AUTOMATION AND CONTROL IN INDUSTRY

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Keywords: *Service-Oriented Architecture (SOA), platform one4all, information system*

Daniel GĄSKA*, Antoni ŚWIĆ **

POSSIBILITIES OF USING PLATFORM ONE4ALL IN IMPLEMENTING COMPUTER SOLUTIONS IN SERVICE ORIENTED ARCHITECTURE

Abstract:

The paper presents the foundations of building the systems of Service Oriented Architecture, SOA, their conception and influence on functioning of the whole enterprise. The newly presented platform one4all uses several computer products implementing as services for realization of the basic/fundamental business processes, communication and workflow management, project management, or the analysis of business activities.

1. INTRODUCTION

What is Service Oriented Architecture, SOA? There are many different answers to this question:

"Service-oriented architecture (SOA) is an emerging architectural style that helps meet several demands. SOA projects designed to quickly and iteratively deliver on business goals are referred to as a "real-world" approach to service orientation [5]"

"Based on that we can define Service Oriented Architecture as an architectural style for building systems based on interacting coarse grained autonomous components called services. Each service expose processes and behavior through contracts, which are composed of messages at discoverable addresses called endpoints. Services' behavior is governed by policies which are set externally to the service itself."

Creating systems based on the model of service oriented architecture has become a widely applied practice thanks to which it is possible to create computer solutions for enterprises which are characterized by the higher elasticity and expandable architecture.

Companies implementing computer solutions strongly emphasize close cooperation with business partners which leads to creating complex structures with many applications communicating in order to exchange information between them.

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To prevent the negative outcomes of the integration of many applications which should cooperate during the exchange of information, the enterprise should develop and integrate two main areas: business applications and the environment in which they work. Business applications are the services created or bought which can be applied directly to various functions of business organizations. On the other hand, the working environment is a set of services realized by the computer infrastructure which are used by business applications [3].

Thanks to implementing the philosophy of SOA, the enterprise can become fit and the services which we initiate in the enterprise lead to the introduction of the general government.

2. THE CONCEPT OF SOA - ASSUMPTIONS

Service-oriented architecture (SOA) as shown in Fig. 1 is currently the most popular conceptual architecture for the IT industry addressing the problem of business integration. The concept is brought forward by distinct business motivations. Drivers for SOA in the enterprise domain include the tremendous growth of IT applications, the ever-increasing use of IT tools throughout every aspect of each business, and the resulting need to integrate both in a coherent, scalable, and manageable fashion. The trend toward outsourcing noncore competencies, including the outsourcing of IT as a utility, further fuels this movement. In addition, the plethora of mergers and acquisitions, and the significant increase in business-to-business partnerships and supply chain relationships also point to the pressing need to integrate IT tools and business processes. These are significant drivers that can be summarized as continuous business transformation, and these are the drivers that in large part shape the approach required to address this problem space. These drivers lead to an adoption of service middleware based on loosely coupled granular components and message-based communication; they expose only as much or as little of the underlying network capabilities as needed to ensure successful reuse of the components by multiple services [1].

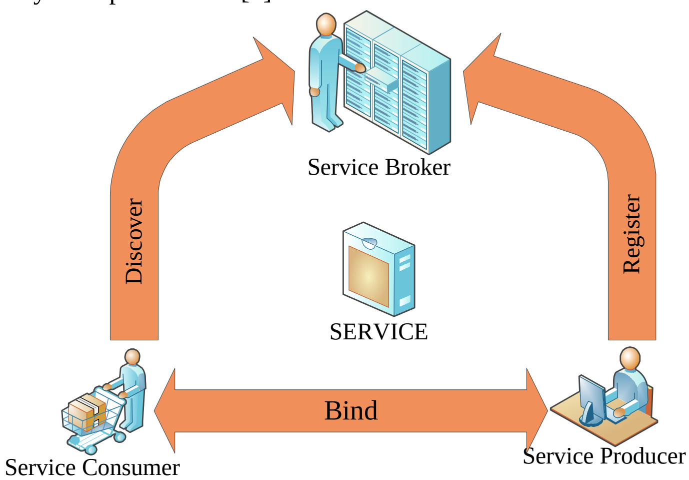

Fig. 1. Basic service-oriented architecture concept

In order to better understand this concept it is necessary to implement of a larger number of components and the relation between the service consumer and service producer, thanks to which SAO becomes easier to understand.

Fig. 2 shows the Service-oriented architecture with more components and more their relations:

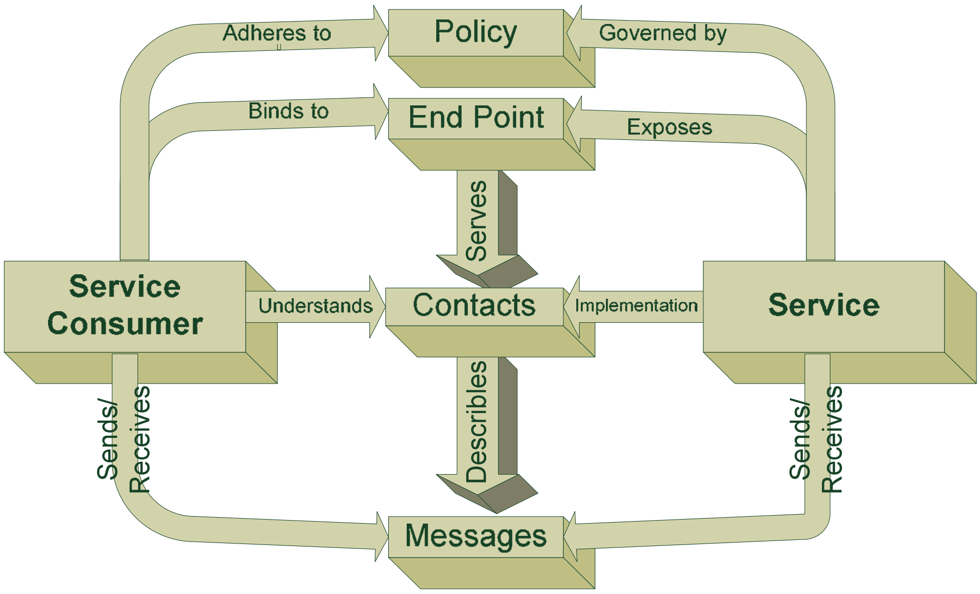

Fig. 2. SOA components and their relations

The components of SOA and the relations among presented in Fig. 2 above define the directions we can take in creating the system.

Services

The central pillar of SOA is the service. We can defines service as "a facility supplying some public demand". A Service should provide a high cohesion and different services. Services should be coarse grained pieces of logic. One of the characteristics of services is service autonomy. Autonomy means the services should be self-sufficient, at least to some extent, healing properties.

Contract

The collection of all the messages supported by the Service is collectively known as the service's contract. The contract can be unilateral, meaning a closed set of messages the service chooses to provide. A contract might also be multilateral or bilateral, that is, between a predefined group of parties. The contract can be considered the interface of the Service akin to interfaces of object in object oriented languages.

End Point

The Endpoint is an address, a URI, a specific place where the service can be found and consumed. A specific contract can be exposed at a specific endpoint.

Message

The unit of communication in SOA is the message. Messages can come in different forms and shapes, for instance, http GET messages (part of the REST style) ,SOAP messages, JMS messages and even SMTP messages are all valid message forms. The differentiator between a message and other forms of communication such as plain RPC, is that messages have both a header and a body. The header is usually more generic and can be understood by infrastructure and framework components without understanding, and consequently coupling to, every message type. The existence of the header allows for infrastructure components to route reply messages (e.g. correlated messages pattern) or handle security better (see Firewall pattern).

Policy

One important differentiator between Object Orientation or Component Orientation and SOA is the existence of policy. If an interface or contract in SOA lingo, separates specification from implementation. Policy separates dynamic specification from static/semantic specification. Policy represents the conditions for the semantic specification availability for service consumers. The unique aspects of policy are that it can be updated in run-time and that it is externalized from the business logic. The Policy specify dynamic properties like security (encryption, authentication, Id etc.) , auditing, SLA etc.

Service Consumer

A service doesn't mean much if there isn't someone/something in the world that uses it. So to complete the SOA picture we need Service Consumers. A service consumer is any software that interacts with a service by exchanging messages with the service. Consumers can be either client applications or other "neighboring" services their only requirement is that they bind to an SOA contract.

Looking at this SOA definition we can see SOA has a lot of emphasis on interface. Starting from the messages which are the parts of the interface, the contract which is the collection of the messages, the endpoint where the contract is delivered and the policy which governs the behavior of the endpoint. Thus SOA has a total of four different components that deal with the interface vs., for example, OO which only has one. The focus on interfaces is what gives SOA the ability to create loose coupling, composable components, reuse and achieve the various design goals. Another nice attribute of this definition is that we can use as a base for both the technical and the business perspectives of SOA as the common elements of both perspective are used in this definition [6].

3. PLATFORM ONE4ALL

Platform one4all uses Microsoft software to integrate computer solutions in an enterprise. Thanks to using XML language to exchange data between applications it is possible to implement the solution of other manufacturers, such as SAP.

Fig. 3. One4all platform and Microsoft Dynamics business management software in SOA architecture

Decision on choosing the strategy of the informatization requires from the organization (both public institution and private) defining the concrete and measurable goals that will assure them a possibility of their future progress and development, obtaining competitive advantage on the market and also increase effectiveness and rapidness of actions.

one4all is a comprehensive solution that can be easily adopted to the need of the both public and private sector. The solution is built based on the proved technology and environment of the Microsoft systems and know-how and experience of the specialists working on its creation and further development. Operational activity of an organization becomes more effective and forecasting of the desired development directions is possible due to the application of the one4all solution.

one4all in the particularly helps to:

– eliminate the “bottle-necks” and integrate business processes and actions
– manage available funds in the most effective way
– simplify complex processes of human resource and payroll management
– improve project management
– ensure safe and efficient communication and exchange of information among the members of the organization
– organize the work in the most effective way
– assure a proper safety and data protection.

The solution one4all integrates such areas of the organization activity (Fig. 4):

– realization of the basic/fundamental business processes
– communication and workflow management
– project management
– an analysis of the business activity

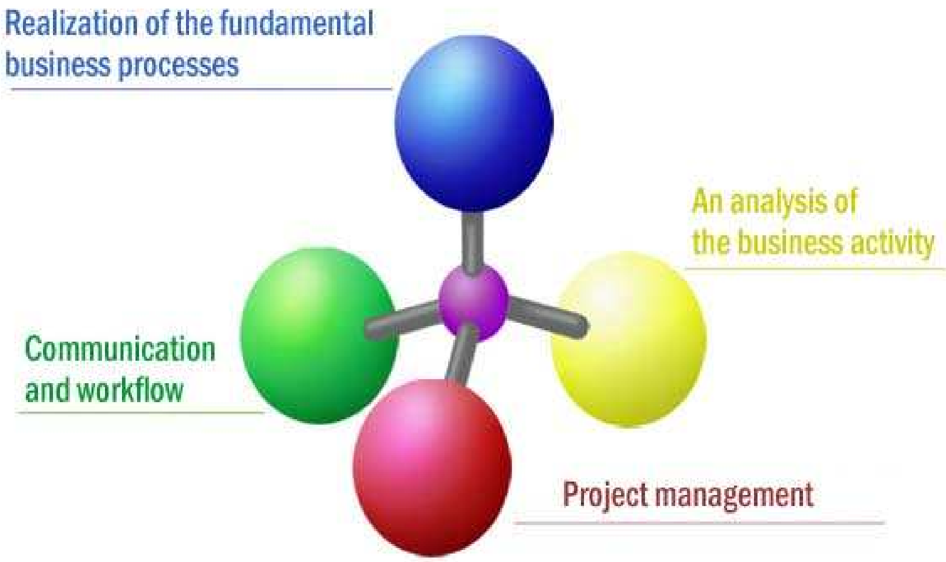

Fig. 4. one4all integrates such areas of the organization activity

Realization of the basic business processes

Area of the realization of the basic business processes is covered by the hand of the ERP class solution to manage organization. This solution makes it possible for the employees and the whole organization to make more optimal business decisions. It contains comprehensive functionalities that automate and improve management of the financial processes, petitioner relations, services for the community, human resources and other. It allows therefore on the integration of processes, technology and employees that can be in the any place in the world. Use of this part of one4all influences then efficiency improvement and overall better functioning the whole organization.

A great example of the processes in this area is a situation in which an institution is assigned with the additional financial means to perform a concrete project. To our institution is sent a letter with such notification. Thanks to the one4all solution within just a few seconds this information is available to all managers who should be informed about this. Also, money is transferred on an account of the institution that on the other hand what has its effect in budget enlargement. Due to the home banking functionality accountant doesn't have manually enter date into the system, only needs to check and book them. So, the work is automated and accelerated and error free.

one4all:

- automates and improves financial processes in each area of functioning the institution
- increases efficiency of the employees
- influences the overall level of the petitioner satisfaction

Communication Management

In today’s' times accessibility, exchange and passing through an information is a key aspect of every institution’s activity. one4all allows managing knowledge database and sharing the documents through the built-in Documents Center which improves the flow of information in the organization. All data is accessible through the internet and intranet portals created to ensure quick, easy and intuitive access to the required information. Information about events is sent to entitled and interested persons automatically. one4all also gives an opportunity for many engaged persons in concrete task to work on one document at the same time. Another plus is an ability to manage the following versions of the same document with a full insight into changes tracking with an option of reviewing and accepting them. Also, in order to: ensure better communication and understanding of the sent information, create better relations between employees and eliminate barrier of distance one4all uses a communication platform that allows voice and vision transmission for the unique chance to have tele- and video conferences.

The situation when a director of an institution receives a letter with a request to prepare an opinion for the superior institution can be a great example of how to use functionality of this area of one4all solution. The letter is scanned and registered in one4all and from that level is sent to director and then he gives order to the managers and they to their employees. At this time an employee receives an alert which means that he was just assign a task; it also gives them the information about the deadline, other people involved in the task and so on.

Employees of the departments located in a considerable distance from each other use internet cameras to communicate. This way they can effectively exchange ideas and information. During work they create working versions of documents about which other member of the team are notified by e-mail and have access to them. The director receives one and final version of the document already accepted by the managers, but in each second can see how the works were performed.

one4all:

- assures the safe access to information with the use of internet and intranet
- causes simplification of procedures concerning the information and documents exchange
- makes team working in various locations more effective
- eliminates or limits the quantity of paper work
- gives a full insight into the history of the versions of the documents

Project Management

In order to more effectively achieve goals and in optimal way use given resources more and more organizations uses a projectile approach towards their activity. Answering such needs one4all makes it possible to manage and run projects. By just one click managers are able to check use of resources, their accessibility in the concrete moment, work progress and deadlines of each task in the schedule. Resources are booked as a result of full automation in the moment of creating the project and participating employees informed about assigned tasks and deadlines of the particular stages of the project. one4all tracks the whole cycle of the life of the project in a quick and easy way, plans expenditures and controls costs.

We can imagine a situation when a director of an institution is asked to deliver a report concerning the progress of works of the project co-financed by the superior institution. In such situation he asks his employees to indicate the stage of the works for which they are responsible for. Employees who can work in various locations after receiving e-mail with such request actualize the stage of their work. After doing that they send a feedback e-mail that is received by the director what gives him knowledge about the current stage of the particular works in the project. Such report in a graphic form shows whether works are done on time, tasks are assigned in optimal way to the employees or changes need to be done. Thanks to the functionality of the project management a director not only can easily make a need report but also in any time react to the dynamically changing situation.

one4all:

- supports planning and using of accessible human, material and other resources
- allows controlling the course of the realization of the particular stages of the project
- allows automatically tracking of the cause- effects linkages between individual tasks
- automatically informs participating human resources about allotments and changes in the project and assures obtainment of the back information about the progresses of works (also through internet)

Reporting and Analyses

It is possible to create measurable and effective reports and analyses due to the fact that one4all uses the information from the areas of the realization of business processes, communication and workflow management and project management. Such personalized and answering to specific needs reports are used by the managers and specialists and support them in decision making processes and forecasting future actions. Managers are able to quickly and wisely react to the changing situation due to the fact that analytical data is accessible in the real time. The solution is very functional and friendly use considering the fact that data is presented both in a graphic and tabular form.

Nowadays, many institutions participate in the distribution of the money coming from the external sources (e.g. grants or the financial means of EU) both as final incumbents and intermediary institutions. It isn’t uncommon that project managers need to prepare wide and very detailed periodical and final reports. In order to do so they need information from various areas and it is often causing many problems. Using one4all all necessary is already gathered in one solution and creating such multidimensional report is done practically at once. As a result of the use of one4all project managers can concentrate on the realization and the maximization of the obtainment of the positive effects and not on details of reporting.

