water}} = 1000\ \text{kg/m}^3$ (constant value).

$g = 9.81\ \text{N/kg}$ (constant value).

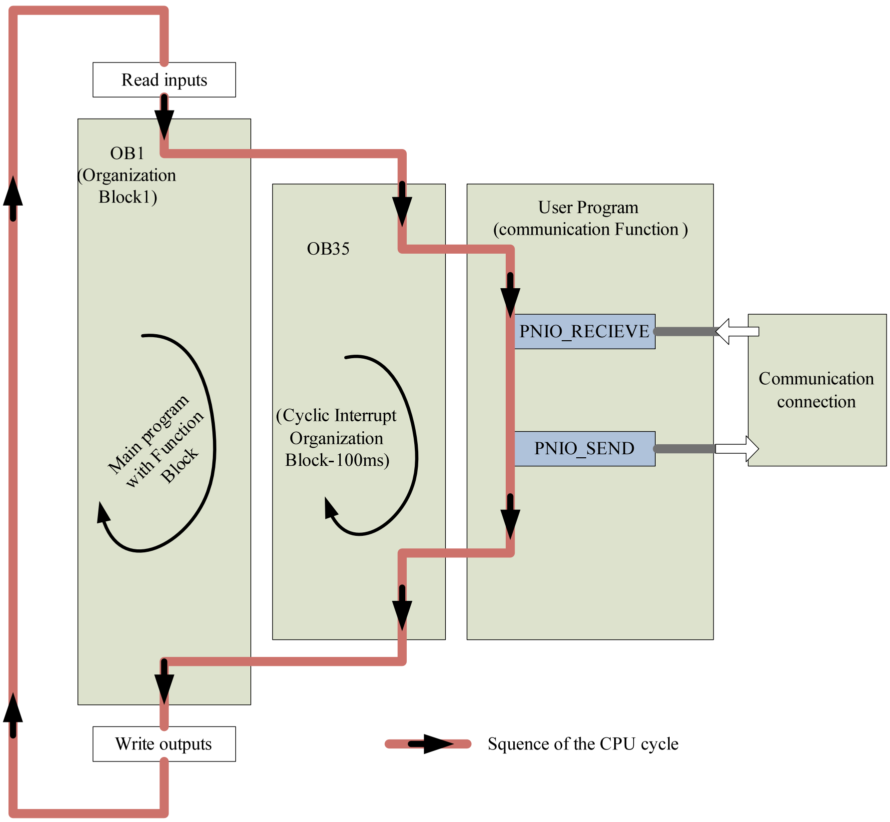

Fig. 8. Typical sequence of FC11 and FC12 calls in the CPU cycle.

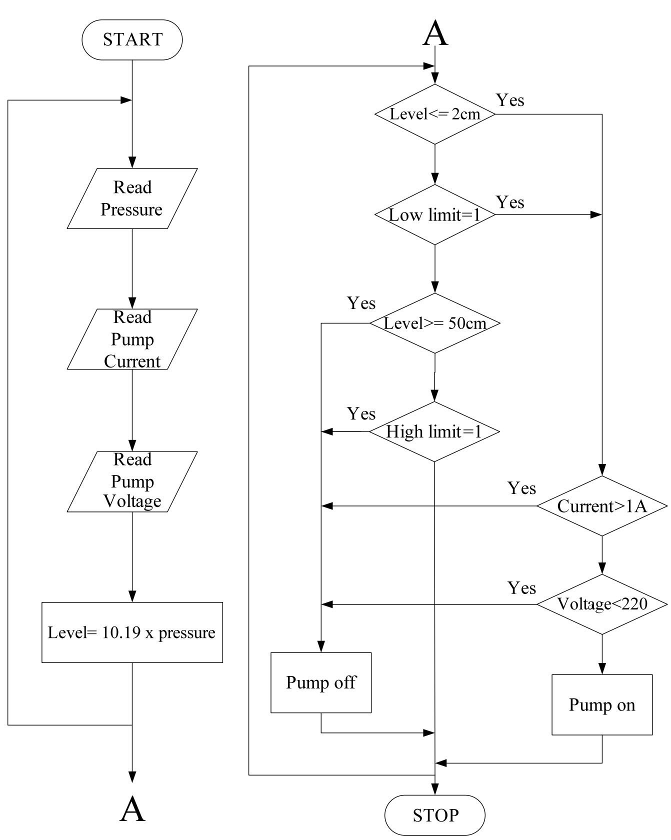

Fig. 9. Flow chart of pump control.

