Smart Controller for Industrial Internet of Things: Design and Implementation

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Abstract—**This paper states a description of the development of smart controllers that allow connection of standard industrial equipment with various interfaces to one industrial network for monitoring and interaction purposes in enterprises. The aim of this paper is to form up a methodology on the development of Industrial Internet of Things (IIoT) compatible and relevant solutions. As a result of this project, a smart controller itself was developed and a detailed step-by-step development and manufacturing process description was written. In addition, a concept of remotely updatable devices and open-source approach suggested in order to structure and simplify all the further processes of full-cycle development and implementation in production in the context of IIoT. Finally, a technology of development of housing for electronics using a standardized set of elements has been announced.**

I. INTRODUCTION

An integration of cyber-physical systems (CPS) to all kinds of activities remains one of the most anticipated changes in the modern world. Due to such global changes, none of the known life aspects could stay unaltered, however, the most significant effect would be caused to the methodology of development of industrial systems of future [1]. And one of the key components to be used in the development of a modern enterprise is an Industrial Internet of things (IIoT) since it gives a lot of possibilities to improve all the manufacturing processes using the collected data and ability to swiftly influence on the production process. It is worth noting that the use and continuous integration of the industrial Internet of things (IoT) solutions allow the use of other relevant technologies, such as Digital Twin, Big Data, Deep Learning, Cloud solutions, Blockchain, each of which opens up new opportunities to increase the level of automation, reliability and efficiency of the enterprise. In the 21st century, it is information that determines the course of industrial development, and the use of the IIoT systems is one of the key methods for its receipt and control.

Despite all the positive qualities of the use of Industrial Internet technologies, at the current stage of development, low implementation is observed. A detailed description of the methodology for the development and implementation of the IIoT solutions, as well as the application of the principles of open source code and project materials, would reduce the cost and complexity of the implementation process, making it easier for modern enterprises to take a significant step forward in automating their processes. In terms of this project, a software and hardware solution for the IIoT is being developed that connects equipment, status monitoring devices and other components of an industrial system to one industrial network in order to increase its level of automation. The architecture of the solution includes an intelligent controller of the IIoT with Wi-Fi interface, a digital matrix indicator, an Ethernet for connecting peripheral TCP devices, a real-time clock module, as well as a cloud database with its own API for processing, storage and data exchange between devices.

As part of this work, the development process of an intelligent controller is described in detail, namely:

1) Analysis and selection of the microcontroller;
2) Development of a printed circuit board;
3) Programming the main functionality of the microcontroller;
4) Design and manufacture of the housing;
5) Assembly of the printed circuit board and assembly of the intelligent controller;
6) Testing.

A scientific novelty of this work is stated by:

1) A relevant step-by-step development and manufacturing process description of intelligent controllers is formed;
2) A concept of remotely updatable devices and open-source approach in context of IIoT is suggested;
3) A technology of development of housing for electronics using a set of standardized elements is suggested.

The practical significance of the work lies in the fact that the presented approach to the development of devices will reduce the cost of developing and implementing elements of the IIoT in CPS. This would simplify the implementation process and allow small enterprises that have no professional design development bureaus and software development department to use described approaches, avoiding strict and closed solutions that require restructuring existing business and production processes.

II. RELATED WORK

To assess the potential of the IoT, the McKinsey Institute studied the economic possibilities of IoT solutions in various conditions [2]. The study estimated the total potential economic impact of 3.9 to 11.1 trillion US dollars per year by 2025, which gives us a vivid image of significant interest growth in the IoT. Such growth allows using more affordable and sustainable solutions [3] that can be used anywhere, even in E-Health [4] or Smart Cities.

It was estimated that the amount of IoT devices connected to the Internet can reach up to 75 billions by 2025 [5]. This means that with Traditional Cloud Computing following a centralized scheme where computing and storage are deployed in a remote data centre [6], many challenges can arise. Such approach experiences significant limitations when dealing with these emerging technologies that require real-time response and reduced latency. In this regard, recent researches propose the use of the Edge Computing paradigm as a way of improving Cloud Computing capabilities [7], [8].