Additionally, the report which in this moment is merely a fulfillment of the formal requirements can serve to yet better planning next projects in the future thanks to it’s

one4all:

- allows making very advanced reports and analyses
- assures access to the information in a real time
- allows making simulations of the various actions, their analysis and predicting results therefore better planning and managing processes in a institution

Using the technologies of Web services, the platform one4all makes it possible for logged-in users to use implemented services in the intranet. Fig. 5 represents the co-operation of the platform with the technology of Web services.

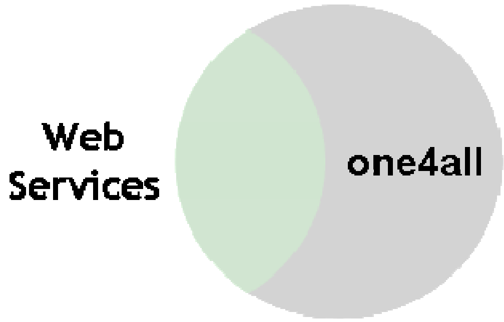

Fig. 5. Web services and one4all field of action

The utilization of services contained in one4all system is possible thanks to using http protocol and an internet browser (Fig. 6).

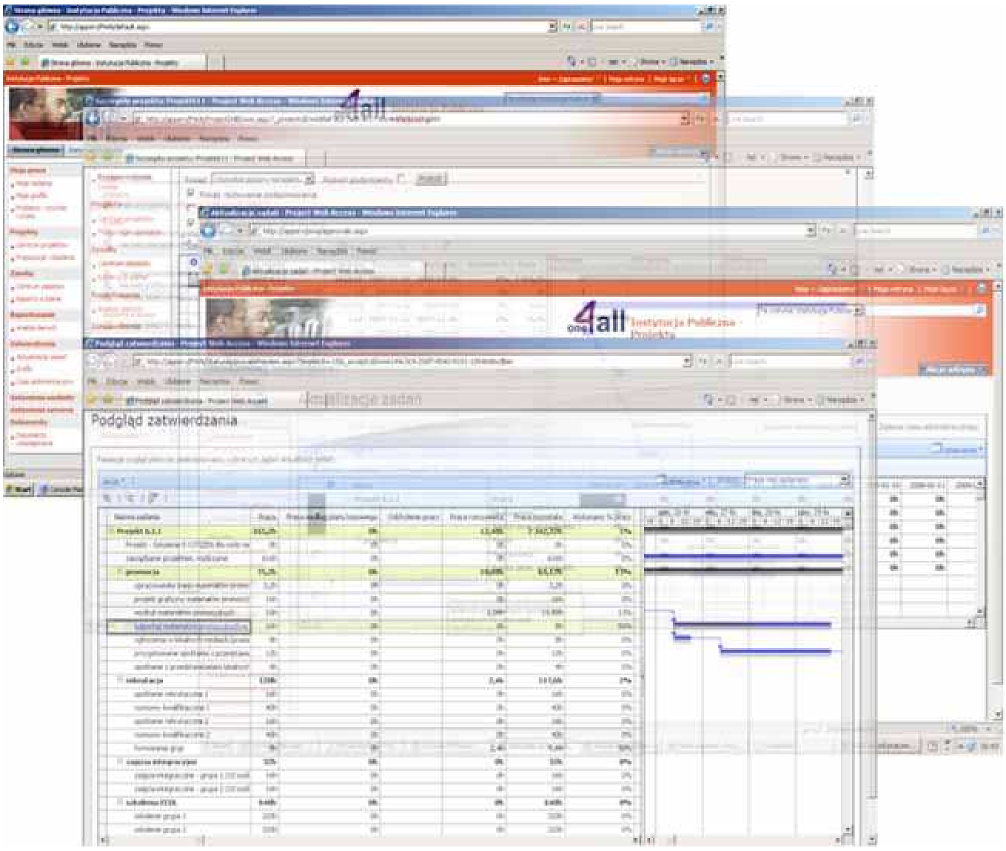

Fig. 6. Platform one4all in internet browser

The area of the realization of basic business processes is done with the help of services realized by the solutions of class ERP (**Enterprise Resource Planning**) which support the management of the organization. This solution enables employees and the whole organization to make optimal business decisions. The complex functionalities which the solution contains automate and improve financial processes, customer relationships management, business services, human resources management and logistic processes (**SCM – Supply Chain Management**), which include the efficiency of transportation (**TMS - Transportation Management System**), the optimization of utilization of the area (**WMS - Warehouse Management System**), selling-buying production processes, and other processes within the organization (Fig. 7,8).

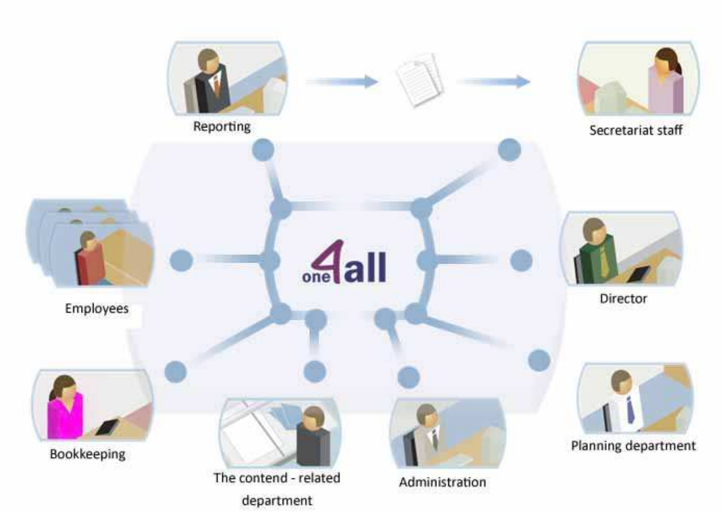

Fig. 7. Description of content-related schedule for the platform one4all

Fig. 8. Description of increase a budget.

4. ENVIRONMENT AND THE COMPONENTS OF SERVICES IN THE PLATFORM ONE4ALL

The solution **one4all** uses the data from the areas of the realization of business processes, the management of transport and workflow and the management of projects. In this system, it is possible to create effective reports and analyses. Such personalized reports and analyses are used by managers and experts, helping them in the process of making future decision and predicting future behaviors. Because that analytic information is accessible in the real time, managers can react immediately to the changing situation.

The platform **one4all** facilitates leadership and management projects. **one4all** allows to follow the whole cycle of the life of the project in the quick and easy way, to plan expenditures and control the costs.

The following Services are included in the solution **one4all**:

- **Microsoft Dynamics AX 4.0** is the elastic solution to the management of the organization which enables employees the organization to make optimal business decisions. The work with the software Microsoft Dynamics AX is similar to working with other application from Microsoft, such as Microsoft Office or Microsoft SQL Server. This means that the new application possesses the same elements as the systems and software which are already used in the organization.

- **Microsoft Dynamics CRM 4.0.** The key processes realized by using the system of CRM are, for example, gaining new customers and building long-lasting relationships with them.

- **SAP Business All-in-One** offers the complex solutions of the world class in the form of pre-configured packets at the affordable price to small and medium-size firms. SAP In the case of firms working in the specific line of business, SAP solutions reflect processes realized in the given environment / sector.

- **ILS.NET**. Sending goods in the chain of deliveries requires the co-ordination of many business processes, including transport, storing and the management of orders. Thanks to the solution Integrated Logistics Solutions ™ one can balance the demand with the supply in the chain of deliveries assuring the delivery of the goods expected by the customers. Exactly compiled orders, the improved process of the realization of deliveries and the total transparency of the goods stored in warehouses will allow to tie all processes in the chain of deliveries.

- **Microsoft Office SharePoint Server 2007** is the integrated packet of easy to use server applications which increase the efficiency of the organization and optimize the co-operation of people, content, processes and business applications.

- **Microsoft Office Communications Server 2007** administers communication in real time (synchronic communication): instant messages, technology VoIP and videoconferencing. Because it co-operates with other existing telecommunication systems, the enterprises can implement advanced technology VoIP without the need to exchange older telephone nets.

- **Microsoft Office Project Server 2007** allows for more effective management of the work of an organization by coordinating it during the entire project, beginning from single and finishing with more complex projects.

- **AX People** is a modern, licensed by Microsoft system which allows managing human resources in the organization. AX People is fully integrated with Microsoft Dynamics AX, but it can also work in the independent way, using only the core of this system.

- **Microsoft® SQL Server™ 2008** is the newest platform for managing and analyzing data which offers the highest safety of information data along with the comfort and low costs of data management.

5. CONCLUSIONS

The platform one4all is the new concept of the platform which can offer a potential customer a range of services which can be implemented and developed, depending on the specific needs of the organization. The nature of the platform **one4all** makes it possible to implement several services, thanks to which

- Helps to promote the development of the **informative society** since the platform **one4all** allows to work **"at the distance"** and create the new global possibilities of employment; increase the availability of experts services; decrease of costs connected with creating new work places and commuting. The platform one4all makes communication services accessible, enabling the broadcast of sound and picture, employees can contact through tele- and video-conferences which assure more effective communication and better understanding of information, building perfect relationships and overcoming distance barriers.

- The platform **one4all** for higher education institutions – the Modern University, makes it possible to realize advanced functions of e-learning/distance learning which results in raising the quality of teaching and lowering of the costs of education; the access to attractive teaching materials; the better possibilities for self-education.

- The platform **one4all** allows access to services of advanced internet applications which allow implementing the electronic trade and give access to global markets; allowing consumers the choice of the best offers; lowering of the costs of distribution and promotion.

- The utilization of the platform **one4all** is effective in improving the organizational economic activity through: improvement exchanging of information between enterprises and inside enterprises in distant geographical locations; lowering of the costs of the economic activity; facilitation and the acceleration of accounts; the possibility of the remote management of the financial centers at the banks.

- The platform **one4all** for public institutions allows the remote access to legal acts, information about realized undertakings, auctions organized by the administration, legislative plans and the electronic exchange of the correspondence.

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Keywords: *multidimensional systems, digital-analogue systems*

Vadym KRAMAR*

ANALYZE OF EQUIVALENT ONE-TIME MODEL OF MULTIVARIABLE MULTI-STAGE CONTROL SYSTEM

Abstract:

The paper presents the analysis equivalent one-time model of multivariable multi-stage control system. If a control system contains a few digital chains of treatment of information with different periods of quantum, its research is strongly complicated. In the case of rational commensurable periods of quantum transformation of a multirate system it is possible to design an equivalent one-time system with enhanceable dimension. The general going is offered to the design of an equivalent one-time system, allowing to transform the vectorial-matrix model of the initial multirate system into a vectorial-matrix one-time model of the system, characteristic for vectorial-matrix models of multidimensional continuous systems. Due to that, it becomes possible, in principle, to transfer of methods of analysis of continuous multidimensional systems onto the class of digital-analogue multirate systems.

1. INTRODUCTION

The usage of microprocessors or IBM in the measuring and processing channels along with continuously working arrangement is typical for modern automatic control systems. As a rule, similar control systems carry out measurements and processing of some signals sharing time. Mathematical models of such systems are represented in a multivariate multistep uninterruptedly discrete automatic control systems. Investigations of similar systems lead to the need of their model development in a complex range, with transfer functions as main modelling elements. The problem of linear digital-analogue (uninterruptedly discrete) multistep systems contains two essential complexity aspects within the system multiextent variety of quantum circuits; second aspect characterizes the problem as unsolvable. In the case of commensurable periods (their multiplicity to some "efficient" period), the second aspect becomes in general equal to the first, significantly strengthening it by great multiplicity of numbers of "efficient" period quantum periods, due to which the system can be converted into a monostep multivariate impulse system of extensive dimension. Also, to obtain CAY models in the form of transfer functions, methods using signal graph have found a wide application. Signal graph provides evident representation of system variables and their interaction. It is well

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known that to determine transfer functions of linear permanent systems the Manson equation can be applied. In [1], [2] approaches of Manson equation application in one-time uninterruptedly discrete systems are observed. If there are some various times, the Coffi and Williams matrix approach should be applied. This article gives a description of the matrix approach to the design of an equivalent model of multivariate multirate uninterruptedly discrete system and also to the creation of a signal graph one-time uninterruptedly discrete system for which the Manson equation can be applied.

2. MATHEMATICAL MODULE OF INVESTIGATED SYSTEM

Consider a multivariate linear system with digital and analogue control circuits adjusted to certain transfer function. Let $u(s)$ be an object governing vector, and $y(s)$ - object output vector. Dimensions of the vectors are m and p, respectively. Consider $x_1(s), x_2(s), \ldots, x_r(s)$ to be variables, quantified in $T_1, T_2, \ldots, T_r$ times (periods) accordingly (among which there can be equal ones) and consider

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \ldots \\ x_r \end{bmatrix}$$

to be the appropriate vector.

Equation of uninterrupted object and system analogue circuits from the object to the key quantification can be identified as follows:

$$\begin{aligned} y(s) &= W_0(s)u(s), \\ x(s) &= E(s)y(s) + B(s)u(s), \end{aligned} \tag{1}$$

where $W_0(s)$, $E(s)$, $B(s)$ are transfer function matrixes of the correspondent dimensions.

Thus $$x(s) = U(s)u(s), \tag{2}$$

where: $U(s) = E(s)W_0(s) + B(s)$.

Suppose the quantum periods $T_1, T_2, \ldots, T_r$ equal some rate, i.e. are shown in the form

$$T_1 = n_1 T,\ T_2 = n_2 T,\ \ldots, T_r = n_r T, \tag{3}$$

where: $n_1, n_2, \ldots, n_r$ are identity numbers.

Consider

$$\overset{*}{x}_{1T_1}(s),\ \overset{*}{x}_{2T_2}(s), \ldots, \overset{*}{x}_{rT_r}(s)$$

to be Laplace discrete transformation quantified in periods $T_1, T_2, \ldots, T_r$ with variables $x_1(t), x_2(t), \ldots, x_r(t)$ respectively.

Each quantified signal $x_i(k_iT_i)$, $k_i = 0,1,\dots$, $i \in \overline{1,r}$ is converted by a certain digital circuit and summarized with two similar signals, resulting in control effect formation. Besides digital circuits, in the control effect formation analogue circuits can also be applied (from object outputs). Taking that into account, we can identify the equation for k-th component of control vector as follows:

$$u_k(s) = -\sum_{i=1}^{r} d_{ki}(s) x^*_{iT_i}(s) - \sum_{i}^{p} f_{ki}(s) y_i(s) + u_{кз}(s),$$

where: $d_{ki}(s)$, $f_{ki}(s)$ are transfer functions of parallel digital and analogue circuits, and $u_{кз}(s)$ is effect setting formed by digital circuit. In most cases of summarizing and digital-analogue signal conversion we can state that

$$d_{ki}(s) = a(s) W^*_{kiT_i}(s), \quad (4)$$

$$u_{кз}(s) = a(s) u^*_{кзT}(s), \quad (5)$$

where: $a(s) = \dfrac{1 - e^{-Ts}}{s}$, and $W^*_{kiT_i}(s)$, $u^*_{кз}(s)$ are periodic functions (with periods $2\pi j / T_i$ and $2\pi j / T$, respectively) characterizing digital and digital analogue conversion.

Let us take into consideration matrix $W_*(s)$ with elements $W^*_{kiT_i}(s)$, and also vectors $x_*(s)$, $v^*(s)$ with elements $x^*_{iT_i}(s)$ and $u^*_{кзT}(s)$. Symbol * beneath will be used hereafter to define periodicity properties of matrix $W_*(s)$ and vector $x_*(s)$ at particular periods. At the same time, all these elements in equation (3) meet equation $x(s + 2\pi j / T) = x(s)$, and for a given matrix $W_*(s)$ and vector $x_*(s)$ the following equations are possible

$(cb_*)^*_T = c^*_T b_*$ (or $(b_* c)^*_T b_* c^*_T$).

