

DEVELOPMENT AND IMPLEMENTATION OF INTEGRATED SOLUTIONS BASED ON IIOT FOR THE INTELLIGENT PACKAGING

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ABSTRACT: The synthesis of mechatronic modules combining heterogeneous physical principles is an urgent task of modern engineering. The study focuses on the development and implementation of integrated solutions based on IIoT to optimize the operation of robotic manipulators intended for product packaging. A methodology for processing data at the level of IIoT endpoints is proposed to minimize the amount of transmitted information and increase the efficiency of the system. To solve the tasks, an unconventional approach was taken, identifying certain methods of mathematical modeling and optimization. Models and simulation methods were developed for processing information on the endpoints of IIoT devices related to packaging equipment, aiming to reduce the amount of data transmitted and stored in IIoT systems. In the paper, based on the research results, a study was conducted on the influences of various parameters on the accuracy of dosing and recommendations were developed for optimizing the process.

KEYWORDS**:** IIoT, packaging, mechatronic module, robotic

1. INTRODUCTION

1.1 *Industry 4.0*, characterised by the widespread use of digital technologies in manufacturing, is opening new horizons for process optimisation and efficiency. This transformation is accompanied by a shift from traditional production systems to intelligent, self-organised and interconnected ones. One of the key elements of this transformation is the Internet of Things (IoT), which connects physical objects into a single network, creating a so-called ‘digital twin’ of the physical world. Within the IoT, a special place is occupied by the Industrial Internet of Things (IIoT), which focuses on the integration of sensors, actuators and other smart devices into industrial systems, allowing for the collection and analysis of large amounts of data on the condition of equipment, production processes and other information in real time. [1, 2]

1.2. *IIoT* not only connects devices but also enables the creation of self-organising systems that can adapt to changes in the environment. Using various communication interfaces, such as Wi-Fi, Bluetooth Low Energy, fieldbus and IO-Link, every element of the production line, from the smallest sensor to complex equipment, can be integrated into a single system. [3]

This provides detailed information on the status of each component, which is critical for proactive maintenance, fault prediction and optimisation of production processes. Of particular interest are mechatronic modules, which are integrated systems that combine mechanical, electronic and software components. Functional mechatronic modules, such as electropneumatic systems, can perform complex tasks, such as dispensing liquid food products with high accuracy and repeatability. Integrating such modules into an IIoT system allows for flexible and adaptive production lines that can be quickly adjusted to produce new products or change production parameters depending on demand [4].

Our research involves a nonconventional approach, focusing on the creation and/or identification of certain mechatronic modules usable in various industries, with detailed references for the food industry. In addition, we will provide an overview of current research in the field of IIoT and prospects for the development of this technology. We will analyse the challenges associated with the implementation of IIoT, such as cybersecurity, standardisation and integration with existing systems of dosing and packaging modules for food production.

We will also consider potential directions for the development of this technology, such as the use of pilot solenoid valves in the structure of a feedback mechatronic module. Based on the analysis of the concept of Industry 4.0 and the Internet of Things, we can identify three relevant scientific tasks:

• Developing effective methods to ensure cybersecurity in distributed IIoT systems that include many interconnected devices. It is necessary to develop comprehensive solutions to protect against cyber-attacks that can lead to production disruptions, data loss and financial losses.

• Creating universal platforms and standards for integrating different production systems and devices into a single information space. This will increase the flexibility and adaptability of production, as well as reduce the cost of developing and implementing new technologies.

• Developing machine learning algorithms to analyse large amounts of data collected in IIoT systems to predict equipment failures, optimise production processes and create intelligent control systems.

Despite their significant potential , Industry 4.0 systems have both advantages and disadvantages. The advantages include increased production efficiency, reduced costs, improved product quality and production flexibility. However, there are also certain disadvantages, such as the high cost of implementation, the need for skilled professionals, cybersecurity risks, and the complexity of integration with existing systems [5]. One of the most promising areas of development is the use of pilot solenoid valves in the structure of a feedback mechatronic module to improve the accuracy and speed of dosing systems. This will enable the creation of more flexible and adaptive process control systems [6].

1.3. *Description of the generalised mechatronic system of the IIOT*

In general, a cyber-physical system is a computer system that can continuously interact with the physical system in which it operates. In Fig. 1. An example of the structure of a production module with IOT elements is shown.