To support the sustainable intelligent interaction between the services and all kinds of equipment in the industrial field, an Edge Computing [9] shall be implemented in the industrial wireless network. Exploration of existing solutions that endorse Edge Computing approach shows positive impact from using Systems-on-Chip (SoC) [10] and IIoT gateways [11]. Using an architecture in which field devices (FDs), acting as sensors, actuators or relaying nodes, a decentralized consensus-based technique for joint estimation of key parameters can be achieved [12], [13].

III. Architecture

Considering the whole architecture of IIoT systems, the structural basis of the complex IIoT consists of four main levels:

1) User level—interaction with the end user through a multi-platform user interface;
2) Service level—maintenance of user-device interaction, database support, data processing and storage in order to obtain new information;
3) Communication level—ensuring stable communication and data transfer between transmitters and data receivers;
4) Device level—device circuitry, autonomous operation, interaction with equipment and sensors, primary data processing.

Within this work, the communication level and the device level are described in details, however, both the user and service levels were taken into account throughout the project.

During the research a list of currently most relevant technologies at the communication level has been analyzed. The following protocols are most widely used:

- MQTT [14];
- REST API;
- CoAP [15];
- SOAP;
- XMPP [16];
- UPnP [17].

At the device level, the list of relevant supported interfaces is divided into two parts: wired and wireless. So, the list of the most used wired interfaces (buses) includes:

- Modbus;
- Canbus;
- Profibus.

Most of these interfaces are used for direct physical connection of IoT devices and sensors to industrial equipment. Wireless interfaces are used directly to connect IoT devices to each other, to a base station or server:

- Wi-Fi
- Bluetooth, Bluetooth Low Energy;
- ZigBee;
- Z-Wave;
- LoraWAN;
- LPWAN;
- GSM/GPRS;
- 5G (NB-IoT).

A power supply is required for any embedded device or IoT device [18]. Depending on the application, power may be provided by wire, batteries or using hybrid power sources. The power supply has a significant impact on the design of the entire system. If a limited power source, such as a battery, is used, then the selected hardware, in addition to the application-level logic and communication technology, in the aggregate has a significant impact on the durability of the solution. This results in limited application time or increased maintenance costs.

For many devices of the IIoT, the question of the certain sensors compactness arises in connection with which the requirements for calculating the power source are growing. The development process requires a precise analysis of the energy efficiency of the components used, the available operating modes and scenarios for activating the device, the optimization of the methods used, the volume and format of the data being sent, the communication channel used and other aspects that affect the final duration of the device. In some cases, the elements of the industrial Internet require the installation of spare power sources based on renewable energy.

Another thing to consider is time and there are many ways to get the current time and date. They differ in the recording method, accuracy, and also the methods used to obtain data.

One of the ways to implement the time acquisition functionality is to use RTC chips—real-time clocks. These are special devices designed to record chronometric data. Nevertheless, the use of such chips has a number of disadvantages. They increase the cost of the final product, and is also not very accurate, in addition, for their synchronization, sometimes manual adjustment is required.

Another common solution is to use NTP, the network time protocol. NTP takes into account the time of data transfer and uses UDP protocol for its transmission.

Changing the time in a device can be made in two general ways: installation and adjustment. By setting a new time, the old time value is overwritten with a new one. This method is the simplest, but its use can lead to a violation of the sequence of entries in the event log. The solution to this problem is to change the time through adjustment, i.e. changes in the speed of the passage of time in the device until the restoration of equality with the result. This approach allows you to save the sequence of events in the log.

As a result of the study, the key requirements for up-to-date solutions as well as methodologies have been formed, which must be adhered in the process of developing of intelligent devices for the IIoT, among which:

- Keeping to a multilevel structure;
- Support for actual protocols;
- Support for actual interfaces;
- Ensuring sufficient autonomy;
- Caring of time control and adjustment;
- Security and fault tolerance.