Considering (4), (5), and writing equations for control effects in vector-matrix form

$$u(s) = -a(s) W_*(s) x_*(s) - F(s) y(s) + a(s) v^*(s),$$

where: $F(s)$ - matrix $m \times p$ with elements f_{ki}, is obtained due to equation (1) and (2)

$$u(s) = -G(s) W_*(s) x_*(s) + G(s) v^*(s), \quad (6)$$

$$x(s) = -C(s) W_*(s) x_*(s) + C(s) v^*(s), \quad (7)$$

$$y(s) = -L(s) W_*(s) x_*(s) + L(s) v^*(s), \quad (8)$$

where: $G(s) = a(s)(I + F(s) W_0(s))^{-1}$,

$$C(s) = U(s)G(s),$$

$$L(s) = W_0(s)G(s).$$

3. EQUAL MODEL OF THE SYSTEM

The multirate system model can be converted into a one-time system model with quantum period T which is the biggest common devisor of quantum time $T_1, T_2, \ldots T_r$. Let us rely on such equations [3]

$$y^*_{nT}(s) = \frac{1}{n}\sum_{k=1}^{n} y^*_T\left(s + \frac{2\bullet j}{nT}(k-1)\right), \qquad (xy^*_{nT})^*_T = x^*_T y^*_{nT} .$$

Further on, symbol T will be avoided in defining a certain impulse conversion.
Considering this equation (7) we see that

$$x^*(s) = - C^*(s)W_*(s)x_*(s)+C^*(s)v^*(s).$$

Changing s into $s + \frac{2\pi j}{NT}(\upsilon - 1)$, where N, υ - some natural numbers, we obtain

$$x^{*\upsilon}(s) = -C^{*\upsilon}(s)W_*^{\upsilon}(s)x_*^{\upsilon}(s) + C^{*\upsilon}(s)v^{*\upsilon}(s) , \tag{9}$$

where for each function $\varphi(s)$ we apply

$$\varphi^{\upsilon}(s) = \varphi\left(s + \frac{2\pi j}{NT}(\upsilon - 1)\right).$$

Suppose that in equation (9) $\upsilon = 1, \ldots, N$, thus we obtain the equation

$$\hat{x}^*(s) = -\hat{C}^*(s)\hat{W}_*(s)\hat{x}_*(s) + \hat{C}^*(s)\hat{v}^*(s) , \tag{10}$$

where:

$$\hat{x}(s) = (x^{1\prime}(s), x^{2\prime}(s), \ldots, x^{N\prime}(s))' , \tag{11}$$

$$\hat{x}_*(s) = (x_*^{1\prime}(s), x_*^{2\prime}(s), \ldots, x_*^{N\prime}(s))' , \tag{12}$$

$$\hat{v}(s) = (v^{1\prime}(s), v^{2\prime}(s), \ldots, v^{N\prime}(s))' , \tag{13}$$

$$\hat{C}(s) = diag(C^1(s), C^2(s), \ldots, C^N(s)), \tag{14}$$

$$\hat{W}(s) = diag(W^1(s), W^2(s), \ldots, W^N(s)). \tag{15}$$

Consider vector components $x^{\upsilon}{}_{*}(s)$

$$x^{*\upsilon}_{iT_i}(s)=\frac{1}{n_i}\sum_{k=1}^{n_i}x_i^*(s+\frac{2\pi j}{NT}(\upsilon-1)+\frac{2\pi j}{n_iT}(k-1)) \ . \tag{16}$$

Let N be the least common multiple $n_1,n_2,...,n_r$, such as

$$N = \upsilon_1 n_1,\ N = \upsilon_2 n_2,\ ...\ ,N = \upsilon_r n_r\ ,$$

where $\upsilon_1, \upsilon_2, ... , \upsilon_r$ - natural numbers. Thus, equation (16) can be defined as

$$x^{*\upsilon}_{iT_i}(s)=\frac{1}{n_i}\sum_{k=1}^{n_i}x_i^*(s+\frac{2\pi j}{NT}[\upsilon+\upsilon_i(k-1)-1]) \ . \tag{17}$$

Let us define that for each $l > N$ we will have, considering $l = fN+\upsilon$,

$$x_i^*(s+\frac{2\pi j}{NT}l)=x_i^*(s+\frac{2\pi j}{NT}\upsilon) \tag{18}$$

according to periodic functions $x^*{}_i(s)$ with s in times $2\pi j/T$. Due to equation (18), the right side of equation (17) contains only $x(s)$, meaning that there is a linear vector conversion $\hat{x}^*(s)$ into $\hat{x}_*(s)$, $\hat{x}_*(s)$, i.e. we obtain

$$\hat{x}_*(s)=\prod\hat{x}^*(s) \ , \tag{19}$$

where Π – rN x rN number matrix. Substituting equation (19) into equation (10), we define

$$\hat{x}^*(s)=(I_{rN}+\hat{C}^*(s)\hat{W}_*(s)\prod)^{-1}\hat{C}^*(s)\hat{v}^*(s) \ . \tag{20}$$

Defining the equation thus

$$\hat{y}(s)=-\hat{L}(s)\hat{W}_*(s)\hat{x}_*(s)+\hat{L}(s)\hat{v}^*(s)$$

where:

$$\hat{y}(s)=(y^{1'}(s),y^{2'}(s),...,y^{N'}(s))',\quad \hat{L}(s)=diag(L^1(s),L^2(s),...,L^N(s)), \tag{21}$$

and using equation (19), (20), we obtain

$$\hat{y}(s)=\hat{L}(s)\{-\hat{W}_*(s)\prod(I_{rN}+\hat{C}^*(s)\hat{W}_*(s)\prod)^{-1}\hat{C}^*(s)+I_{mN}\}\hat{v}^*(s) \ . \tag{22}$$

By applying identity

$$I-A(I+BA)^{-1}B = (I+AB)^{-1} \tag{23}$$

we define also

$$\hat{y}(s)=\hat{L}(s)(I_{mN}+\hat{W}_*(s)\prod\hat{C}^*(s))^{-1}\hat{v}^*(s)$$

and

$$\hat{y}^*(s) = \hat{L}^*(s)(I_{mN} + \hat{W}_*(s)\prod\hat{C}^*(s))^{-1}\hat{v}^*(s)\,. \tag{24}$$

Let us define matrix Π as block one in the form of $\Pi = \{\Pi_{\upsilon p}\}$, $\upsilon \in 1,..., N$, where $\Pi_{\upsilon l}$ – r x r - matrix and, giving the definition

$$W^* = \hat{W}_* \prod \hat{C}^* \tag{25}$$

define the elements of block representation of this matrix

$$W^*(s) = \{W^*_{\upsilon p}(s)\}, \upsilon, l \in 1,...,N\ , \tag{26}$$

$$W^*_{\upsilon l}(s) = W_*^{\upsilon}(s)\prod\nolimits_{\upsilon l} C^{*l}(s), \upsilon, l \in 1,...,N\ . \tag{27}$$

In this representation

$$W_*^{\upsilon}(s) = W_*(s + \frac{2\pi j}{NT}(\upsilon - 1)), \upsilon \in 1,...,N,$$

$$C^{*l}(s) = C^*(s + (l-1)\frac{2\pi j}{NT}), l \in 1,...,N\ .$$

Block elements $\Pi_{\upsilon p}$, $\upsilon, l \in 1,...,N$ have the form of

$$\prod\nolimits_{\upsilon l} = diag(\pi^1_{\upsilon l}, \pi^2_{\upsilon l}, ..., \pi^r_{\upsilon l})\,. \tag{28}$$

Carrying out simple actions in such a representation, from equation (27) we obtain for the matrix elements $W^*_{\upsilon l}$

$$W^{*\sigma\mu}_{\upsilon l}(s) = \sum_{i=1}^{r} \pi^i_{\upsilon l} W_{*\sigma i}(s + (\upsilon - 1)\frac{2\pi j}{NT})C^*_{i\mu}(s + (l-1)\frac{2\pi j}{NT})$$

The created matrixes (26) of open equivalent one-time system allow to find out outputs of the closed initial system, quantified in points kT, $k=0,1,...$ defining for this purpose the matrix

$$H^*(s) = (I_{mN} + W^*(s))^{-1}$$

as block type

$$H^* = \{H^*_{\upsilon p}\},\ \upsilon, l \in 1, ... , N$$

From representation (24) we find out

$$y^*(s) = \sum_{l=1}^{N} L^*(s) H^*_{1l}(s) u^{*l}(s)\ , \tag{29}$$

where: $$y^*(s) = y^{*1}(s), L^*(s) = L^{*1}(s)\,.$$

4. STRUCTURAL INVARIANT OF QUANTUM CIRCUITS

In the common case of multivariate multistep control systems description, a complex chain of mutual quantum process effect in close system digital circuits with different quantum steps takes place. Typical description feature of this chain is matrix Π , i.e. transformation (19).

The dimension and complexity of this matrix is conditioned by mutual number characteristics of digital circuits on numbers $n_1,\ldots,n_r$ determining mutual relation between quantum steps and N - the least common multiple of given numbers. Non-zero elements of this matrix determine only numbers $1/n_i, i=1,\ldots,r$, making sense for relative quantum density (relations of «rear» number counting out to «frequent» numbers). As in system structure particularly digital circuits and quantum keys arrangement does not adversely affect matrix Π , so it is a quantum circuit structure invariant. To complete the formation of the equivalent one-step system model, let us now point out the way of Π matrix element calculation. Let us find them in the form of matrix (18). We examine the equation

$$\sum_{l=1}^{N} \pi_{\nu p}^{i} x_i^{*l} = \frac{1}{n_i} \sum_{k=1}^{n_i} x_i^{*\nu+(k-1)\nu_i} , \qquad (30)$$

which takes place according to (19) and (17) with indication

$$x_i^{*l}(s) = x_i^{*}(s+(l-1)\frac{2\pi j}{NT}),\ i=1,\ldots,r ,$$

which was mentioned above. Note that, considering equation (30), periodicity ratio should be concerned

$$x_i^{*N+p} = x_i^{*p},\ \ l=1,2,\ldots$$

as the abovementioned function property $x_i^{*}(s),\ i=1,\ldots,r$.

For this purpose let us consider the right side of equation (30) and numbers multitude

$$p(k) = \nu + (k-1)\nu_i,\ \ k=1,\ldots,n_i \qquad (31)$$

with fixed index value ν, i . It is evident that numbers of this multitude pose property

$$p(k'') > p(k'),\ \ k'' > k' .$$

Let p_{max} be the greatest from numbers $p(k,\nu,i) = \nu + (k-1)\nu_i$ with free index $k \in \overline{1,n_i};\ \nu \in \overline{1,N};\ i \in \overline{1,r}$.

$$p_{max} = \max_{i \in \overline{1,r}} (N + (n_i - 1)\nu_i) = N + N - \overline{\nu} = N + \overline{\gamma} ,$$

where: $\overline{\nu}$ - the least number $\nu_i,\ i \in \overline{1,r}$. According to the ratio $N = n_i\nu_i$, if even one of all numbers $n_i,\ i \in \overline{1,r}$ is less than N (even one of all numbers $n_i,\ i \in \overline{1,r}$ is bigger than 1), it means $\bar{\gamma} < N$. Owing to this, all numbers from (31), bigger than N, may be $N + \gamma,\ 0 \le \gamma \le N - 1$. Now at one's own choosing k'', k', k so that $k'' > k' > k$ we obtain

$$p(k) = \nu + (k-1)\nu_i = \gamma \le N,$$

$$p(k') = \nu + (k'-1)\nu_i = N + \gamma',$$

$$p(k'') = \nu + (k''-1)\nu_i = N + \gamma''.$$

Subtracting we find out

$$\gamma'' - \gamma' = (k'' - k')\nu_i,\ \gamma - \gamma' = (k - k'')\nu_i + N = (n_i + k - k'')\nu_i.$$

Thus

$$\gamma' < \gamma'' < \gamma.$$

On account of equation (30), the following rule can be derived to calculate the elements of the quantum density $\pi^i_{\nu l},\ l = 1,\dots,N$ matrix Π by fixed indexes ν, i

$$\pi^i_{\nu l} = \begin{cases} 1/n_i,\ l = l(k) = p(k),\ p(k) \le N \\ 1/n_i,\ l = l(k) = p(k) - N,\ p(k) > N \\ 0 \qquad l \ne l(k), \end{cases}$$

where: value $p(k),\ k = 1,\dots,n_i$ is calculated in (31).

Thus there is an algorithm for which we can create a Table

Table 1. Table of algorithm

l	1	2		*		*		N
$\delta(l)$			…0	1	0…0	1	0…	

The upper row of the table is for identity numbers from 1 to *N*, some of them are marked with a star. The lower one is for values of $\delta(l)$, equal to 1 below marked numbers and 0 on the contrary. The rule of marking the upper row is the following. Values are calculated as $p(k) = \nu + (k-1)\nu_i,\ k = 1,\dots,n_i$. If $p(k) \le N$, we mark the number $l_* = p(k)$, if $p(k) = N + \gamma(k)$, then number $l_* = \gamma_k$. In this way the lower row determines the value of $\delta(l),\ l = 1,\dots,N$, and

$$\pi^i_{\nu l} = \frac{1}{n_i}\delta(l),\ l = 1,\dots,N.$$

Thus, in this way we define the whole matrix row Π, i.e. the diagonal elements with fixed indexes ν, i of all big matrixes, equal to either $1/n_i$ or 0. Suppose $\nu = 1$, then using algorithm r times in values of $i = 1,\dots,r$ we find the first row of Π matrix

$$\Pi_{11},\ \Pi_{12},\ \dots,\ \Pi_{1N-1},\ \Pi_{1N}.$$

This row, by means of series circle permutation, determines the whole matrix Π. The lower row looks as follows

$$\Pi_{1N},\ \Pi_{11},\ \dots,\ \Pi_{1N-2},\ \Pi_{1N-1}$$

etc. E.g., by $N = 3$ the whole matrix Π is given by

$$\Pi = \begin{Vmatrix} \Pi_{11} & \Pi_{12} & \Pi_{13} \\ \Pi_{13} & \Pi_{11} & \Pi_{12} \\ \Pi_{12} & \Pi_{13} & \Pi_{11} \end{Vmatrix}.$$

This conclusion is easy to come to if we compare $\pi^i_{\nu l}$ and $\pi^i_{\nu+1l}$, corresponding to $k \in \overline{1,n_i}$. According to equation (31), $p(k,\nu+1) = p(k,\nu)+1$. Thus, if $l(k) < N$, then $l'(k) = l(k)+1$, and if $l(k) = N$, then $l'(k) = 1$. For block matrixes which are defined by $k \in \overline{1,n_i}$, such number will be represented as $\Pi_{\nu+1l'} = \Pi_{\nu l+1}, l < N;\ \Pi_{\nu+1l'} = \Pi_{\nu 1},\ l = N$,

which is the rule definition .

It is also essential to emphasize the opportunity to form prescribed matrix blocks Π. Let us consider block $\Pi_{\nu l}$. Diagonal elements $\pi^i_{\nu l}$, $i = 1,\dots,r$ should be defined with values ν, l.

Let us set $i \in \overline{1,\dots,r}$, then:

1. If there is $k \in \overline{1,n_i}$, satisfying any equation

$$\nu + (k-1)\nu_i = l, \quad \nu + (k-1)\nu_i - N = l, \tag{32}$$

then $\pi^i_{\nu l} = 1/n_i$ and

2. If there is no $k \in \overline{1,n_i}$, then

$$\pi^i_{\nu l} = 0.$$

Example. Suppose $r = 2,\ n_1 = 1, n_2 = 3$.

Thus, $N = 3, \nu_1 = 3, \nu_2 = 1$. For block Π_{11} there is an equation

$$\begin{aligned} &i = 1 \quad 1+(k-1)3 = 1,\ \ 1+(k-1)3-3 = 1,\ \ k \in \overline{1,3}; \\ &i = 2 \quad 1+(k-1)1 = 1,\ \ 1+(k-1)1-3 = 1,\ \ k \in \overline{1,3}. \end{aligned}$$

That is why $\pi^1_{11} = 1, \pi^2_{11} = 1/3$.

For block Π_{12} :

$$i=1 \quad 1+(k-1)3=2,\ 1+(k-1)3-3=2,\ k\in\overline{1,3};$$
$$i=2 \quad 1+(k-1)1=2,\ 1+(k-1)1-3=2,\ k\in\overline{1,3}.$$

Thus, $\pi_{12}^{1}=0,\ \pi_{12}^{2}=1/3$.

Finally, for block Π_{13} :

$$i=1 \quad 1+(k-1)3=3,\ 1+(k-1)3-3=3,\ k\in\overline{1,3};$$
$$i=2 \quad 1+(k-1)1=3,\ 1+(k-1)1-3=3,\ k\in\overline{1,3}.$$

Thus, $\pi_{13}^{1}=0,\ \pi_{12}^{2}=1/3$.