The diagram shows the basic principle of data transmission in the *Industry 4.0* system, where the physical world (mechatronics) is closely integrated with the digital world (digital twin) [7, 8]. The lower level contains physical components, such as pneumatics and electricity, which directly interact with the real world. Sensors installed at this level collect data on various parameters (pressure, temperature, current, etc.) [9].

This data is transferred to the data processing layer, where it is initially processed and prepared for further analysis. The resulting data is transferred to the cloud, where it is stored and processed using big data and physical modelling tools. Based on this data, analytical systems generate valuable information about the condition of equipment, production efficiency and other key indicators. This information is visualised on dashboards that are available to users for decision-making. The digital twin, which contains a virtual model of a physical object, allows simulating various scenarios and optimising production processes [10, 11.

Thanks to the feedback between the digital and physical worlds, the system can self-learn and adapt to changes in the production environment. This cycle of data collection, processing, and use ensures continuous improvement of production processes and the efficiency of technological equipment.

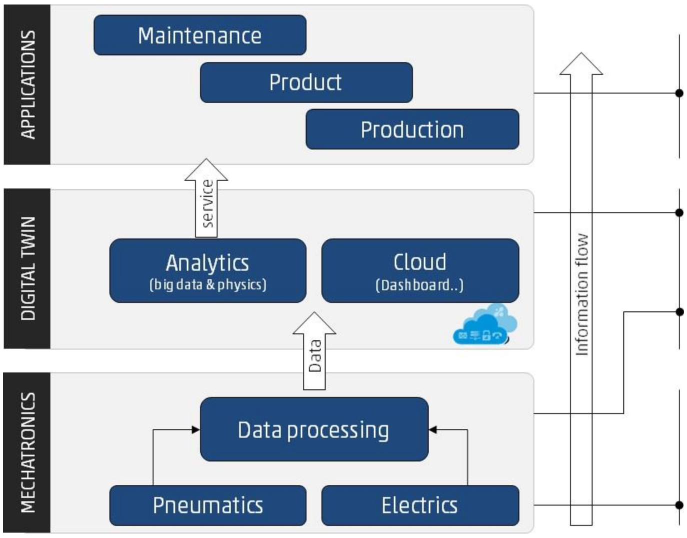

Figure 1. An example of the structure of a production module with IoT

1.4. *Control and measurement systems*

Sensors play a key role in mechatronic modules with IIOT, an example of which is shown in Fig. 2.

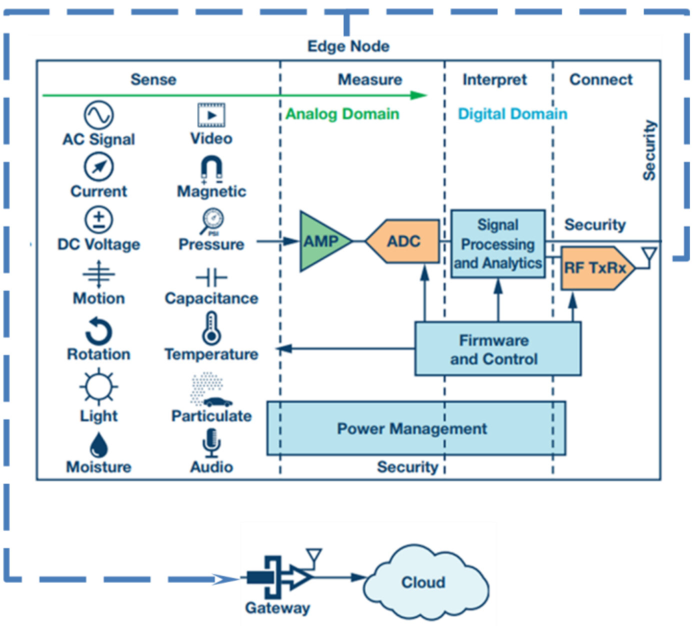

Figure 2. Control and measuring system of the module with IoT

They collect data on a variety of physical quantities (current, voltage, pressure, temperature, etc.), which are then processed and analysed for decision-making. Using analogue-to-digital converters (ADCs), the signals from the sensors are converted into digital form, which allows them to be processed on microcontrollers or special processors [12, 13].

The data obtained can be transferred to a higher level for further analysis or used to control actuators in real time. This ensures high measurement accuracy, system reliability and the ability to adapt to changing environmental conditions [14].