Adding the possibility of updating the firmware and making it modular is a key element in ensuring a high fault tolerance of the developed product, as well as its subsequent maintenance in the ever-changing world of technology. Currently, the border between hardware and software is becoming thinner, and their interaction is becoming more flexible and dense. In this regard, the life cycle of a finished device in the modern world goes into a state of constantly evolving and adapting to current conditions. It is the capability of hardware and software updating of the device that will allow meeting these conditions. In addition, it is recommended to maintain the maximum simplicity in the design of the devices, increase information redundancy, share and distribute tasks between components, apply standard components and techniques, provide the ability to update and keep the source materials open [19]. The application of the principles of open source code and project materials allows us not only to simplify the process of implementing the developed solution in production but also to get the support of the world community at future stages of the product life cycle. Such a principle will allow us to get a fuller view of problem-solving from the community, and also greatly simplify the process of forming standards and their application.

IV. Design and implementation

In this work the development process of an intelligent controller is described in detail, namely:

- Selection of the microcontroller;
- Development of a printed circuit board;
- Programming the main functionality of the microcontroller;
- Design and manufacture of the housing;
- Assembly of the printed circuit board and assembly of the intelligent controller, testing.

Choosing a kernel for the developed intelligent controller, many options for building a system have been analyzed such as microcomputers and microcontrollers based on various microprocessors.

A distinctive feature of microcontrollers is the presence of a set of auxiliary and peripheral devices in addition to the processor core that allows the microcontroller to be self-sufficient in most of the tasks. A correct choice of a microcontroller for the basis of the device allows minimizing the time and labor costs for the formation of the circuitry architecture of the device during its development. When choosing a microcontroller, it is worth considering the main features of its architecture, namely: bit depth, clock speed, flash memory, the presence of the required peripherals, ports and supported interfaces, power consumption—as well as such important factors as relevance, market availability and both developer and the community support level.

Among the options analyzed were considered:

1) Raspberry Pi 3 Model B (ARM Cortex-A53);
2) Raspberry Pi Zero (ARM11);
3) Arduino Uno (ATmega328p);
4) Arduino Nano 3.0 (ATmega328p);
5) Arduino Micro Pro (ATmega32u4);
6) NodeMCU v3 (ESP-12E);
7) ESP32S (ESP32-WROOM32);
8) DFRobot firebeetle ESP32 (ESP32-WROOM32);
9) STM32F103C8T6 (AEM STM32).

These options have strong support from developers and the community—on the Internet you can quickly find the necessary libraries for working with various modules and interfaces, which greatly speeds up the development process.

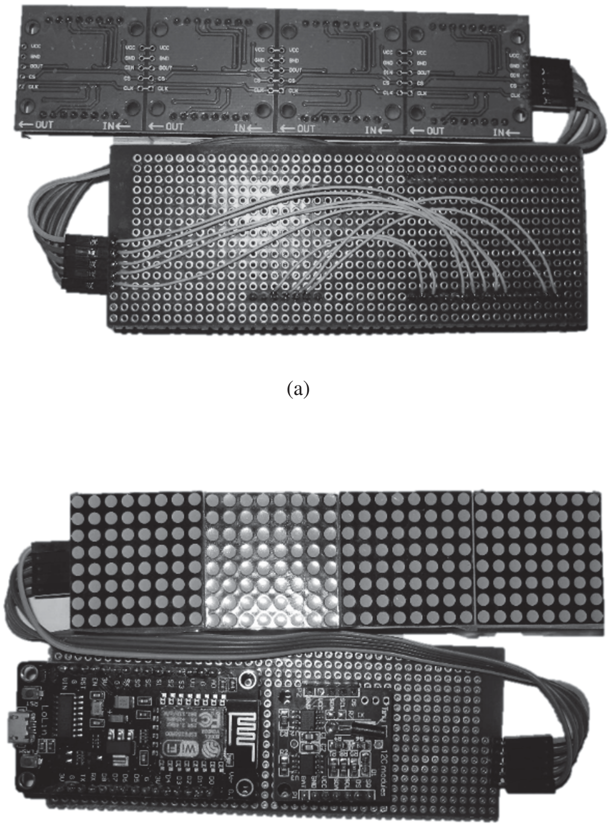
When developing an intelligent controller for the IIoT, it was decided to use the NodeMCU v3 microcontroller based on the ESP-12E, a modification of the ESP8266EX chip as the basis for the device. This microcontroller has the ability to connect to a 2.4GHz wireless Wi-Fi network (802.11 b/g/n) and can interact with external devices or web services. As well as low cost and small overall dimensions, its main feature is in having a built-in module for working with Wi-Fi wireless networks, built-in SPI and I2C interfaces, 4MB of flash-memory, the ability to flash firmware via a USB-micro connector due to CH340 chip.