The whole matrix is given by

$$\Pi=\left\|\begin{array}{cc:cc:cc} 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 1/3 & 0 & 1/3 & 0 & 1/3\\ \hdashline 0 & 0 & 1 & 0 & 0 & 0\\ 0 & 1/3 & 0 & 1/3 & 0 & 1/3\\ \hdashline 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 1/3 & 0 & 1/3 & 0 & 1/3 \end{array}\right\|.$$

Differences in quantum density are seen in matrix Π in the form of inhomogeneous filling of its blocks. When quantum density is equal in all the circuits, i.e. $n_1=n_2=\cdots=n_r=n,\ N=n$ and $\nu_1=\nu_2=\cdots=\nu_r=1$, then matrix Π is fully filled and all block elements $\Pi_{\nu l}$, $\nu, l=1,\ldots,n$ are equal to

$$\Pi_{\nu l}=\frac{1}{n}I_r\ ,$$

where: I_r - - single matrix $r\,x\,r$.

It is clear that the first equation (32), by $\nu=1, \nu_i=1$ by any $l\in\overline{1,n}$, has solution $k=l$, which means that $\pi_{\nu l}^{i}=1/n\,,\ i\in\overline{1,r}$.

5. FORMATION OF EQUIVALENT MODELS OF MULTIRATE SYSTEMS IN THE FORM OF SIGNAL GRAPH

To obtain a CAY model in the form of transfer functions, methods using signal graph have found a wide application. Signal graph provides obvious introduction of system variables and their interaction. It is well known that to define transfer functions of linear uninterrupted systems the Manson formula can be used. In [1], [2] approaches using Manson formula in one time uninterrupted discrete systems are considered. In this article the formation of signal graph multirate uninterrupted discrete system for which Manson formula is applicable is observed.

While constructing signal graph of multirate uninterrupted discrete system, let us consider the symbol system of Sodper and Becky [2]. White knot in the graph is used to define uninterrupted variable system. Black knot is used to define discrete variable and quantum operations, variable significance represented by any black knot being discrete form of sum transformation of all variables, being in the knot, according to a certain rate. Because in uninterrupted discrete, as a rule, it is impossible to outline inlet variable in presentation for, thus it is worthwhile to coordinate inlet influence. It is carried out by introduction of branches with transfer function equal to inlet variables so that entire transfer function belonging to the single output, transfer function and output become equal [11].

The construction of algorithm for uninterruptedly discrete system signal graph on the basis of equations in [11], will be as follows:

1. On the basis of structure scheme an uninterruptedly discrete system initial graph is formed. All quantifiers in it, T_j $j = 1,\ldots,N$, are considered to be regulated by diminution open, at the same time output signals of keys are considered to be input ones into the system where $\sum_{j=1}^{N} m_j$ is the quantity of black knots and m_j – key number with time T_j.

2. Form n_j $j = 1,\ldots,N$ of the discrete graph, corresponding to time T_j on the following procedures:

a1) $j = 1;$

a) in the initial graph we compose only knots corresponding to quantifiers input signals with time T_j and connected with them input knots (initial and from quantifiers). As a result we obtain the intermediate graph;

a2) $i_j = 0;$

b) in the intermediate graph we replace all transfer functions of links W with $We^{i_j T_j s}$;

c) we make input signals parallel from keys T_k, $k = 1,\ldots,N$, $k \neq j$ to n_k branches, substituting each transfer function of the branch W for $We^{-l_k T_k s}$ $l_k = 0,\ldots,(n_k - 1)$, $k = 1,\ldots N$, $k \neq j$.

d) we substitute knots for black, and transfer functions for their discrete transformation in time T. We enter input knots in the Table through $Y^T_{k(i_k)}$, then state conformity between knots x^T and $Y^T_{k(i_k)}$ by means of identity connections, where it is necessary. We obtain a discrete graph corresponding to time T_j.

e) points b) ÷ d) are now executed n_j times, supposing $i_j = i_j + 1$; this results in discrete graph n_j, corresponding to time T_j, $i_j = 0,\ldots,(n_j - 1);$

f) j – we increase by one and repeat points a) ÷ e) for discrete graph construction for all N quantifiers, i.e. $j = 1,\ldots,N$.

3. Now we turn back to the initial graph and make all input signals parallel from keys $y_j^{T_j}$, $j = 1,\ldots,N$, into n_j corresponding branches $j = 1,\ldots,N$.

We transfer each function from n_j branches W and substitute for $We^{-k_jT_js}$ $k_j = 0,\dots,(n_j - 1)$, $j = 1,\dots N$, respectively. We now enter the input knots in the Table through variables $Y^T_{j(i_j)}$, $i_j = 0,\dots,(n_j - 1)$.

We connect to the marked inputs all of discrete graphs, got in item 2, by single connections. We set, where necessary, other single connections, proper identical knots. We get the component graph.

4. We substitute all the knots with black, and transfer functions on their discrete transformations on time the least common multiple – on time of T. We get the final discrete graph of the system.

5. By applying the Mason rule we determined the necessity of input-output correlation for the system variables of x^T for the obtained graph of the system.

Now we can formulate the algorithm of receipt of signal graph of multivariate of the continuously-discrete system for the case of multiple times.

1. On the basis of the flow diagram of the system, an initial graph containing white and black knots is formed. Black knots have indexes of *Ti*, *I = 1,.,N*, proper to the value of time of discreteness. Times are considered well-organized on a decrease. In the initial graph keys are considered broken; here the output signals of keys are considered entrance knots in the system and black knots correspond to them.
2. On the initial graph of the system, through the application of the Mason algorithm, the discrete graph of 1st level is formed in conformance with the following:

All the knots, being by an entrance for the keys with the smallest time of *TN*, get out in the initial graph. They are considered output knots. All the entrance knots, related to the indicated output, get out then. Entrance knots can be the entrance signals of the initial system, and also outputs of keys with large times. In the Mason algorithm, connections between these knots are determined and the intermediate count of 1st level is formed.

Further, all white knots of the intermediate graph are replaced with black knots, with the index of variables of *TN*, which corresponds to discrete transformation of variables in time of TN, and the transmission functions of connections are replaced by their discrete transformations in time of *TN*. Black knots that are proper discrete variables for large times remain unchanged. The discrete count of the system of 1st level is formed in the same manner. We set, where necessary, single connections for proper identical knots.

3. The component graph of 1st level is formed. It turns out to be a combination of the initial graph of the system and discrete graph of 1st level. Thus the proper black knots of the graph, being weakened signals of keys Ti, are united by single connections, *i = 1,.,N*. A component graph of 1st level is the basis for the construction of discrete graph of 2nd level.
4. Algorithms for the discrete graph of 2nd level, et cetera till *N*-th number of levels 2, are formed as per item a, with the change that in place of keys with time of TN, keys are utilized accordingly with time of *TN-1* et cetera, till time of T_1. As a result of the expounded procedure, *N* number of discrete counts of the system will be formed.
5. The final count of the system is further formed, which turns out to be a combination of the initial and N of discrete counts of the system. By single connections, the accordance of knots of discrete counts is set with the entrance knots of the initial count.
6. In the algorithm of Mason, the input-output correlations are determined for the system variables of multirate continuously-discrete system with multiple times.

The offered method provides a formalised procedure of construction of input-output correlations of multirate continuously-discrete systems.

6. ABOUT ANALYSIS OF MULTIRATE SYSTEMS PROCESSES

Observed multirate systems applications in the form of equivalent one-time models give common reasons for process analysis in given one-time systems. While observing resultant correlation, it is not difficult to see that in all cases impulse images of equivalent models outputs have the form of rational functions of given variables. Turning to Z–images we will have an equation defining the output images as of z. They correspond to:

$$Y(kT) = \frac{1}{2\pi j}\oint f(z) z^{k-1} dz \ . \tag{33}$$

The closed contour of integration in equation (46) covers all poles f(z) . Thus, the problem of process analysis in given multirate systems becomes reduced to the problem of rational functions of pole distribution analysis f(z) concerning a single circle.

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Keywords: *artificial intelligence, works transport, control, simulation*

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AN ARTIFICIAL INTELLIGENCE IN WORKS TRANSPORT CONTROL

Abstract:

This paper presents an innovative approach to the problem of works transport control proposing the use of the mechanisms of artificial intelligence (computer intelligence) to determine the route of the Automated Guided Vehicles (AGVs). The authors attempt to apply the artificial intelligence methods to optimize transport processes at the factory.

1. INTRODUCTION

The subject-matter of control in the context of AGVs using the mechanisms of artificial intelligence is widely discussed in numerous publications from the last half of previous century. Quite often the authors describe various approaches to this issue but in last few years an increase of activity in this area of science is observed. Partly it is connected with an observed revival of methods based on so-called computer intelligence. This is due to increasing frequency of application of methods such as artificial neural networks, genetic algorithms and fuzzy logic. Recently the authors have made attempts to create artificial computer systems operating on the basis of the defense system of living organisms known as the immune systems LAU, WONG, LEE [3].

This paper is aimed to overview the current state of knowledge in terms of topics related to the AGVs control using artificial intelligence methods and to propose, on this background, the simulation system for modeling and control of the works transport in industrial conditions. The authors try to use the application of artificial intelligence methods to optimize transport processes at the factory.

2. PROCESSES CONTROL PROBLEMS OF WORKS TRANSPORT IN LITERATURE

The issue of control in transportation systems is really important from the point of view of exploring of the free efficiency reserves in manufacturing systems. This is illustrated by the

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large number of literature on the subject. A special place among these are the applications of artificial intelligence. Many authors using the theoretical and practical arguments demonstrate that computer intelligence is a special way suitable for solving problems related to transportation issues. This argument is confirmed by the problems associated with planning and scheduling tasks of transport for the vehicles moving in any way (free choice of route) or limited route (only along designated paths such as rail vehicles). Many researchers take attempts of simultaneous scheduling means of transportation and workstations in order to obtain better efficiency of transport operations.

The approach to the problem of routing a single Automated Guided Vehicle (AGV) based on self-organizing neural networks is mentioned by SOYLU, OZDEMIREL, KAYALIGIL [1]. The authors analyze a particular AGV routing problem in which the objective is to find the shortest tour for a single, free-ranging AGV. This AGV has the task to carry out multiple pick and deliver (P&D) requests. This type of problem is classified as a asymmetric traveling salesman problem that is known as a NP–complete. To solve this problem – the authors propose the use of artificial neural networks algorithm which is based on Kohonen's self-organizing feature maps. They introduce a lot of their own particular improvements especially in self-organizing feature maps. The efficiency of the algorithm is tested in various configurations of parameters for different sets of P&D requirements and for different sizes of problems. Then the solutions are confronted with a solution that is treated as an optimal solution. The results are promising both in terms of algorithm quality (effectiveness) and calculation times.

ULUSOY, SIVRIKAYA-SERIFOGLU, BILGE [2] present example of the use of genetic algorithms (GA = Genetic Algorithm) as an approach to simultaneous scheduling of the machines and automatic guided vehicles (AGVs).

They attempt to simultaneously schedule machines and a number of identical AGVs working together in one flexible manufacturing system. The aim is to minimize the production cycle length by schedule optimization. To solve this problem they propose to use the genetic algorithm (GA). The chromosomes refers to both activities priority and dimensions of establishing of considered space. The third dimension – time, is put in place by default through organizing chromosomes activities. The authors have developed a single chromosomes operator exchange which generates output (descendant) from the two parental chromosomes. The operator moves models of the action sequences to the "child" and/or allocation of AGV tasks which both "parents" have. They also introduced two mutation operators: a "bitwise" mutation for the allocation of AGV tasks and a "swap" mutation for operations of work stations (P&D). Any case of infeasibility from "swap" mutation is removed by so-called repair functions. The schedule associated with a chromosome is determined by a simple schedule constructor.

The authors passed many problems trying to evaluate different search strategies and adjust the parameters of genetic algorithm. 180 example problems have been solved. In order to better assess of the solutions quality they introduced easy-evaluated, so-called contractual lower limit in relation to which the various solutions were evaluated. In case more than 60% of the problems GA reached the lower limit showing optimum. The average deviation from the lower bound for all the problems amounted to 2,53%. The authors also introduced additional comparison of the solutions quality comparing the results of those same cases to the results obtained using the method called "time window". 82 test problems described in literature have been tested in this way. 59% of the problems GA surpassed the traditional approach of "time window". This illustrates the higher performance of methods based on artificial intelligence from traditional methods in the area of works transport control.

Another example of genetic algorithms utilization to design a single and multi-linear, flexible manufacturing system arrangement (FMS = Flexible Manufacturing System) is presented by FICKO, BREZOCNIK, BALIC [4]. The authors present a diagnostic approach to design issues. At the outset they analyze the characteristics of the FMS and after studying the methods of system elements layout designing they make a choice the method of genetic algorithms as the most suitable for FMS designing. The genetic algorithm model, the most appropriate way of coding solutions to the organisms and selected genetic and evolutionary operators are presented. In the presented model AGVs have been used to transport between components of the FMS. The result of using the application based on GA is obtaining the most favorable order of the rows and the sequence of devices in a single line of FMS. At the end the results of tests of the developed software are discussed.

A novel approach to AGV control based on the immune system is described by LAU H, WONG, LEE [3]. The authors present the argument that the human immune system is self-organizing, vast and complex system. These features cause a high degree of resistance to faults in the system and enhance its performance, which is a huge advantage in the implementation of systems engineering. Technical equivalent of the immune system is called artificial immune system (AIS). The authors present the idea of control based on the immune system, which has the ability to detect changes, adapt to a dynamic environment and coordinate the vehicles activities and AGV deployment for the movement of materials in the automated warehouse. Because of the approach based on the concept of AIS it becomes possible to create a reliable and scalable storage system through self-controlled and decentralized AGVs.

The issue of works transport control generally appears in the context of flexible manufacturing systems. The subject-matters of intelligent scheduling and track vehicles control as well as the loading/unloading activities within the flexible manufacturing system (FMS) is discussed by CHEN, HUANG, CENTENO [5]. They describe a framework of intelligent scheduling and manufacturing control through the special application for rail-guided vehicle systems (RGVS) control. The architecture of RGVS control is discussed through the example of a simulated experiment in the field of action of loading/unloading real, industrial FMS. Process of control takes place within the material handling system (MHS). All the data from the workshop are subject to change with the running time. It is therefore a dynamic system. These data are stored in a dynamic database. RGVS simulator used by the authors in an experimental study is designed in such a way as to take account of certain situations showing the well-known materials handling scenarios to assess alternative tactics of control.

At the controller development stage all possible combinations of the most common scenarios have been simulated such as RGV failures, changes in the schedule of production, breakdowns of machinery and rush orders. Then the data corresponding to the mentioned above emergency situations have been collected. These data have been organized in so-called a training set to properly train an artificial neural network. Neural network that was trained using sets of input/output data received from a number of simulations provided guidance on control strategy recommendations.

At the stage of application whenever there is an invalid (abnormal) script it starts preprocessor whose goal was to prepare the input data vector for the training set. Recommended control strategies were transferred to the control system MHS and executed in real time. If any further cases of irregularities were not reported the database dynamic module continued to monitor the activity of MHS.

The proposed by the authors the MHS control system contained the characteristics of neural networks technology based on examples with elements of modeling simulation in a dynamic control process. The system took appropriate actions in a given situations.

The system impacted on improving quality decision-making processes control for the continuous learning on the already gained experience during MHS system activity.

In the flexible manufacturing systems, in order to achieve the effectiveness of control close to optimal efficiency, the controller must be able to identify the current state of work stations and the location of tools and palettes. The controller must also be able to decide when and what parts should be moved between machines and when parts must be loaded/unloaded. The huge number of decisions and states of the system significantly complicates the management process. Therefore, efficient handling of materials and scheduling becomes necessary for the optimal control of FMS.

Material handling system (MHS) is a key element of the integration of the various work stations within FMS. Without an integrated MHS many modern FMS remain a collection of "isolated islands of automation" (ASKIN and STANDRIDGE [7]). From 1980 AGV systems have become the dominant mechanisms of advanced materials handling for FMS (SARIN and CHEN, 1987). We can distinguish 3 main elements in the AGV system: the vehicle, the AGV route (or path of material) and the process of control. The flow route determines the position and direction of movement of the mean of transport. The aim of AGV control process is to provide the best scheduling features that accomplish the objectives of the FMS by utilizing the full production capacity of the company and reducing level of inventories.

The main tasks of the AGVs system control are as follows:

1) vehicles moving control,
2) traffic control (if the system has more than one vehicle),
3) responding to rush events in the system.

The item No. 3 is a major challenge for AGV controller because it must react quickly, taking into account the various alternative solutions and generating a decision as soon as possible on the basis of precise information derived from the workshop (MANIVANNAN and BANKS [8]).

