Modular hardware platform for the development of IoT devices implemented using multi-chip packaging technology

D A Kirienko¹, P V Lunkov¹, V V Putrolaynen¹, S I Aryanov² and M A Belyaev¹

¹Institute of Physics and Technology, Petrozavodsk State University, 33 Lenin pr., 185910, Petrozavodsk, Russia
²Scientific Research Institute of System Analysis, Russian Academy of Sciences, 36 Nahimovskiy pr., 117218, Moscow, Russia

E-mail: biomax89@yandex.ru

Abstract. The paper presents the concept of a modular hardware platform for the development of IoT devices using the example of a system for collecting and analyzing information. Design variants of modules that implement the basic functions of IoT devices are presented: obtaining primary data and their preliminary processing, data aggregation and transmission, data analysis and storage of results. The technologies of multi-chip packaging and three-dimensional integration are presented, which can significantly reduce the size of the developed modules.

1. Introduction

Currently, the concept of a computer network that combines a large number of “smart” devices interacting with each other and is called the Internet of things (IoT) has drawn the great attention of researchers [1]. This concept involves the use of various wired (Ethernet, USB, RS-485, etc.) and wireless (Wi-Fi, Bluetooth, Zigbee, etc.) data transmission standards [1–4] for the exchange of information between devices without human intervention. In addition, IoT combines such areas of IT technologies as cloud [5] and fog [6] computing, machine learning [7], multi-parameter data analysis [8], fuzzy logic [9], etc. Such a distributed computing environment can be used for automation of household tasks (smart home, caring for elderly people, people with disabilities, pets) [10], medical diagnostics [11], monitoring of transport infrastructure [12], production automation [2, 13], equipment maintenance [14], etc.

Such a variety of technologies and applications is the reason for a large number of studies in the field of IoT, the number of which has been growing rapidly since 2010 [15]. This, in turn, led to the fact that both individual devices and entire ecosystems of devices which are combined using interaction tools unified within this ecosystem began to appear on the market [16]. It is worth noting that despite the large number of different hardware platforms of IoT devices [17], they have similar functionality: receiving information from the external environment, transmitting it through various protocols, analyzing the information received and storing the results of work. It is also worth noting that not all IoT devices use all the indicated functionality, therefore, when developing a universal hardware platform for such devices, it must be guided by the modular approach to designing the system. This approach allows one to arbitrarily configure the device by adding or modifying individual modules.
Another requirement for IoT devices is the need for miniaturization and reduction of power consumption, which can be achieved using multi-chip packaging technology and three-dimensional integration, such as Multi-Chip Package (MCP) [18] and Package-on-Package (PoP) [19]. Such technologies enable three-dimensional integration of both individual crystals (MCP) and packaged microcircuits (PoP). In addition to a significant reduction in the used space on the printed circuit board, the module can have improved characteristics in terms of throughput and power consumption by reducing the length of interconnects between pads.

This paper describes the concept of a modular hardware platform for developing IoT devices using an example of a system for collecting and analyzing information. The work presents the functional diagrams of the developed system and individual modules. Also the technologies for manufacturing individual modules using multi-chip packaging technology and three-dimensional integration are presented.

2. Systems architecture
A modular system for collecting and analyzing information consists of the following components: control computing module (CCM), tensor computing module (TCM), data storage module (DSM), data transfer modules (DTM), sensor computing modules (SCM), backplane, Wi-Fi access point.

Figure 1 shows the functional diagram of the developed system.

![Functional diagram of a modular system for collecting and analyzing information](image)

**Figure 1.** Functional diagram of a modular system for collecting and analyzing information.

The CCM, TCM, DSM, DTM modules are designed for placement on the backplane, which organizes the communication of the modules with each other and aggregates the transmitted data. SCM modules can be of two types (1 and 2) depending on the activity rate of the measured quantity, the accuracy of digitization, and the algorithmic complexity of the initial processing of the initial data received from the sensors. In addition to these modules, the backplane also has a switch, which uses the Microchip KSZ9477S and is designed to organize a local area network for SCM and connect a Wi-Fi access point. Power-over-Ethernet (PoE) technology is used to power the SCM Type 1, for which a PoE injector (Befact PSE-QD) is located on the backplane. There is also an inertial sensor with 9 degrees of freedom (LSM9DS1) on the backplane, combining a three-axis accelerometer, gyroscope...
and magnetometer. This sensor is necessary for monitoring the state of the backplane itself, the operation of which can be affected by electromagnetic fields, vibration, shock loads.