After choosing the microcontroller for the basis of the intelligent controller, a prototype printed circuit board was developed, on which the electronic components were installed. The structure of the prototype included:

- Printed circuit board;
- Microcontroller NodeMCU v3 (ESP-12E);
- RTC real-time clock module (DS1307);
- Module for connecting to the Modbus TCP (W5500);
- Four modules of the LED matrix display 8x8 (MAX7219);
- Photoresistor (GL5528).

First of all, a prototype of an intelligent controller with an indicator was developed (Figure 1), which is based on the use of a microcontroller, a matrix display and a real-time clock module on a breadboard. Subsequently, a Modbus connection module was added to the device design in order to support equipment connected via this interface. Any additional interfaces can also be added at this stage.

In the OrCAD design environment, a circuit board for an intelligent controller has been developed (Figure 2). PCB



(a)

(b)

Fig. 1. A prototype of smart controller, bottom view (a), top view (b)

development can also be done in other software packages for PCB design, such as Altium Designer, KiCAD, Eagle, DesignSpark PCB, ExpressPCB, SprintLayout and many others. As a result of designing the board in the OrCAD, a file with the extension .gbr (gerber) was obtained, which was used for further production.

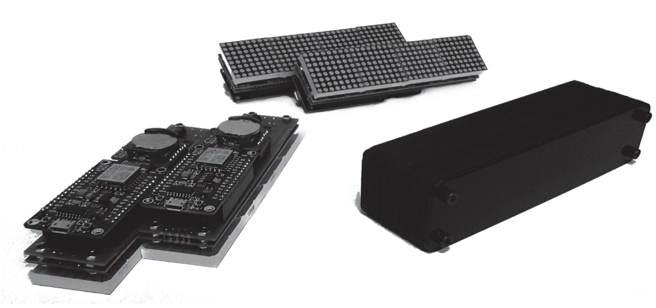


Fig. 2. A photo of assembled prototypes

The microcontroller was programmed in the Arduino IDE v1.8.8 development environment. For programming in the Arduino IDE, the Arduino programming language is used, which is based on languages C and C++. A compilation process of the code after the initial transformations is performed using the C/C++ compiler. All supported libraries are also written in C/C++.

During the development of the smart controller, the following basic functionality has been programmed:

1) Connect to a Wi-Fi network and maintain a connection;
2) Sending HTTP requests using the developed web service API, receiving a response and processing it;
3) Sending and receiving data from the Modbus using Ethernet module;
4) Information output on the matrix display MAX7219;
5) Writing and reading time from the DS1307 clock module;
6) The formation of the web interface (HTML) (Figure 3);
7) Implementing remote OTA firmware updates.

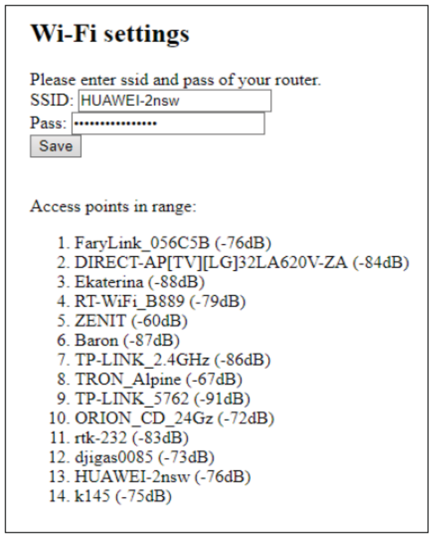


Fig. 3. A screenshot of web-interface of smart controller

The process of firmware over-the-air update is regulated from the web-server side for security reasons and does not require physical access. Once a new firmware presented as a binary file is available, a notification to all the devices from the supported group is being sent. If an automatic update is possible, it can be updated fully automatic. In most cases it is highly recommended to update intellectual controllers of the facility remotely one by one or in a groups. Once a new firmware for the microcontroller is uploaded to allocated memory the process of self-flashing is being performed. After the first run, a microcontroller can access the web-server to check if the process was correct.