Unexpected interruption in working process means that the activity of the FMS is perturbed by the device failure and/or excess production capacity, due to rush orders placed into the FMS, changes in orders priority, etc. (Wu, 1994). Resources failure includes damage of machinery, material transport system fault and damage of the tools. In the event of disruption it is required to identify alternative ways to deal with control and to take corrective action. When the failure of machinery occurs, other operations on the parts should be performed on alternative machines but it usually results in delays. In this case decisions concerning the loading/unloading and the time schedule should be changed in order to minimize delays. Interruptions due to rush orders cause the reorganization of the priorities of the parts processing sequence and affect the current order of loading AGVS (AGV System). Most of existing AGV control systems offer static solutions to the problems of dispatching and scheduling. In such systems, where the efficiency of the work station is reduced (e.g. as a result of breakage), AGVS stops sending another parts to such damaged machine. Such "common sense" control strategy of the interruptions gives time to remove the breakage on the damaged work station. However, such a strategy contributes to a longer average time of the parts flow leading to delays and thus threatens the entire manufacturing system efficiency.

As result of literature analyzing it seems that the most correct concept is an idea of a dynamic and flexible response to some changes in the system of production. It is necessary to take decisions regarding the transport control in an optimal manner considering the objective function that refers to the entire manufacturing system.

3. MODEL OF WORKS TRANSPORT CONTROL SYSTEM PROPOSAL

This paper presents the concept of simulation of dynamic works transport system control acting on the basis of the mechanisms of artificial intelligence. The system was created with the following assumptions:

- At the workshop of a company operating in industrial engineering sector there are several dozen work stations (usually machine tools) that require at a certain time some handling pick & deliver (P & D) operations;
- Parts can be transmitted from one position to another through the switching station (interim storage) only;
- Means of transport (e.g. trolley platform) is operating in a continuous mode starting and ending each loop in the switching station;
- Means of transport can move freely among the work stations;

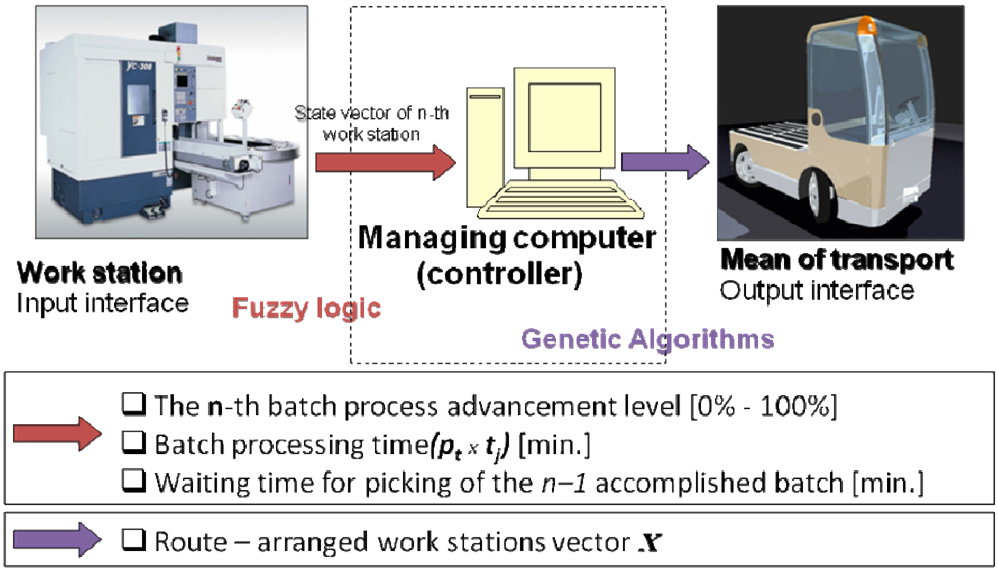

Fig. 1. Information flow

This model consists of three main elements: work stations, managing computer (controller) and mean of transport (Fig. 1).

Work stations must be equipped with proper sensors. Each working center transmits the following parameters to the managing computer: the ***n***-th batch process advancement level [0% - 100%], batch processing time (p_t x t_j = *batch quantity* x *single part processing time*) [min], waiting time for picking of the completed batch (processed in 100%) [minutes]. The main element of system control is the managing computer (controller). It has to perform two basic tasks. The first of them is to isolate only those posts which require support in the next loop which AGV will perform after leaving the switching station (**x** vector), from all the employed work stations. The **x** vector size (formula 5) may be fixed or variable.

Typically, the appropriate setting of **x** vector size depends on the specific features of each case and can be properly determined through simulation. This task is realized by a fuzzy logic mechanism which has been designed with Matlab Simulink software. Sample set of fuzzification rules in graphic form is shown in Fig. 2.

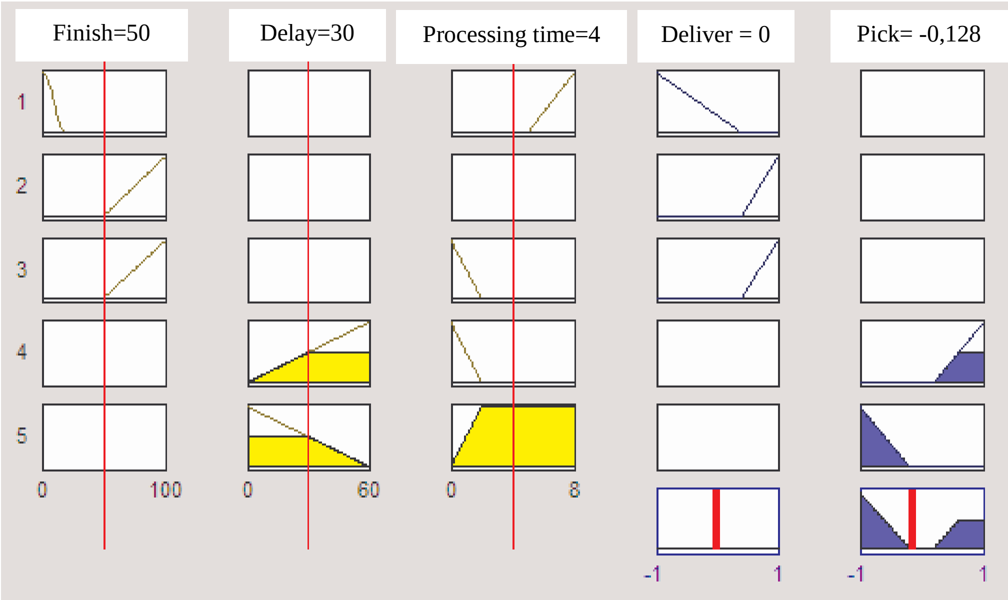

Fig. 2. Fuzzification rules

The rules are designed in such a way that the output parameters such as pick and deliver would be contained within <-1; 1> and are real numbers. In this way it is given the opportunity not only to select work stations for pick or/and deliver P&D operations but also to rank the urgency for a specific type of maintenance operations (pick & deliver). If one of the output parameters of the work station exceeds the value of zero then there is a need for support. The higher is the value of the parameter the higher is priority of maintenance activity. The values of zero or negative don't qualify the given work station for a particular maintenance operation.

Units of fuzzy logic are located at each work station. They aim to select those work stations which require a specific type of service. This information is transmitted in real time to managing computer which extracts the work station with the lowest priority among all the posts that **x** vector consists of.

The next stage of control is selecting the optimal route of the transport vehicle (AGV). Such a kind of problem is known as the symmetric Travelling Salesman Problem. The case discussed in this paper however has certain characteristics and limitations. First of all AGV always goes from the switching station. It has also imposed work station with the lowest priority which should be handled as the last one. Therefore it remains the problem of defining the order of handling the remaining work stations. The arranging of **x** vector is determined by the module operating on the basis of genetic algorithm. It has been implemented with Matlab software and cooperates closely with the module called Matlab Simulink which has been used for designing the previously discussed fuzzy logic unit.

The goal function has been established as a function of cost in the manner proposed by TANIGUCHI, SHIMAMOTO [6].

$$C(t_0, \mathbf{X}) = \sum_{l=1}^{m} c_{f,l} \cdot \delta_l(\mathbf{x}_l) + \sum_{l=1}^{m} C_{t,l}(t_{l,0}, \mathbf{x}_l) + \sum_{l=1}^{m} C_{p,l}(t_{l,0}, \mathbf{x}_l) \quad (1)$$

where

$$C_{t,l}(t_{l,0}, \mathbf{x}_l) = c_{t,l} \sum_{i=0}^{N_l} \left\{ \bar{T}\left(\bar{t}_{l,n(i)}, n(i), n(i+1) \right) + t_{c,n(i+1)} \right\} \quad (2)$$

$C(t_0, \mathbf{X})$	total cost (PLN)
t_0	departure time vector for all vehicles from the switching station
$\mathbf{X}$	assignment and order of visiting customers for all vehicles
$\mathbf{x}_l$	assignment and order of visiting customers for vehicle *l*
$n(i)$	*i*-th customer visited by a vehicle
N_l	total number of customers visited by vehicle *l*
m	maximum number of vehicles available
$c_{f,l}$	fixed cost for vehicle *l* (PLN/vehicle)
$\delta_l(\mathbf{x}_l)$	:= 1if vehicle *l* is used; = 0 otherwise
$C_{t,l}(t_{l,0}, \mathbf{x}_l)$	operating cost for vehicle *l* (PLN)
$C_{p,l}(t_{l,0}, \mathbf{x}_l)$	penalty cost for vehicle *l* (PLN)
$c_{t,l}$	operating cost per minute for vehicle *l* (PLN/min)
$t_{l,n(i)}$	departure time of vehicle *l* from customer *n(i)*
$\bar{T}\left(\bar{t}_{l,n(i)}, n(i), n(i+1) \right)$	average travel time of vehicle *l* between customer *n(i)* and *n(i + 1)* at time $t_{l,n(i)}$
$t_{c,n(i)}$	loading/unloading time at customer *n(i)*

Because only one AGV is used for the entire production department and for the resignation from the penalty cost associated with too early or too late arrival to the customer (work station) this formula is reduced to the following:

$$C(t_0, \mathbf{x}) = \sum_{l=1}^{m} C_{t,l}(t_{l,0}, \mathbf{x}_l)$$, so it becomes similar to the formula (2).

It can be assumed that the time of loading and unloading at all the work stations is the same. Then the goal function for this case will be as follows:

$$C_{t,l}(t_{l,0}, \mathbf{x}_l) = c_{t,l} \sum_{i=0}^{N_l} \overline{T}\left(\overline{t}_{l,n(i)}, n(i), n(i+1)\right) \tag{3}$$

The operating cost of the mean of transport expressed in [PLN/min] is constant and the average transit time between *n(i)* and *n(i +1)* position is directly proportional to the distance so it can be assumed that the cost is expressed as a distance function. Then the goal function is as follows:

$$C_{t,l}(s_{l,0}, \mathbf{x}_l) = c_{s,l} \sum_{i=0}^{N_l} \left(s_{l,n(i)}, n(i), n(i+1)\right) \tag{4}$$

where,

$C_{t,l}(s_{l,0}, \mathbf{x}_l)$ total operating cost for vehicle *l* as a distance function [PLN]

$c_{s,l}$ operating cost per minute for vehicle *l* [PLN/m]

$\left(s_{l,n(i)}, n(i), n(i+1)\right)$ distance between $n(i)$ and $n(i+1)$ for *l*-th vehicle run

As in the case here there is one vehicle only so the goal function depends on the distance solely and looks as follows:

$$S(s_0, \mathbf{x}) = \sum_{i=0}^{N} \left(s_{n(i)}, n(i), n(i+1)\right) \tag{5}$$

The function mentioned above is optimized by genetic algorithm. Fig. 3 shows the plot of production hall with designated transit route example. The work stations are marked as the circles.

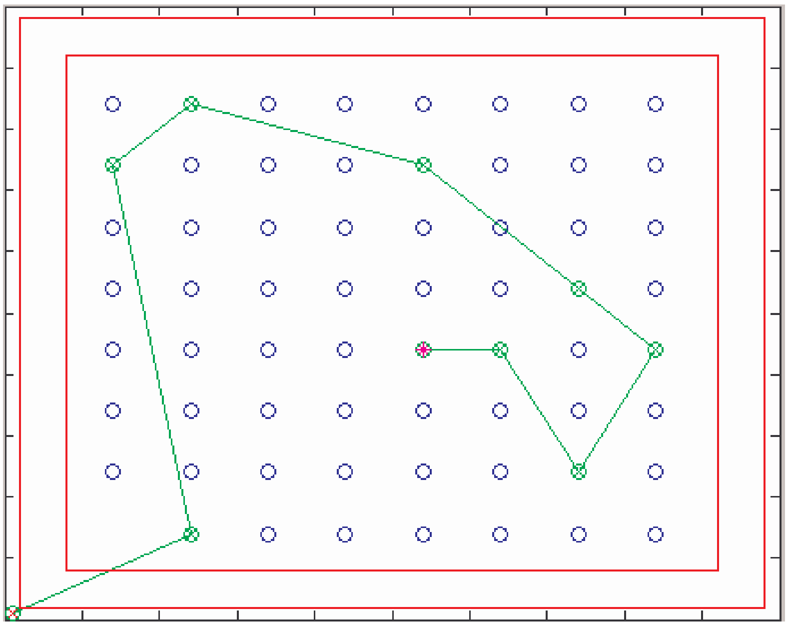

Fig. 3. AGV route example

Broken line connects the individual work stations ranging from switching station (on the bottom-left corner) until the last position with the lowest priority.

Both, mentioned in the model description, methods of artificial intelligence (fuzzy logic and genetic algorithms) have been used to build a dynamic simulation model of the production department. This model was developed using Matlab Stateflow software. An example of model for a single machine tool with a fuzzy logic unit is shown in Fig. 4.

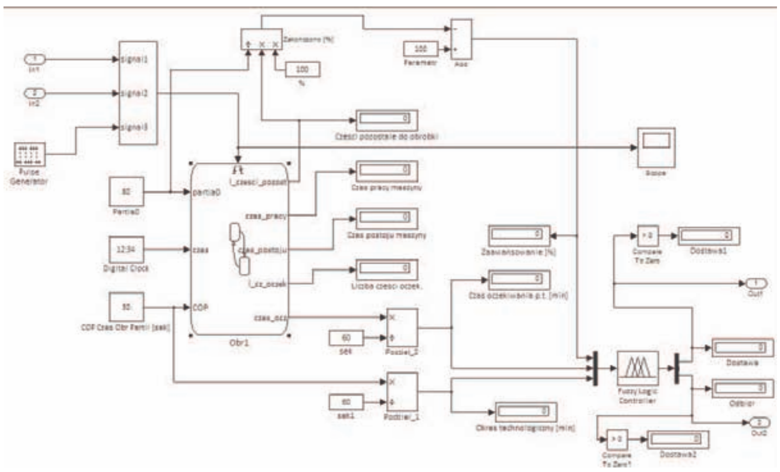

Fig. 4. Model of a single machine tool including fuzzy logic unit

4. CONCLUSION

Fig. 5 presents a vision of the simulation model proposal. It shows that before starting simulation each machine tool has the particular initial conditions e.g. the batch quantity, the batch processing time and the initial time when simulation begins. The last parameter is the same for all the machine tools in tested group. The other two parameters may be different for each of them.

After beginning a simulation process the work stations continuously send information to the fuzzy logic modules which generate output signals in second intervals. These signals are the basis to make decision about including the given work station to the transport operation of a certain kind (pick & deliver) or not. These data are analyzed and can be used any time to designate tasks and vehicle route which is reflected by **x** vector.