2. ACTUATOR WITH DISCRETE VALVES IN THE STRUCTURE OF THE MECHANICAL MODULE

2.1. A feature of the control systems for the tracking electropneumatic drive of the dosing and packaging module with discrete pneumatic valves is their nonlinearity caused by the discrete nature of the valve operation (Fig. 3).

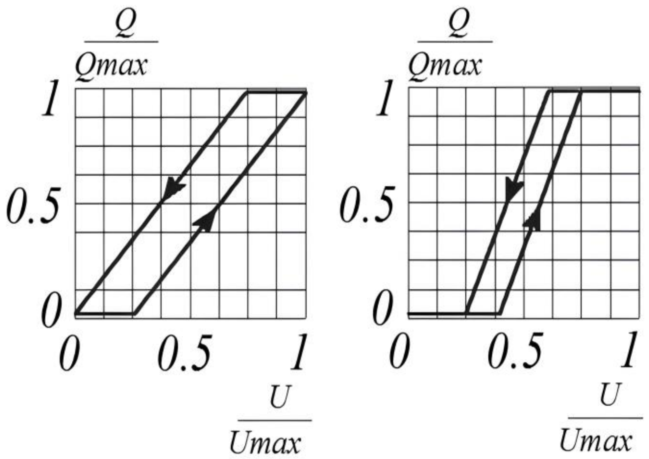

Figure 3. Characteristics of valve dead zones

Most discrete valves exhibit nonlinearities, such as zones of insensitivity at the beginning of the characteristic, saturation at the end, hysteresis (Figure 3 left), and a combination of these (Figure 3 right). The valves operate in a relay mode.

This leads to the sampling of control signals and, accordingly, to the discrete nature of the entire control loop. However, the use of the pulse width modulation (PWM) method allows for partial linearisation of the discrete valve response, namely, to ensure that the compressed air flow rate is proportional to the pulse width of the control signal.

The choice of a sufficiently high PWM frequency allows achieving almost smooth control, which brings the characteristic of the discrete valve closer to the compressed air flow rate as a function of the control signal value.

The presence of a linear section on this characteristic is a prerequisite for the selective use of PWM control.

In the case of a nonlinear characteristic, it may be necessary to introduce additional analogy characteristics.

Another important aspect is the nonlinearity of the static characteristic of discrete valves, which describes the dependence under study.

2.2. *Pilot valves: study of operation*

The operation of the valve of the dosing and packaging module was studied based on the movement of the plunger in the dc solenoids (Fig. 4).

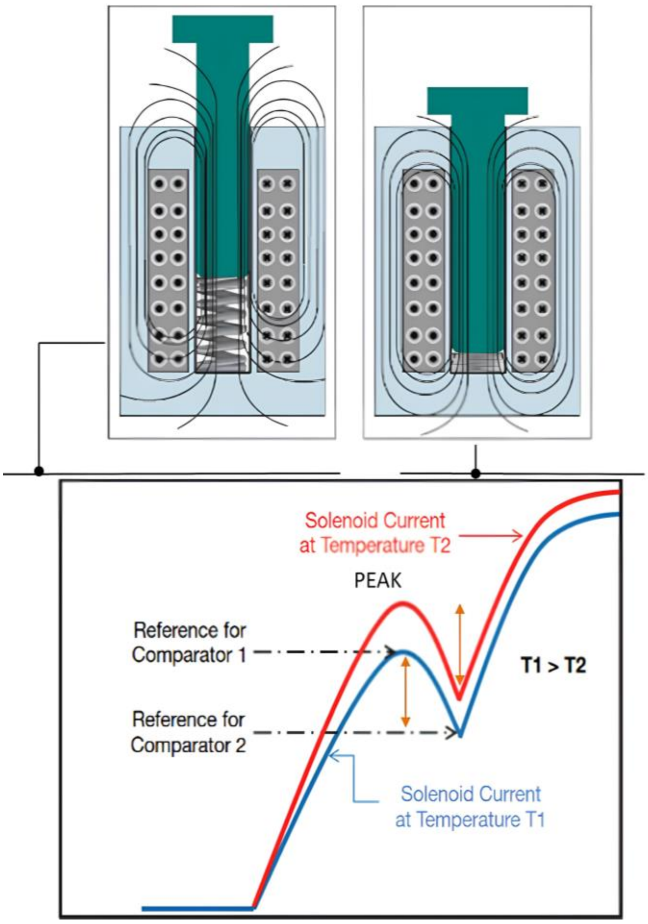

Figure 4. Generalized characteristic of plunger motion in dc-solenoids

The peculiarity of control systems for pneumatic actuators with discrete valves is a significant nonlinearity of their static characteristics, which manifests itself in the form of saturation zones and insensitivity to the control signal at the beginning and end of the range.
The above significantly complicates the use of proportional control methods, in particular, pulse width modulation (PWM), since the linearization of the valve characteristic in a wide range In some cases, when the nonlinearities are excessively pronounced, the use of PWM may be ineffective at all, and it is advisable to use relay control laws that provide for switching the valve between two extreme positions.