The presented concept is based on 4 levels of organization: the level of receiving initial data from sensors, the level of initial processing of initial data, the level of transmission of processed data and the level of data analysis. The first level is represented by sensors of various physical quantities (linear acceleration, angular velocity, temperature, voltage, current, etc.), sound and video recording devices. They allow one to obtain primary data, which will be subjected to further processing and analysis. Sensors located directly on the SCM board transmit the signal via digital interfaces (SPI or I2C), and external sensors provide data in analog, discrete or digital form and are connected to specialized SCM inputs. In addition, initial data can be obtained using a sensor on the backplane or from external sources of information through network sharing.

The second level of the modular system is related to the pre-processing of data received from sensors. This function is implemented by SCM modules, which could be of two types depending on the activity rate of the measured quantity, the accuracy of its digitization and the need for complex mathematical operations to process the received data. SCM type 1 can work with high-speed sensors, the data of which must be digitized with high accuracy and processed using complex mathematical operations (for instance, Fourier Transform). Therefore, when developing this module, it is supposed to use a high-performance microprocessor 1890VM108, which controls an external ADC with a resolution of 24 bits (ADS127L01) using the SPI protocol. Functional diagram of the device is shown in Figure 2a. As a preamplifier and a digital filter, the LTC1564 chip is used. The module is powered by PoE, for which the board has a PoE splitter (Befact SPD-50) and a DC-DC voltage converter ADP5054. A controlled voltage converter for powering the sensor is selected based on its technical characteristics. To receive commands and transmit processed data, Ethernet is used with a transmission rate of 1 Gbit/s, which is implemented by the Marvell 88E1512 chip. Multiple Type 1 SCMs can be connected through a switch on the backplane.

SCM type 2 can be designed to work with sensors of narrowband signals with a small dynamic range, which require simple mathematical operations (for example, averaging the measured values over time). In this regard, this module uses a less efficient STM32F030 microprocessor with a built-in 12-bit ADC. Functional diagram of the device is shown in Figure 2b. The module is powered by a DTM power line (12 V) and a DC-DC voltage converter. To receive commands and transmit processed data via the RS-485 interface, the SN65HVD78 chip is used. The module has several inputs

Figure 2. Functional diagrams of SCM type 1 (a) and type 2 (b).
for sensors of various types having an analog or discrete signal. Between the outputs of the sensors and the inputs of the ADC, a matching circuit on discrete elements is used. The discrete signal is given to the digital interface of the microcontroller via optocouplers. Also on the board is a three-axis acceleration and angular velocity sensor, implemented by the LSM6DSO chip. The interaction between this sensor and the microprocessor is carried out using the SPI protocol.

The third level of the modular system manages the data transfer between individual modules and between the system and external devices. On the backplane, these functions are performed by the switch, which aggregates the data received from SCM and is used for network communication with external devices using a Wi-Fi access point. Furthermore, network exchange using an Ethernet connection can be carried out directly by the CCM module. In addition, a DTM is used to transmit the data stream from SCM type 2. The functional diagram of the DTM is shown in Figure 3a. For communication with SCM on the RS-485 interface, the SN65HVD78 chip is used. In total, up to 4 SCM modules can be connected. Aggregation of data, their reception and transmission are carried out by the microprocessor STM32H745IIK6. In addition, the module has the ability to connect sensors via the Bluetooth wireless protocol, for which the NRF52832 chip is used. The module is powered by a power line from the backplane and voltage converter, which is also used to power the SCM.

The last level analyzes and stores data and is represented by 3 modules that are located on the backplane: CCM, TCM and DSM. The CCM module is the main controller of the modular system, the prototype of which is an 1890VM108 microprocessor, integrated with RAM and flash memory. Its functions include controlling the selection of SCM data, fulfilling requests for processing data using TCM, sending the results of data analysis to DSM and presenting the results to external devices through network exchange. Unix/Linux operating systems can be used as system software. This microprocessor is also used in SCM type 1 and is produced using the three-dimensional packaging technology - PoP. In addition to the microprocessor die, CCM contains random access (DDR) and flash (NAND and NOR) memory dies. CCM packaging technology will be described in the next section.

The DSM module has the mSATA-mini form factor and consists of a Phison PS3111-S11 memory controller and two 128 GB NAND memory chips that exchange data via the Toggle protocol (Figure 3b). Furthermore, the DSM includes a DC-DC voltage converter, which is used for power supply. The main function of the module is to record, read and store analysis results that come from CCM. Memory microcircuits are manufactured using the technology of three-dimensional multi-chip packaging (MCP), which is described in the next section.
The main functions of TCM are to accelerate the mathematical operations (matrix multiplication) required for data analysis using artificial neural networks. The prototype of the TCM module is an 1890VM118 microcircuit with a tensor coprocessor and a PCI-E interface for connecting to CCM. This interface is used for transmitting commands and data for processing from CCP and processed results from TCM. TCM has interfaces for connecting DDR-memory, which stores processing parameters, source data and intermediate results. The neural network calculation algorithm can be stored in the NAND memory connected to the TCM.