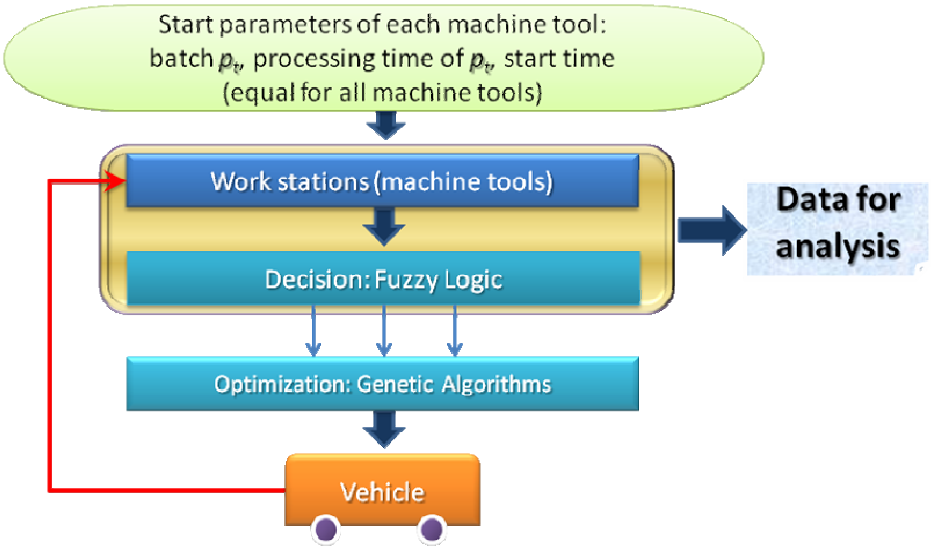

Fig. 5. Vision of the model

The proposed model allows to simulate the works transport operations within each company. Simulation is fast and affordable way of testing various configurations of the transportation system. Through simulation it is possible to select a suitable optimal number of AGV in organization, to select the vector size of the work stations that need to be serviced (P&D) in a single loop, as well as to make a choice of appropriate the work-in-progress stock level. Moreover after a particular model testing we can make an implementation in real conditions using the mentioned above control mechanisms based on fuzzy logic and genetic algorithms. Presented solution is a comprehensive system that could play an important role in planning, scheduling as well as control and monitoring of processes in works transport logistics.

Research running by many scientists point to a higher (up to 60%) effectiveness of transportation control methods based on artificial intelligence than traditional methods (e.g. time window method) (ULUSOY, SIVRIKAYA-SERIFOGLU, BILGE [2]).
Moreover common methods (e.g. knowledge-based expert systems) are often limited to their knowledge domains while the artificial intelligence systems are able to learn, generalize and always can give the results, even in an uncertain state (CHEN, HUANG, CENTENO [5]). These are the obvious arguments that the transportation problems should be solved with the artificial intelligence methods (genetic algorithms, fuzzy logic, artificial neural networks) whose advantages are: flexibility, durability, accuracy, efficiency and performance.

In this paper, where function optimized with genetic algorithm is the cost function, high efficiency of the method means a significant logistics cost reduction. This is a clear reason of significant and reasonable need to conduct further research in this field of science.

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Keywords: *mechatronics, artificial intelligence, manufacturing system, control system*

Jerzy LIPSKI*

ARTIFICAL INTELLIGENCE TECHNIQUES IN MANUFACTURING

Abstract:

Enterprises are required constantly redesign their products and continuously reconfigure their manufacturing system. Traditional approaches to design manufacturing systems do not fully satisfy this new situation. This paper is a review of mechatronic methods, particularly artificial intelligence (AI), applied to design components of manufacturing systems. The paper first defines components of designed systems and show examples applied in real conditions.

1. INTRODUCTION

The growing of industrial manufacturing and the need for higher efficiency, better product quality and lower cost have change methods of design and control processes. Based on classical theory, engineers has devised several procedures which analyze or design systems. This procedures can be summarized as [6]:

- control procedures such as series compensation, pole placement, optimal control, robust control etc.
- behavioral procedures of systems such as controllability, observability and stability tests;
- modeling procedures which consist of differential equations, input-output transfer functions and state-space formulations.

The application of this procedures alone may not be sufficient to maximize the performance of a manufacturing organization, in today's complex manufacturing systems. We can stated that when examining the nature of the different manufacturing processes, no single unifying mathematically-provable theory can cope with. We can observe the following problems:

- incomplete or excessive data;
- unidentified processes;
- inherent instability of the process;
- mixture of continuous and batch operations;
- changed processes;

Modern manufacturing technology is interdisciplinary in nature. In process design we must apply different knowledge from other scientific fields such as manufacturing, computer science,

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informatics, management, marketing and control systems. We also need to look at all aspects of the process before manufacturing a product. In many cases we also need to predict how our system will perform under certain circumstances. Our aim is to model production and control processes as accurately as possible. This aim can be obtain when we apply mechatronic methods in design process of machinetools and products. This paper is a review of the use of AI (artificial intelligence) techniques in manufacturing and control systems. Described methods make a significant contribution to improving control and manufacturing systems.

2. CASE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence has provided several techniques with applications in manufacturing. The first attempt to be widely used to equip manufacturing systems with some degree of intelligent was the use of KBS (knowledge-based systems). It was seek to incorporate human knowledge about en application area, usually elicited from experts in the particular domain. The human knowledge is represented using the IF-THEN production systems or more structured formats such as frames and semantic nets. An intelligent control system can be organized as an *on-line expert system* and comprises:

- multi-control functions (executive functions),
- knowledge base,
- inference mechanisms,
- communication interfaces.

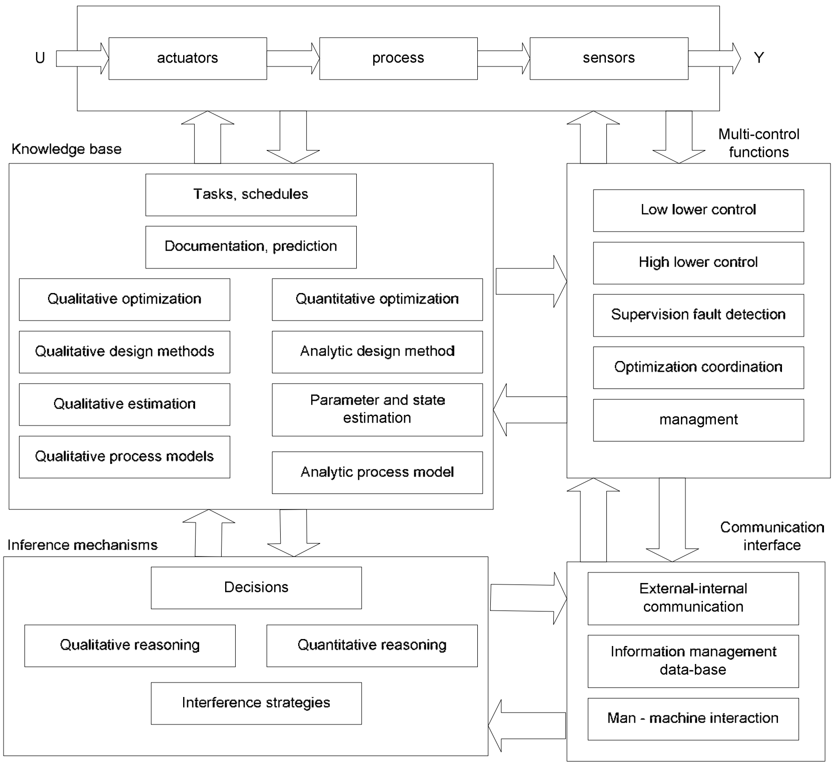

Fig. 1. Advanced intelligent automatic system

2.1. On-line expert system

The on-line *control functions* are usually organized in multi-levels. The *knowledge base* contains quantitative and qualitative knowledge. The quantitative part operates with analytic (mathematical) process models, parameter and state estimation methods, analytic design methods (e.g. for control and fault detection), and quantitative optimization methods. Similar modules hold for the qualitative knowledge, e.g. in form of rules (fuzzy and soft computing). Further knowledge is the past history in the memory and the possibility to predict the behavior. Finally tasks or schedules must be known. The *inference mechanism* draws conclusions either by quantitative reasoning (e.g. Boolean methods) or by qualitative reasoning (e.g. possibilistic methods) and takes decisions for the executive functions. Finally *communication* between the different modules, an information management data base and the man-machine interaction, has to be organized. Based on these functions of an on-line expert system an intelligent system can be built up, with the ability "to model, reason and learn the process and its automatic functions within a given frame and to govern it towards a certain goal". Hence, intelligent mechatronic systems can be developed, ranging from "low-degree intelligent" [6], as intelligent actuators, to "fairly intelligent systems", as e.g. self-navigating automatic guided vehicles. An intelligent mechatronic system e.g. adapts the controller to the mostly nonlinear behavior (adaptation) and stores its controller parameters in dependence on the position and load (learning), supervises all relevant elements and performs a fault diagnosis (supervision) to request for maintenance or if a failure occurs to fail safe (decisions on actions). In the case of multiple components supervision may help to switch off the faulty component and to perform a reconfiguration of the controlled process.

2.2. Neural networks

Neural networks (NN) have been applied with success in the identification and control of dynamic systems. The universal approximation capabilities of the multilayer perceptron make it a popular choice for modeling nonlinear systems and for implementing general-purpose nonlinear controllers. Neural network can be applied as architectures:

- Model Predictive Control;
- Feedback Linearization Control;
- Model Reference Control.

Design of control systems with Neural Network [1] can be make in two steps: system identification and control design. In the system identification stage, it is developed a neural network model of the plant that we want to control. In the control design stage, it is used the neural network plant model to design (or train) the controller. In each of the three control architectures, the system identification stage is identical. The control design stage, however, is different for each architecture.

For model predictive control, the plant model is used to predict future behavior of the plant, and an optimization algorithm is used to select the control input that optimizes future performance. This controller uses a neural network model to predict future plant responses to potential control signals. An optimization algorithm then computes the control signals that optimize future plant performance. The neural network plant model is trained offline, in batch form, using backpropagation error algorithms. The controller, however, requires a significant amount of online computation, because an optimization algorithm is performed at each sample time to compute the optimal control input.

For Feedback Linearization Control, the controller is simply a rearrangement of the neural network plant model, which is trained offline, in batch form. The only online computation is a forward pass through the neural network controller. The drawback of this method is that the plant must either be in companion form, or be capable of approximation by a companion form model.

For model reference control, the controller is a neural network that is trained to control a plant so that it follows a reference model. The neural network plant model is used to assist in the controller training. the model reference architecture requires that a separate neural network controller be trained offline, in addition to the neural network plant model. The controller training is computationally expensive, because it requires the use of dynamic backpropagation [1]. On the positive side, model reference control applies to a larger class of plant than does Feedback Linearization Control.

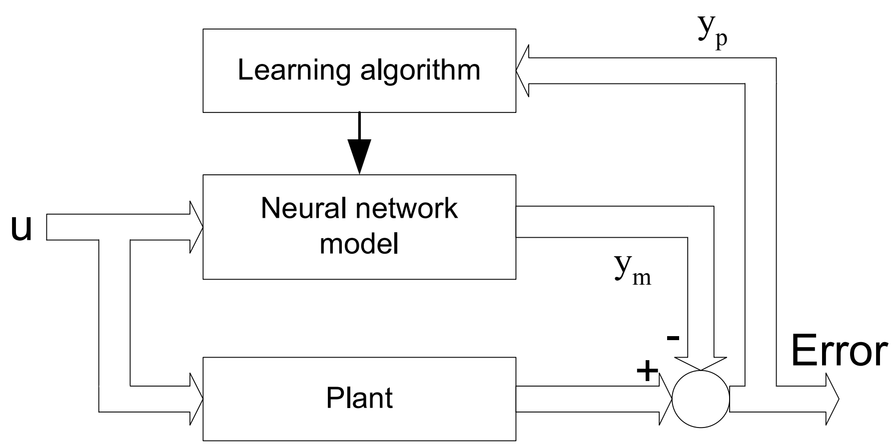

Fig. 2. System Identification

2.2.1. Model Predictive Control

The following block diagram fig. 3 illustrates the model predictive control process. The controller consists of the neural network plant model and the optimization block. The optimization block determines the values of u' that minimize J, and then the optimal u is input to the plant.

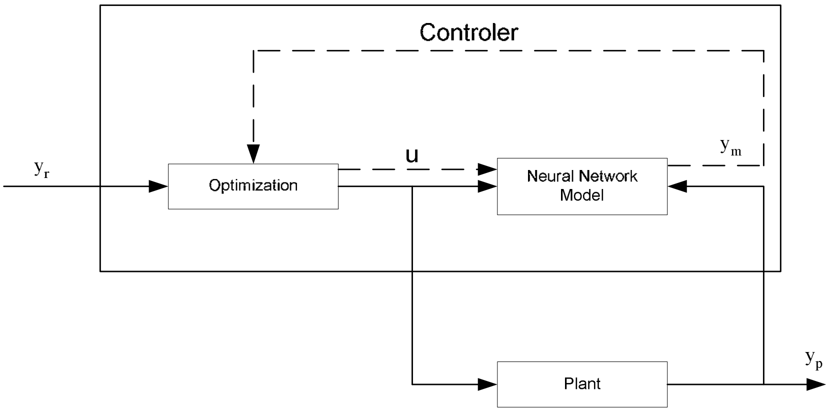

Fig. 3. The model predictive control process

2.2.2. Feedback linearization control

The second neurocontroller is referred to by two different names: feedback linearization control and NARMA-L2 control. It is referred to as feedback linearization when the plant model has a particular form (companion form). It is referred to as NARMA-L2 control when the plant model can be approximated by the same form. The central idea of this type of control is to transform nonlinear system dynamics into linear dynamics by canceling the nonlinearities.

As with model predictive control, the first step in using feedback linearization (or NARMA-L2) control is to identify the system to be controlled. We train a neural network to represent the forward dynamics of the system. The first step is to choose a model structure to use. One standard model that is used to represent general discrete-time nonlinear systems is the nonlinear autoregressive-moving average (NARMA) model:

$$y(k+d) = N[y(k), y(k-1),..., y(k-n+1), u(k), u(k-1),..., u(k-n+1)] \quad (1)$$

where u(k) is the system input, and y(k) is the system output. For the identification phase, we could train a neural network to approximate the nonlinear function N. This is the identification procedure used for the NN Predictive Controller. If we want the system output to follow some reference trajectory y(k + d) = y_r(k + d), the next step is to develop a nonlinear controller of the form:

$$u(k) = G[y(k), y(k-1),..., y(k-n+1), y_r(k+d), u(k-1),..., u(k-m+1)] \quad (2)$$

The problem with using this controller is that if you want to train a neural network to create the function G to minimize mean square error, you need to use dynamic backpropagation. This can be quite slow. One solution, proposed by Narendra and Mukhopadhyay [7], is to use approximate models to represent the system in form:

$$y(k+d) = f[y(k), y(k-1),..., y(k-n+1), u(k), u(k-1),..., u(k-n+1)] + \\ + g[y(k),..., y(k-n+1), u(k),..., u(k-n+1)]u(k+1) \quad (3)$$

Using the feedback linearization model, we can obtain the controller:

$$u(k+1) = \frac{y_r(k+d) - f[y(k),..., y(k-n+1), u(k),..., u(k-n+1)]}{g[y(k),..., y(k-n+1), u(k),..., u(k-n+1)]} \quad (4)$$

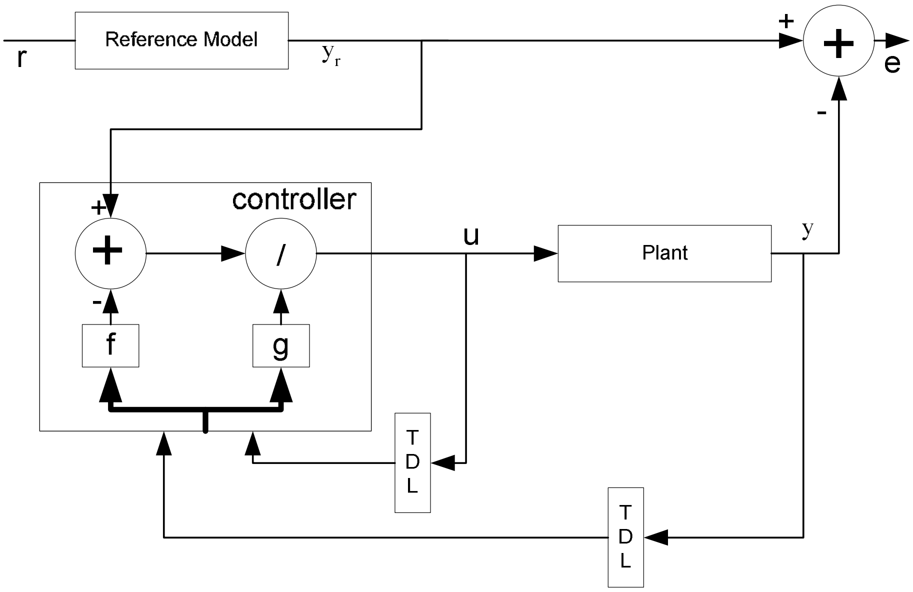

Fig. 4. Block diagram of the feedback linearization control controller

2.2.3. Model Reference Control

The neural model reference control architecture [2] uses two neural networks: a controller network and a plant model network, as shown in the following figure. The plant model is identified first, and then the controller is trained so that the plant output follows the reference model output.