Once all the design construction and equipment requirements of the intelligent controller were formed, it was decided to manufacture the housing using the standardized panels. This design is promising, despite the fact that it has not been previously used in electronic equipment, computing devices and other areas of instrumentation. This approach makes it possible to fabricate a wide range of shapes from a variety of sheet materials with the required thickness by combining various panels. It does not require complex equipment for

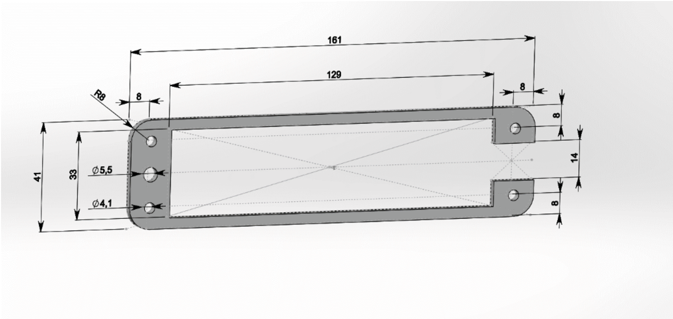


Fig. 4. A 3D-model of housing standard part

Fig. 5. A photo of intelligent controller in work

processing. In the production of simple-shaped cases, it is also possible to achieve the unification of most of the standardized panels. It is cheaper and sometimes faster comparing to additive technologies. So, in the process of developing the case, 13 standard panels were obtained, 10 and 3 of which, respectively, are unified (Figure 4). Assembly of this type of housing can be carried out on an adhesive fixed joint, as well as a collapsible joint by means of standard fasteners. It is also worth mentioning that the assembly of such a product can be carried out without and post-processing or fitting.

The design of the body was carried out in CAD systems SolidWorks 2017 and KOMPAS-3D v17. A wide variety of CAD systems are available on the market, each of which has its own characteristics. In addition to the above, AutoCAD, CATIA, NX, SolidEdge and others are the most popular.

As for the main material for the housing, a foamed PVC sheet material is selected, the processing of which is carried out on a CNC milling machine. The front and back of the device are made of darkened acrylic with a transmittance of 15%, the processing of which was carried out on a laser cutting machine. A material can differ depending on size and shape of smart controller (Figure 5).

Before proceeding to the operation of the device in real conditions, it is necessary to conduct a series of tests in simulated conditions. It was decided to create a special testing device that connects to the controller and by sending test data verifies all the functions in order to check it's sustainability. The test device is a copy of the prototype being developed. NodeMCU ESP8266, using RS485 module responds for data transfer using Modbus TCP. It is important to test the whole system before implementing it to the manufacturing processes.

In case of intellectual controller tests considered:

- The overall stability of the device;
- Modbus data correctness;
- Stability of the device's connection to the Wi-Fi network;
- Stable connectivity Wi-Fi range;
- Latency in receiving information from the server;
- Matrix display information accuracy;
- Light intensity dimming stability;
- Wear resistance of the body.

V. Discussion

During the work, the process of developing an intelligent controller was described in detail taking into account all the relevant protocols and interfaces that are actively used at the moment in modern automated enterprises. Thus, the devices developed according to this methodology are able to have a high level of backward compatibility with equipment of previous generations. This allows enterprises to significantly decrease expenses from the purchase of the most advanced equipment in order to connect it to existing solutions.

An open-source approach described in this work allows small enterprises that do not have their own research, development and implementation bureaus that maintain local digital transformation and automation system processes, to obtain a significant increase in the level of automation at the lowest cost, thereby reducing production costs and obtaining high information redundancy.

Based on the results of the work, an intelligent controller was developed that takes on the function of an intermediate link between equipment and cloud services, and is able to make independent decisions depending on the dynamically changing situation in the production according to the Edge Computing approach, which is necessary for enterprises with a high level of speed and reliability requirements with a large number of sensors, actuators and connected to the industrial network equipment.