3. The multi-chip packaging technology
This chapter presents the MCP and PoP multi-chip packaging technologies that are used to make DSM and CCP, respectively. The use of such technologies makes it possible to achieve miniaturization of modules, reduce power consumption and improve speed characteristics by reducing the length of interconnections. All these factors are important for IoT devices.

MCP technology is an integration of microcircuits at the package level, in which dice are placed in a stack one above the other. This integration method is most widely used for memory dice, since capacious memory chips occupy a large area and have a small number of pads. The most popular arrangement of NAND memory dice is the “ladder” (Figure 4a), which consists of dice shifted by a certain fixed distance from each other. This shift is necessary for arranging interconnections using thermosonic bonding. For mounting dice, an adhesive film (Die Attach Film, DAF) is used. The MCP packaging process consists of the following steps: thinning a NAND-memory silicon wafer, mounting a thinned wafer onto a frame with adhesive film, cutting the wafer into individual dice, mounting the dice onto a multiplicated chip substrate in the form of a ladder structure, making interconnections between pads of dice and microcircuit substrates using wire-bonding, sealing microcircuits with the mold compound, forming solder balls on the bottom side of the substrate, cutting the multiplicated substrate into separate microcircuits, testing and marking of the obtained microcircuits. In the manufacture of NAND memory chips for the DSM module, a dual-die configuration will be used (Figure 4a) based on Toshiba three-dimensional multi-layer BiCS3 memory.

PoP technology is a three-dimensional integration of two circuits that are connected to each other using soldering balls. Typically, this packaging method is used to integrate a processor that has many I/O lines and is located at the lower level, and memory that requires fewer I/O lines and is located at
the upper level. The layout of the CCM is shown in Figure 4b. For the manufacture of dice, standard procedures for thinning plates and their cutting are used. At the upper level, dice of NAND- (2), NOR- (3) and DDR-memory (4) manufactured by Winbond are mounted face up on the substrate of the microcircuit (1) using liquid adhesive. Then, using wire-wrapping, the contact pads on the dice (2-4) and the substrate (1) are connected. After that, the microcircuit is sealed using a mold compound. On the bottom side of the substrate (1), there are contact pads on which an array of soldering balls is formed. This array has response contact pads on the upper side of the substrate (5) of the lower microcircuit. In the center of the substrate (5) there is free space for mounting the 1890VM108 microprocessor chip (6) using Flip-Chip technology. Miniature soldering balls are formed on the contacts of the microprocessor dice (6) at the manufacturing stage, for which there are response contact pads on the chip substrate (5). Thus, the installation of the microprocessor dice consists in the operation of applying flux to the contact pads of the substrate, installing the die and melting the soldering balls in the furnace. After that, an underfill is poured into the space between the die and the substrate to minimize mechanical stresses in the die when the temperature of the microcircuit changes. The bottom chip is not sealed in order to have access to the pads on the upper side of the substrate.

The final stage of assembly is the soldering of two microcircuits in the furnace, and sealing the gap between the microcircuits with underfill material. It is worth noting that the height of the microprocessor chip is selected in accordance with the dimensions of the soldering balls to connect the two microcircuits. If the die height is too large, then the balls during reflow will not moisten the contact pads on the substrate of the lower microcircuit. Moreover, for correct assembly, the melting point of the solder for mounting the microprocessor chip must be higher than the melting point of the solder for connecting the microcircuits. Otherwise, during microcircuit soldering, the die may be displaced with the formation of unnecessary short-circuited connections between nearby contacts.

MCP and PoP technologies can significantly reduce the linear dimensions (almost 2 times) due to three-dimensional vertical integration, as well as reduce the length of the conductors between the memory chips and the processor. The presented multi-chip packaging technologies will be implemented at GS Nanotech company, which has all the necessary infrastructure and equipment.