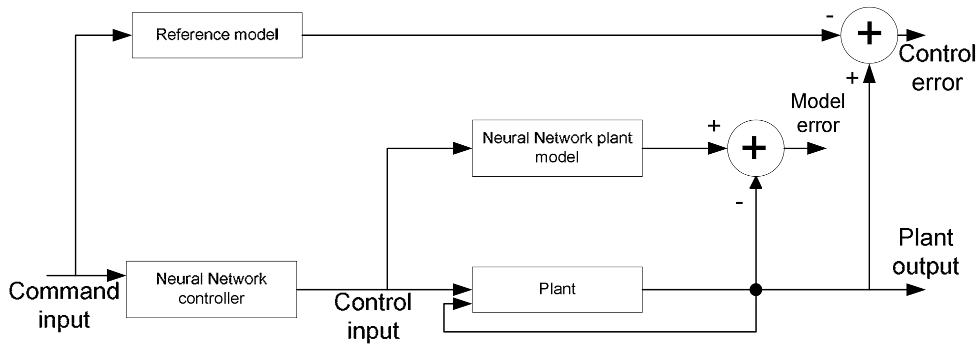

Fig. 5. The neural model reference control architecture

Each network has two layers, and you can select the number of neurons to use in the hidden layers. There are three sets of controller inputs:

- Delayed reference inputs;
- Delayed controller outputs;
- Delayed plant outputs.

For each of these inputs, we can select the number of delayed values to use. Typically, the number of delays increases with the order of the plant. There are two sets of inputs to the neural network plant model:

- Delayed controller outputs;
- Delayed plant outputs.

As with the controller, we can set the number of delays.

2.3. Genetic Algorithm

The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. We can apply the genetic algorithm to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear.

The genetic algorithm uses three main types of rules at each step to create the next generation from the current population:

- Selection rules select the individuals, called parents, that contribute to the population at the next generation.
- Crossover rules combine two parents to form children for the next generation.
- Mutation rules apply random changes to individual parents to form children.

Special form applied of genetic algorithm is Augmented Lagrangian Genetic Algorithm (ALGA) to solve nonlinear constraint problems [4]. The optimization problem solved by the ALGA algorithm is:

$$\min_{x} f(x) \quad \text{such that} \quad \begin{aligned} & c_i(x) \le 0, i = 1...m \\ & ceq_i(x) = 0, i = m+1...mt \\ & A \cdot x \le b \\ & Aeq \cdot x = beq \\ & lb \le x \le ub, \end{aligned} \tag{5}$$

where c(x) represents the nonlinear inequality constraints, ceq(x) represents the equality constraints, m is the number of nonlinear inequality constraints, and mt is the total number of nonlinear constraints. The ALPS algorithm attempts to solve a nonlinear optimization problem with nonlinear constraints, linear constraints, and bounds. In this approach, bounds and linear constraints are handled separately from nonlinear constraints. A subproblem is formulated by combining the objective function and nonlinear constraint function using the Lagrangian and the penalty parameters. A sequence of such optimization problems is approximately minimized using a pattern search algorithm such that the linear constraints and bounds are satisfied. A subproblem formulation is defined as:

$$\Theta(x, \lambda, s, \rho) = f(x) - \sum_{i=1}^{m} \lambda_i s_i \log(s_i - c_i(x)) + \sum_{i=m+1}^{mt} c_i(x) + \frac{\rho}{2} \sum_{i=m+1}^{mt} c_i(x)^2, \tag{6}$$

where:

- the components λ_i of the vector λ are nonnegative and are known as Lagrange multiplier estimates;
- the elements s_i of the vector s are nonnegative shifts;
- ρ is the positive penalty parameter.

The algorithm begins by using an initial value for the penalty parameter. The pattern search algorithm minimizes a sequence of the subproblem, which is an approximation of the original problem. When the subproblem is minimized to a required accuracy and satisfies feasibility conditions, the Lagrangian estimates are updated. Otherwise, the penalty parameter is increased by a penalty factor. This results in a new subproblem formulation and minimization problem. These steps are repeated until the stopping criteria are met.

2.4. Fuzzy logic

Fuzzy inference is a method [3] that interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. Fuzzy logic, the truth of any statement becomes a matter of degree. Any statement can be fuzzy. The major advantage that fuzzy reasoning offers is the ability to reply to a yes-no question with a not-quite-yes-or-no answer. Humans do this kind of thing all the time (think how rarely you get a straight answer to a seemingly simple question), but it is a rather new trick for computers.

The development of fuzzy logic theory [8] stimulated alternative ways to solve automatic control problems. Based on these ideas fuzzy controllers were proposed [5] which describe human control in linguistic form. As fuzzy logic provides a systematic framework to treat vague variables and knowledge it should be applied primarily if sensors yield imprecise outputs, the process behavior is only qualitatively known or the automation functions cannot be described by equations or Boolean logic. As discussed in [6] the potentials of fuzzy logic approaches in general increase with higher-automation levels, because the degree of the qualitative knowledge and the required intelligence in general grow with the hierarchical level.

The static and dynamic behavior of most systems can be rather precisely described by mathematical process models obtained through theoretical modeling and identification methods. Hence, there is in many cases no need to apply fuzzy concepts for the control of mechanical systems in the lower levels. However, fuzzy control concepts may be of interest for:

- fuzzy tuning and adaptation of classical controllers,
- fuzzy quality and comfort control,
- fuzzy control for special (abnormal) operating conditions.

Especially for the reference value generation of underlying (classical) control systems, where the quality or comfort and therefore the human reception plays a role, fuzzy rule based methods offer interesting possibilities, i.e. for the higher-control levels. Examples for such mechatronic systems are:

- the comfort control of suspensions in passenger cars,
- the comfort of start-up of automobiles with clutch manipulation and gear shifting,
- distance and velocity control of automobiles and elevators.

3. APPLICATION EXAMPLES

In Lublin University of Technology has been design the expert system for optimization of cutting tools parameters based on neural network. User this expert system can defined shape, dimensions, tolerance of product and maximal parameters of machinetool. On fig 6. has been shown interface of application destined for learning and examining neural network.

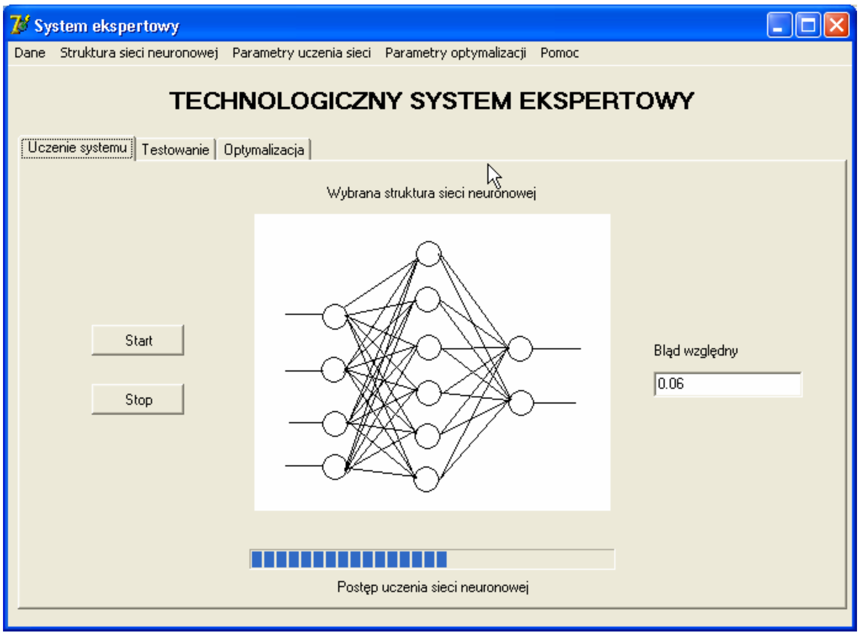

Fig. 6. Interface of expert system destined for optimize machining process

As output expert system define rate of feed, depth of cut and cutting speed for minimum costs and for stability of dimensions in range of tolerance.

Main part of this expert system is neural network which has been learning on data acquired in trying cutting process implemented on the same machine tool for different rate of feed, depth of cut and cutting speed. In trying process has been measured errors of workpiece, too. Value of workpiece deformation can be predicted by neural network in time examining process.

However, process engineer want to know how to find optimal values of this three parameters for acceptable dimensions of workpiece and maximized productivity. Answer can be obtain by optimization module build on base genetic algorithm. This algorithm can find such parameters of cutting which provide minimal machining time for acceptable error of dimensions.

Using described expert system process engineer can realize optimization off line on phase of design manufacturing process. On fig. 7 shown box diagram illustrated ideas of expert system.

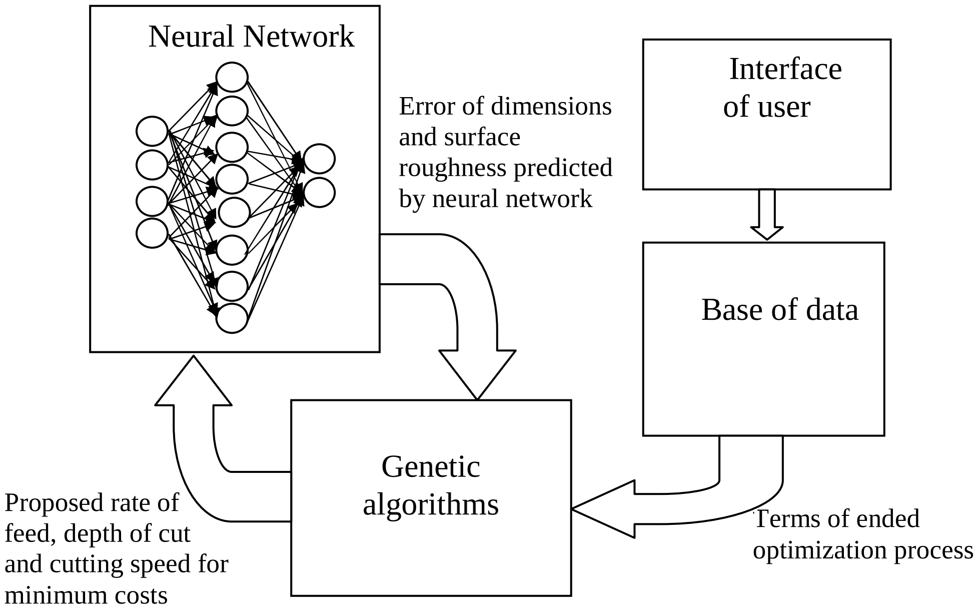

Fig. 7. Ideas for expert system applied to find optimal parameters of cutting

Another example application of artificial intelligence – diagnostic system of state production process.

If production process is monitoring, impotent parameters can be acquired and may be treat as kind of picture represented current state of production process. For deferent states we can assign name and forecast results. If neural network has been learning bases on this information, we can examined it using to diagnostic on line. Ideas of so kind system has been shown on fig. 8.

For implementation ideas expert system with applied neural network and genetic algorithm has been used informatics tools from high-level language and interactive environment MATLAB with SIMULINK.

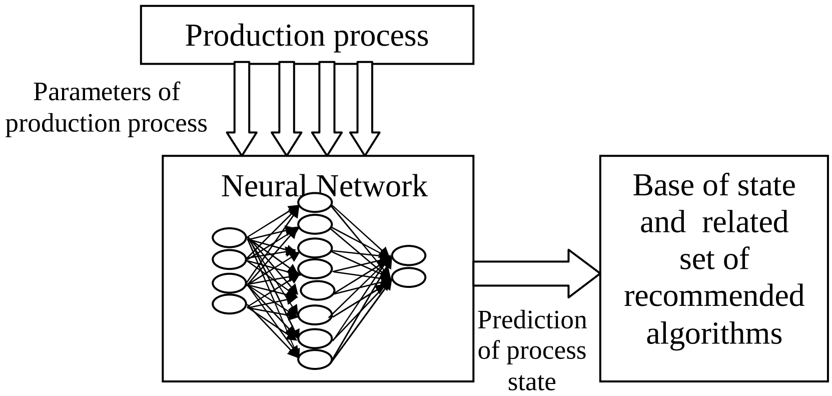

Fig. 8. Ideas of diagnostic system

To conclude, this review shows that the use of AI in design, planning, quality control, process control, can result in significant gains in these particular component areas of manufacturing. The continuing demands of the manufacturing industry will necessitate the development of AI to facilitate more integrated and holistic manufacturing systems.

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Keywords: *automation, gas, pressure, compressed air, regulator, valve*

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AUTOMATION OF GAS STATIONS THAT SUPPLY NATURAL GAS TO CUSTOMERS (PART 1)

Abstract:

The paper presents a concept developed for the automation of gas stations. The theoretical aspects of compressed air generation using natural gas energy are examined. Mathematical model of a pressure regulator created and approved by experimental studies and design projects are presented. A method for the design and use of pneumatic pressure regulators is proposed. Taking into account the process of gas strike in the pipelines, speed limits for opening and closing of gas valves are determined. Models to design gas pressure regulators and pump amplifiers for gas stations are presented. Technical data and results of studies of the pneumatic amplifiers are displayed. Amplifiers to use typical pneumatic automation in pipelines with low pressure of gas were developed.

1. INTRODUCTION

In the major part of Ukrainian gas industry, particularly when it deals with the supply of natural gas to customers at gas-distributing stations (GDS), pipe valves and pressure regulators with manual control are employed. This control process is closely connected with the human factor, and occurs only after 10-30 minutes after the moment when operator has received command from the dispatcher. In certain cases such a kind of delay of the command for change of pressure in the pipeline may lead to negative consequences for gas equipment and pipelines, which greatly decreases safety in worst-case situations. The quick opening of valves leads to hydraulic shock and wave processes in the pipelines. The time of valve opening and closing without a gas strike depends on the gas pressure in the pipeline. Large changes of pressure, even within the limits of operational characteristics for pipelines, may lead to the gas strike if those pressure changes are not taken into account in the process of valve drive control. The use of real-time operator remote control increases pipeline maintenance safety and the accuracy of controlled variables.

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Providing remote control capability to the dispatcher of GDS requires the automation of the processes of valve control and pressure regulation in the pipelines. For safety considerations, the use of electrical power in the drives dealing with gas regulation is almost excluded. The most rational method is the use of natural gas energy by transforming it to compressed air energy. A great variety of designed and produced equipment used for process automation in various industries operates on compressed air energy. It is economically feasible to save the valves and pressure regulators (PR) which are already used in industry by modifying them. Mainly at the GDS we can find PRs with working pressure of 5.5 MPa and adjustment range of 0.3 up to 1.6 MPa. Such a kind of regulators uses the two-stage regulating method, when a pilot plays the role of first stage of regulation and PR at the gas pipeline works as the second stage. The pressure regulator RTUUK-2 works in such a way, equipped with pilots KV2 and KN2 whose design incorporates an elastic diaphragm gate in conjunction with a saddle. The accuracy of such PRs at low pressures is 5%, and at high pressures -10%. In the pilot part of the regulator, for inlet pressures above 2.5 MPa a pressure reducing regulator or stabiliser is employed.

2. MATHEMATICAL MODEL OF PRESSURE REGULATOR

The proposed design with remote control of gas pressure in the pipelines and valves is based on components which are standard for equipment installed on GDS of the Ukrainian gas industry, as presented in Fig 1. The design schematic consists of gas pipeline 1, pipe valve 2, valve pneumatic drive 3, pneumatic valve which controls pipe valve 4, pressure regulator 5, pilot pressure regulator 6, proportional pneumatic pressure valve 7, compressed air supply 8. The compressed air which is used for drive of the pipe valves and for proportional pneumatic pressure valve is obtained from the energy of natural gas which flows through the pipeline.

For the transformation of energy of natural gas flowing through the pipelines into the energy of compressed air at the GDS, a “gas-air” pump-amplifier 8 is used. The pump can be designed in two forms: first – with 24 V DC power supply, second – with compressed air power alone. In Figure 1 we can see the electric pump 8, where DC is used. The parts of the pump are: gas cylinder 11, its rod, mechanically connected to the rod of the pneumatic cylinder 12, two 3/2-valves with solenoid coils 13 for the supply and vent of gas from the chambers of cylinder 11 (the valves are designed as explosion-proof), receiver 14, check valves 15, pressure relay 16.