Analysing the experimental data (Fig. 5) obtained for Camozzi AP valves, which are widely used in industrial automation, we can observe the presence of zones of insensitivity in the range of 0-20% and saturation in the range of 80-100% of the control signal value. However, there is a significant linear section of the characteristic in the range of 20-80%, which allows us to consider the possibility of using linear control laws and PWM. To improve control accuracy in the stability zones of the system, as well as from the characteristics of the dispenser.

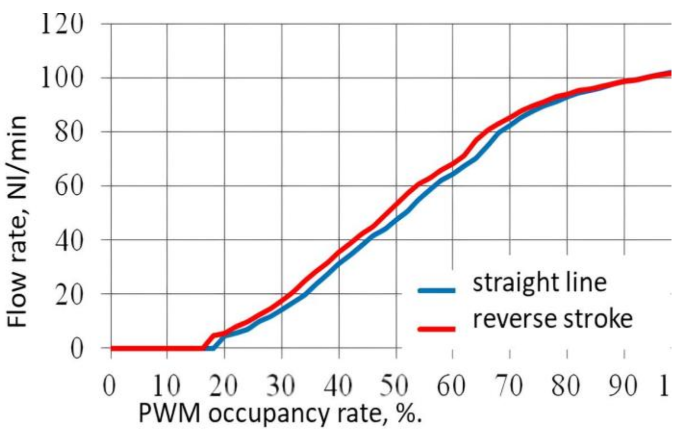

Figure 5. Results of the study of the valve of the dosing mechatronic module

To ensure optimal system performance, a more detailed analysis is required, both statically and dynamically.

In case of nonlinearity, compensation methods can be applied, such as the use of conversion tables or nonlinear elements in the control loop. It is worth noting that the hysteresis value of Camozzi AP valves is relatively small, which simplifies the procedure for identifying and linearizing the characteristic. Thus, the choice of control strategy for pneumatic systems with discrete valves depends on the specific requirements for accuracy, speed, and cost.

3. CONCLUSIONS

To study and optimize the dosing processes in the mechatronic modules of packaging machines, an integrated, modern and unconventional approach was applied. A combination of mathematical modelling, numerical analysis and experimental studies was carried out.

To create an adequate mathematical model of the process of dispensing liquid products, a system of differential equations was developed that describes the change in the kinematic parameters of the liquid in the dispenser channels, considering the influence of programmed airlift dosing modes and the geometry of the product pipeline. To verify the developed model, an experimental bench was created to study the functional characteristics of the mechatronic dosing module in various operating modes. Based on the experimental data obtained, the model was parametrically identified, and its adequacy was evaluated.

To improve the efficiency of dosing process control, digital twins of mechatronic modules were developed. A digital twin is a virtual model of a real object that allows simulating various operating scenarios, assessing the impact of various factors on process results, and optimizing control system parameters [15]. Siemens Simatic S7-1200 software was used to create the digital twin, which made it possible to integrate the model into the production automation system. The developed web interface provides convenient access to data on the system status and allows the operator to monitor the dosing process in real time and make the necessary adjustments.

Based on the results of the research, the influence of various parameters on the dosing accuracy was determined and recommendations for process optimization were developed. It was found that, to ensure the required dosing accuracy, it is important to choose the right parameters of the control system and optimize the geometry of the product pipeline.

It can also be concluded that the developed mathematical models and digital twins can significantly reduce the time and costs for the development and implementation of new dosing technologies, as well as increase the efficiency of production processes.

The innovative methodology presented in the paper is significant, with the help of which the excellent utility of integrated solutions based on industrial internet things for optimizing technological variants of intelligent packaging of industrial products is demonstrated once again.

The initially set goal of making a significant contribution to the expansion of intelligent packaging of food products, through the development and implementation of integrated solutions based on IIoT, is considered achieved.

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