It is also suggested that intellectual controllers can include other functions such as a voice assistant module [20]. Due to high noise pollution in manufacturing, it is mandatory to increase the number of intellectual nodes. Since the amount of IoT-connected devices and equipment is growing, the amount of smart controllers according to the Edge Computing approach would also increase and allow us to obtain a higher quality of individual speech recognition (Figure 6). Implementing a camera module can also help in providing more data needed for computer vision analysis.

In case of using Bluetooth Low Energy (BLE) interface, such smart controllers are able to act as a gateway for wearable devices that can help keeping track of labor physical and psychological conditions. The collected information can then be processed in terms of the dynamic ergonomics system.

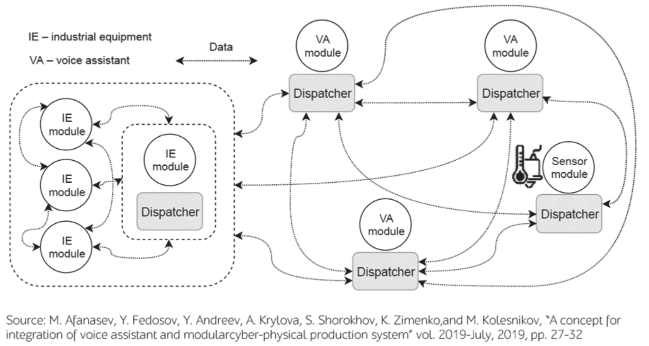


Fig. 6. General architecture of the CPPS with the voice assistant modules

Such system forms up a flexible work schedule and proactively impact on labors physical and psychological condition in the process of work to achieve their maximum effectiveness. It can also be used for indoor positioning using the RSSI of the signal from wearable devices and can prevent accidents (Figure 7).

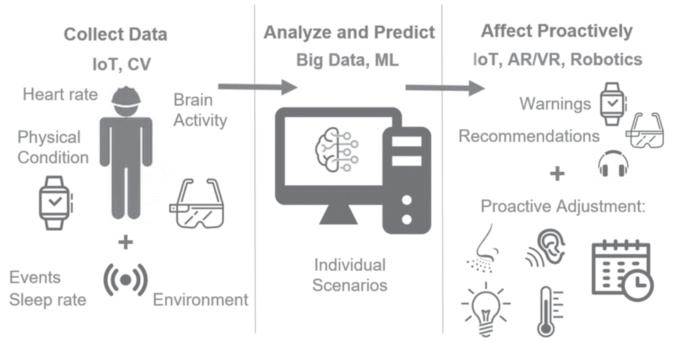


Fig. 7. A structure of the dynamic ergonomics system

Using smart controllers with any wireless network interface, such as Wi-Fi, ZigBee or LoRaWAN can offer building up of a mesh network that increases the coverage of industrial mesh network, reduces latency and additional expenses from the need to install additional nodes specifically for mesh networking. Another thing to mention is that a new approach of housing elements was announced. Such approach allows using sheet materials as a blank material for housing elements that can be easily machined using CNC equipment. This approach allows us to achieve unification in the manufacture of parts of hull products and significantly simplify the configuration of homogeneous devices. In addition, it allows using any sheet materials that can be machined on standard CNC equipment. This significantly speeds up and reduces the cost of the prototyping process in comparison with the use of additive technologies.

VI. Conclusion

As a result of this work, a study out on the concepts of the IoT and the IIoT has been performed. The actual methods and technologies used in the context of the IIoT in modern enterprises and the requirements for the up-to-date devices of the IIoT were formulated. A smart controller for the IIoT was developed and can be used on manufactures. An important thing to note is that the methodology for developing devices for the IIoT is described in detail. In addition, a technology of using standardized panels for electronics housing was described.

At the moment this smart controller is planned to be used in future modular cyber-physical production systems in terms of research work [21].

The use of the developed device at the moment makes it possible to interact with standard equipment that only supports used in project interfaces, which is associated with the restriction of the use of a special type of ports and certain standards. In the future, it is possible to improve the device by adding the use of other standards and increasing the number of ports used. This will make the device more flexible, for example, with respect to aging equipment.

All the collected data can then be used to analyze processes occurring in production using Machine Learning technologies, which, in turn, can be used to optimize production according to various criteria and form up scenarios of automation that smart controller can be responsible for as a field device.

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