4. Conclusions
In this paper, the concept of a modular hardware platform for the development of IoT devices using the example of a system for collecting and analyzing information was introduced. The presented system consists of modules that provide the following functionality: receiving primary values from sensors and their initial processing (SCM types 1 and 2), aggregation and data transmission (DTM), analysis of received information (CCM) including the use of artificial hardware acceleration neural network (TCM), storage of intermediate data and analysis results (DSM). These modules are finished products that can be used to design IoT devices in various configurations depending on the application. The developed modules use standardized interfaces and data transfer protocols, thereby they can be used in conjunction with third-party IoT devices. Moreover, this paper describes the technology of multi-chip packaging and three-dimensional integration: MCP and PoP. NAND-memory chips (as part of DSM) are packed using MCP technology, and the CCP module is manufactured using PoP technology. In the future, the possibility of three-dimensional multi-chip integration of TCM and DTM modules will be considered.

Acknowledgement
This research is financially supported by the Ministry of Science and Higher Education of Russia within project no. 075-11-2019-088.

References
[1] Madakam S, Ramaswamy R and Tripathi S 2015 Internet of Things (IoT): A Literature Review J. Comput. Commun. 3 164–73
[2] Rúbio E M, Dionisio R P and Torres P M B 2019 Industrial IoT devices and cyber-physical
production systems: Review and use case Lecture Notes in Electrical Engineering 505 292–98

[3] Guoqiang S, Yanning C, Chao Z and Yanxu Z 2013 Design and implementation of a smart IoT gateway Proceedings - 2013 IEEE Intern.Conf. on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing, GreenCom-IThings-CPCom 2013 pp 720–23

[4] Krejčí R, Hujňák O and Švepeš M 2018 Security survey of the IoT wireless protocols 2017 25th Telecommunications Forum, TELFOR 2017 2017 1–4

[5] Botta A, De Donato W, Persico V and Pescapé A 2016 Integration of Cloud computing and Internet of Things: A survey Futur. Gener. Comput. Syst. 56 684–700

[6] Mahmud R, Kotagiri R and Buyya R 2018 Fog Computing: A Taxonomy, Survey and Future Directions Internet of Everything (Springer, Singapore) pp 103–30

[7] Mohammadi M, Al-Fuqaha A, Sorour S and Guizani M 2018 Deep learning for IoT big data and streaming analytics: A survey IEEE Commun. Surv. Tutorials 20 2923–60

[8] Ateeq M, Ishmanov F, Afzal M and Naem M 2019 Multi-Parametric Analysis of Reliability and Energy Consumption in IoT: A Deep Learning Approach Sensors 19 309

[9] Meana-Llorián D, González García C, Pelayo G-Bustelo B C, Cueva Lovelle J M and Garcia-Fernandez N 2017 IoFClim: The fuzzy logic and the Internet of Things to control indoor temperature regarding the outdoor ambient conditions Futur. Gener. Comput. Syst. 76 275–84

[10] Alaa M, Zaidan A A, Zaidan B B, Talal M and Kiah M L M 2017 A review of smart home applications based on Internet of Things J. Netw. Comput. Appl. 97 48–65

[11] Farahani B, Firouzi F, Chang V, Badaroglu M, Constant N and Mankodiya K 2018 Towards fog-driven IoT eHealth: Promises and challenges of IoT in medicine and healthcare Futur. Gener. Comput. Syst. 78 659–76

[12] Al-Dweik A, Muresan R, Mayhew M and Lieberman M 2017 IoT-based multifunctional Scalable real-time Enhanced Road Side Unit for Intelligent Transportation Systems Canadian Conf. on Electrical and Computer Engineering

[13] Wollschaeger M, Sauter T and Jasperneite J 2017 The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0 IEEE Ind. Electron. Mag. 11 17–27

[14] Civerchia F, Bocchino S, Salvadori C, Rossi E, Maggiani L and Petracca M 2017 Industrial Internet of Things monitoring solution for advanced predictive maintenance applications J. Ind. Inf. Integr. 7 4–12

[15] Dachyar M, Zagloel T Y M and Saragih L R 2019 Knowledge growth and development: internet of things (IoT) research, 2006–2018 Heiljson 5 e02264

[16] Mazhelis O, Luoma E and Warma H 2012 Defining an Internet-of-Things ecosystem International Conference on Next Generation Wired/Wireless Networking 7469 LNCS (St. Petersburg, Russia: Springer, Berlin) 1–14

[17] Singh K J and Kapoor D S 2017 Create Your Own Internet of Things: A survey of IoT platforms. IEEE Consum. Electron. Mag. 6 57–68

[18] Greig W J 2007 Integrated circuit packaging, assembly and interconnections (Boston, MA, USA: Springer US)

[19] Yoshida A, Taniguchi J, Murata K, Kada M, Yamamoto Y, Takagi Y, Notomi T and Fujita A 2006 A study on package stacking process for Package-on-Package (PoP) Electronic Components and Technology Conference 2006 825–30