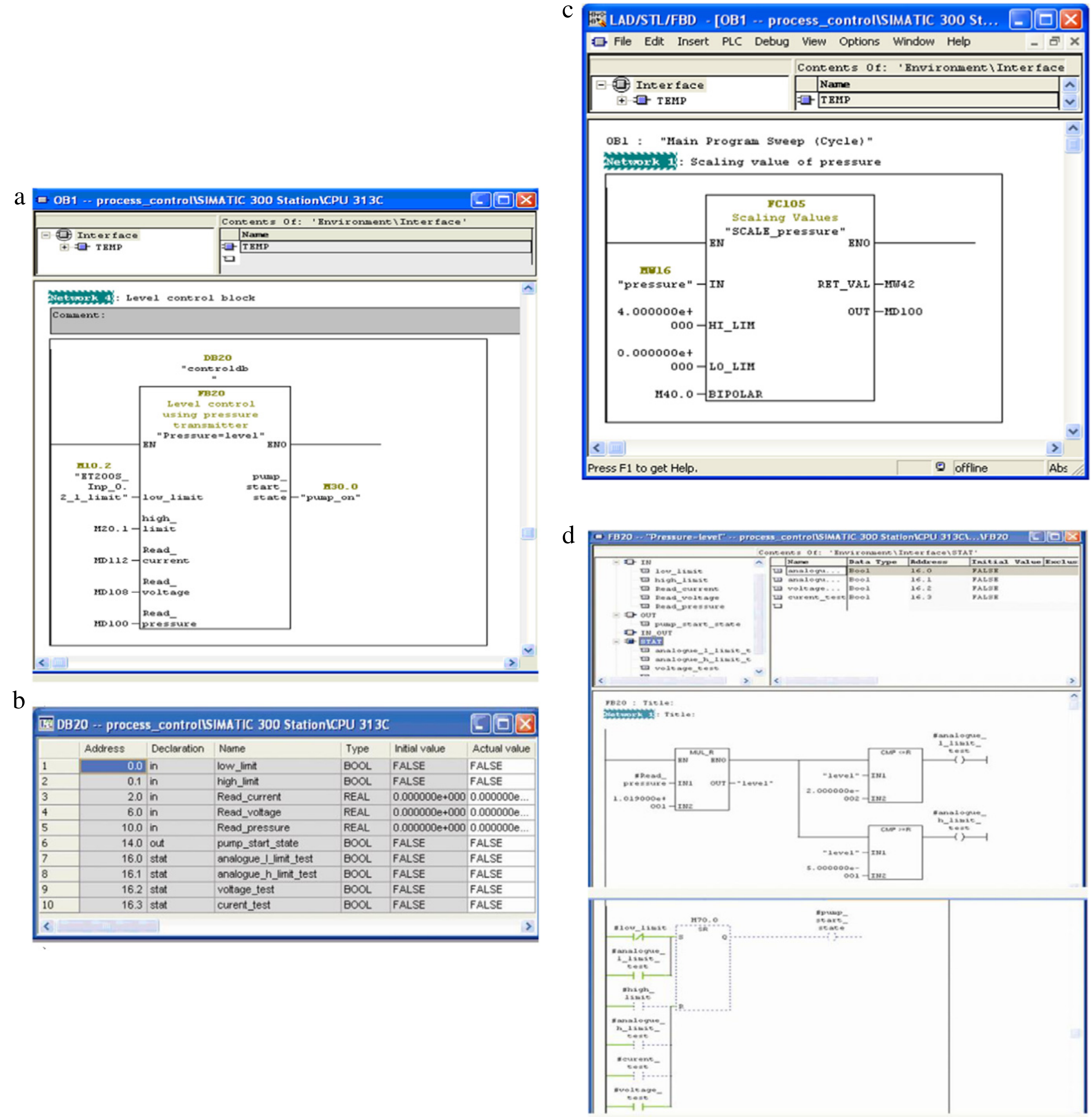

Fig. 10. Program structure of the system: (a) subordinate blocks; (b) data block variables; (c) Scaling block for pressure; (d) LAD view of pump control function block.

Here d is the density of the liquid. This is a constant value, according to the liquid used. g is the acceleration due to gravity.

$$P = 1000 \times 9.81 \times h \text{ N/m}^2 \text{ (1pascal} = 10^5 \text{ bar)}. \quad (2)$$

Using the above formulation, the values reported in Table 1 can be obtained.

SIMATIC Step 7 V5.4 software has been used for programming the system. After a flow chart of operation had been formed, as shown in Fig. 9, the program structure of the system was created with organisation blocks, a function block, and data blocks, and then the call for subordinate blocks as shown in Fig. 10a with a data block as shown in Fig. 10b was programmed in the hierarchy. The application function block contains application-related signal processing, such as scaling, alarm detection or control and calculation [41]. Symbolic names are given in the symbol table (for example, Pressure = level and controldb). To scale values of

Table 1
Relationship between water level and pressure.

Level (m)	Pressure (bar)
0.10	0.00981
0.20	0.01962
0.50	0.04905
1.00	0.09810
1.20	0.11772
1.50	0.14715
2.00	0.19620
2.50	0.24525

pressure, current and voltage converting block as shown Fig. 10c was used from the standard library in STEP 7. Fig. 10d shows the LAD view of the system program. The system program was configured to switch the pump on when the water level drops and switch it off when the tank is full. When the tank is full, the control system signals the pump to switch off, via wireless IWLAN modules. The tank is closed above its maximum fill level, preventing overflow. The pump system operates as follows. The water outflow from the tank passes through a manually controlled valve, operated by the user. When the water level triggers the low-level limit switch, a contact closes and the transmitter sends a digital signal and the pressure transmitter, VMT and CMT send a 4–20 mA signal to the controller via the wireless client module and access point. If the pump current value is not >1 A and the pump voltage value is not <220 V, the PLC's main function is to send a digital signal to the pump, which turns on and fills the water tank. When the water tank is full, the pressure transmitter sends the relevant value which has been scaled, being the high level, or for precaution the capacitance switch opens a contact at the transmitter, and the transmitter sends an "off" signal to the controller. The PLC then sends a digital output to the water pump to turn it off.

4. Conclusion

IWLAN modules and PLC controllers are the natural technology choice for process automation and control. [7,8] Wireless networking provides the needed flexibility, low maintenance cost, and scalability in the design and control of a plant. In this work, we discussed the design and implementation of a water pumping process. The proposed architecture and results demonstrate the feasibility of using IWLAN protocols to communicate effectively with PLCs. The system was tested using an industrial application and it had a very satisfactory performance. Conventional, wired control systems require trenching to lay new wire; repairing old wire or replacing stolen copper wire can be extremely expensive. In this study, wireless communication for the water pump control solved these problems and provided a clear advantage over wired control systems.

Acknowledgement

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