The following changes are applied to the typical GDS schematic in Figure 1: [7]

- for opening and closing of the gas valve a pneumatic drive with valve is used;
- a pneumatic proportional valve is used as the pressure setting device for the gas pressure regulator;
- the pilot pressure regulator is modified for being controlled by a pneumatic signal;
- the “gas-air” pump is used for the control of the pneumatic automation and drives;

The modified design of the GDS inspires the possibility of a special mode of remote real-time control from operator to controller. Modern means of pneumatics operate at low pressures of 0.4–1.0 MPa and, for example, for operation from low pressure lines pneumatic amplifiers like EVBA 1111, SMC (Japan) are used. Those amplifiers, though they have rather high productivity, still have a very high weight. The weight of the amplifier without the receiver is 98 kg. The designed pump-amplifier enables increase of compressed air pressure 3.8-fold to the initial gas pressure, can work at minimal gas pressure of 0.05 MPa in the line, and uses standard pneumatic elements from different manufacturers.

The pressure regulator (Fig. 2) is mounted on support, which consists of two vertical walls, two horizontal shelves and four poles. At the left vertical wall of the support drive cylinder 2 with diameter of 63 mm is mounted. This cylinder is supplied from the low pressure line. At the right vertical wall pump cylinder 3 with diameter of 32 mm is mounted. This cylinder has a vacuum filter and a system of check valves which enable atmospheric air to be sucked in and supplied at a higher pressure to receiver 11. The rods of the cylinders are connected by means of coupling 4 which enables the transmission of only axial force. The design of the coupling enables compensation of non-concentricity which may appear in the process of constructing and installation of support 1.

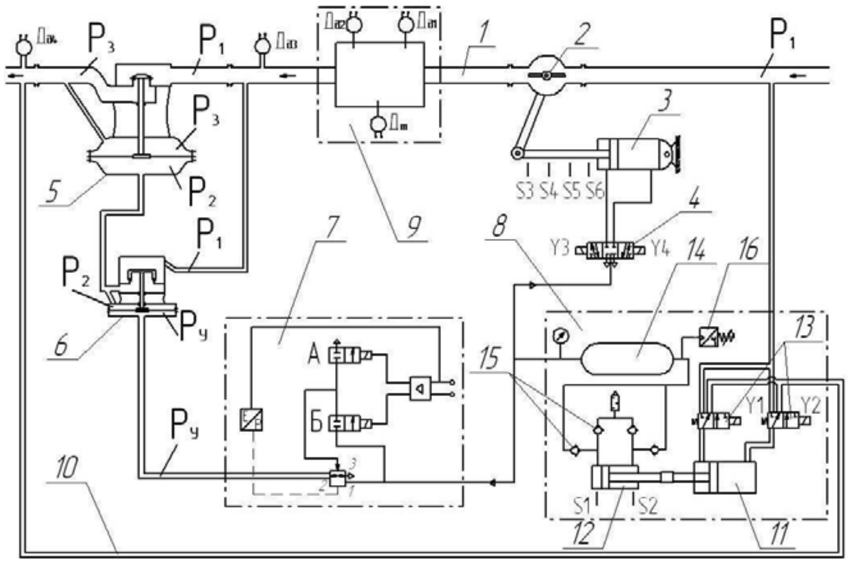

Fig. 1. Schematic of automatic GDS with remote control

The coupling consists of two half-couplings that have conical surfaces, by means of which the control of valves with roller levers is maintained. In the design of the pressure transformer there are two of such end position valves - 6 and 7.

These are mounted on the lowest horizontal shelf of support 1 and are positioned so that in the left end position of the coupling the left valve is switched and in the right end position of the coupling the right valve is switched. For precise adjustment of the positions of the valves, in the lowest horizontal shelf of support 1 special grooves are provided which enable the changeover of the valves positions. At the top horizontal shelf is mounted valve 8 with impulse and manual control. This valve inspires the commutation of gas flow in such a way that it enables forward and backward movements of drive cylinder 2 and, as a result, of the rod of pump cylinder 3. In order to increase the reliability of valve 8 in case of low pressure in the line, in the design of the pressure transformer are included two short-run cylinders 5, the chambers of which are connected in parallel to the control chambers of valve 8. So, in case of low pressure in the line, valve 8 is forcibly switched by means of the rods of pneumatic cylinders 5. At the top horizontal shelf of support 1, pressure regulator 9 with filter and pressure regulator 10 are mounted. These elements are necessary for the creation of stable air pressure drop in drive cylinder 2 power system. By means of selected diameters of cylinders 2 and 3, the pressure amplifier can increase the air pressure at the output up to 10 bar.

The pressure amplifier can work at the pressure drop without the gas vent in the atmosphere, with maximum head of 0.4 MPa, as well with the vent in the atmosphere. The pump amplifier works according to another principle. With the help of pressure regulators 9 and 10, the necessary pressure overflow in the pipeline is set. In case of supplying higher gas pressure in the rod chamber of cylinder 2, the rod moves to the left. In the extreme left position, the conical surface of the left half-coupling gets in touch with the left valve 6, which leads to the activation of one of the pneumatic cylinders 5. This switches valve 8, which in turn leads to higher gas pressure being supplied to the non-rod chamber of cylinder 2, while its rod chamber gets connected with the gas pipeline with lesser pressure. The rod of cylinder 2 moves in the right direction and by reaching (a move of 100 mm) the extreme right position the conical surface of the right half-coupling starts the activation of the right valve 7, which in turn leads to the activation of pneumatic cylinder 5 and, after that, switches valve 8 so that the direction of movement of cylinder 2 rod changes [7].

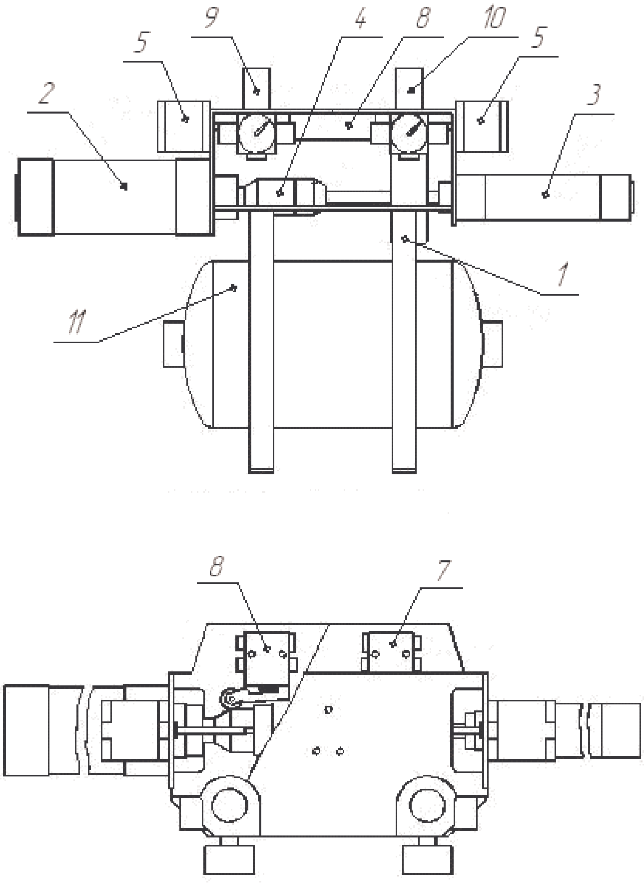

Fig. 2. General view of the “gas-air” pump-amplifier

The backward/forward movement of the rod of cylinder 2 is transmitted to the rod of cylinder 3. The system of four check valves, connected to cylinder 3 chambers, inspires the achieving of air from the atmosphere and its supply, at a higher pressure, in the pneumatic line of the customer. The design of the pressure transformer does not require any external control due to the fact that after receiving necessary air pressure level in the customer line, the forces get balanced and the rod of drive cylinder 2 stops. After the pressure in the customer line drops, the balance is destroyed and the pressure transformer begins its work again. In certain cases the pump amplifier at the GDS must work without the consumption of electrical power. Such a "gas-air" pump amplifier is designed and shown in Figure 3. It consists of pressure transforming elements and a gas distribution unit. The pressure transformer has gas and air sections. The gas section consists of the following elements: pneumatic cylinders Pc1 and Pc2 connected with each other with rods by means of coupling. The pneumatic cylinder Pc1 has a diameter of 63 mm, Pc2 cylinder – 32 mm. The supply of pneumatic cylinder Pc1 is fulfilled by gas from the 2-way 5-line valve P1 with impulse and manual control.

The control chambers of this valve, as well as the chambers of short-run cylinders Pc3 and Pc4, are connected with the outputs of the 3-line valves P and P3 with mechanical actuation by roller lever. The supply of the valves is realized by the preparation module which consists of flow valve Dr1, pressure regulator without release to the atmosphere RD1, with filter F1 and manometer. The pressure regulator RD2 can be mounted between the output of the preparation unit and release chamber, in order to create the necessary pressure reduction of 0.15 MPa. The output lines of the valves P1…P3 are connected with each other and to the output of the gas part. Such a kind of connection prevents gas getting out to the atmosphere.

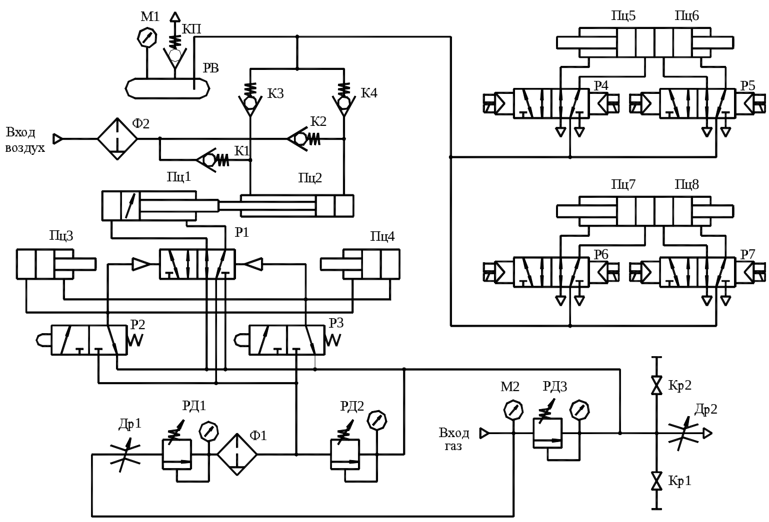

Fig. 3. Pump-amplifier pneumatic schematic

When the rod of pneumatic cylinder Pc1 is in its end position, for example the left one, the coupling pushes the lever of valve P2 which, after its activation, supplies pneumatic cylinder Pc3 and the left control chamber of valve P1. That leads to the switching of P1 in its left position. As a result, the rod of the pneumatic cylinder moves in the right direction.

At this moment the coupling stops pushing the roller of valve P2, but the movement of the rod still continues due to the fact that valve P1 has impulse pneumatic control. After the rod reaches its end right position, the coupling pushes the roller of valve P3 and, as a result, activates the end right position of valve P1 and the rod of the pneumatic cylinder Pc1 moves in the right direction. So, after supplying the gas section of the schematic with pressure, the pneumatic cylinder makes reciprocating movements. The air section of the schematic consists of pneumatic cylinder Pc2, check valves K1…K4, input air filter F1, and receiver PB which has a safety valve KP and a manometer M1. While the rod of the pneumatic cylinder Pc2 makes reciprocating movements, air - by means of check valves K1 and K2 - is supplied from the atmosphere to the chambers of the pneumatic cylinder, and by means of check valves K3 and K4 - to the receiver. The reciprocating movements of the pneumatic cylinders continue until the pressure in the receiver reaches 0.6 MPa. After that the forces on the rods get in balance and the movement stops. After the lowering of pressure in the receiver, the reciprocating movements of pneumatic cylinders resume automatically. The gas distribution unit consists of two digital pneumatic cylinders, Pc5-Pc6 and Pc7-Pc8. They are controlled by valves P4…P7. The supply of this valves is organized by air from the receiver. Digital cylinders initiate the movements of the valves in the ball valves Kr1 and Kr2. The gas supply line is a pipeline with manometer M1, pressure regulator with manometer Rd3, and flow valve Dr2 on the input [7].

Let us look at the dynamic model of the “gas-air” pump-amplifier operation. The amplifier is presented in Figure 4. The movements of gas and air flows are thought to be quasi-steady, in other words – in the flows, in all the points of the flow and chamber volumes all the parameters (pressure, temperature and solidity) tend towards equal values. The conditions of cylinder 1 and 2 rod movements are described in [1] and can be found from the following equations:

$$m\ddot{X} = P_1S_1 - P_2S_2 - P_3S_3 - F_T \ . \tag{1}$$

We can find the change of pressure in the cylinder chambers from the following equations:

$$dP_1 = \frac{dt}{X_{01} + X}\left(\frac{RT_1G_1}{S_1} - P_1\dot{X}\right) \ , \tag{2}$$

$$dP_2 = \frac{dt}{X_K - X + X_{02}}\left(P_2\dot{X} - \frac{RT_2G_2}{S_2}\right) \ , \tag{3}$$

where: m – the mass of the moving parts (rods with pistons) of cylinders 1 and 2, $\ddot{X}$ – the acceleration of the cylinder’s moving parts, P_1, P_2 – pressures in the chambers of cylinder 1, P_3 – pressure in cylinder 2 non-rod chamber, S_1, S_2, S_3 – areas of cylinders 1 and 2 pistons, F_T – friction force in the sealing of elements, R – universal gas constant, dP_1, dP_2 – pressures in the chambers of cylinder 1, X_{01}, X_{02} – initial volumes of cylinder 1 chambers reduced to the initial piston coordinates, X – the current coordinates of cylinder 1 and 2 pistons together with rod movements, X_K – cylinders 1 and 2 piston with rod strokes, T_1, T_2 – gas temperature in the chambers of cylinder1, G_1, G_2 – mass flows at cylinder 1 chambers filling and emptying.

The change of pressure in the cylinder 2 closed non-piston chamber is generally defined by the ideal gas equation:

$$\frac{dP}{dt}\cdot V = m_r \cdot R \cdot T \ . \qquad (4)$$

where: V – gas volume, m_r – gas mass, P – gas pressure, T – gas temperature, K°.

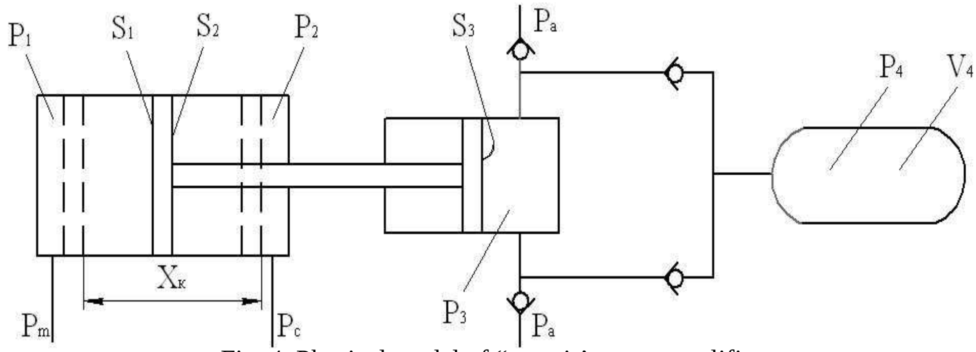

Fig. 4. Physical model of "gas-air' pump-amplifier

Assuming that the process of filling and emptying of cylinder 1 chambers happens by the adiabatic rule, and assuming sub-critical and above-critical flow condition of gas, the mass flow of the gas is described by Sen-Venan and Vanzel equation [3]:

$$G_1 = \mu_1 S_{1d} P_M \sqrt{\frac{2k}{k-1}\cdot\frac{1}{RT_1}\left[\left(\frac{P_1}{P_M}\right)^{\frac{2}{k}} - \left(\frac{P_1}{P_M}\right)^{\frac{k+1}{k}}\right]} \ \text{if} \ P_1/P_M \geq 0{,}528 \ , \qquad (5)$$

$$G_1 = \mu_1 S_{1d} P_M \sqrt{\frac{2k}{k+1}\cdot\frac{1}{RT_1}\left[\left(\frac{2}{k+1}\right)^{\frac{2}{k-1}}\right]} \ \text{if} \ P_1/P_M \leq 0{,}528 \ ;$$

$$G_2 = \mu_2 S_{2d} P_2 \sqrt{\frac{2k}{k-1}\cdot\frac{1}{RT_2}\left[\left(\frac{P_C}{P_2}\right)^{\frac{2}{k}} - \left(\frac{P_C}{P_2}\right)^{\frac{k+1}{k}}\right]} \ \text{if} \ P_1/P_M \geq 0{,}528 \ , \qquad (6)$$

$$G_1 = \mu_2 S_{2d} P_M \sqrt{\frac{2k}{k+1}\cdot\frac{1}{RT_2}\left[\left(\frac{2}{k+1}\right)^{\frac{2}{k-1}}\right]} \ \text{if} \ P_1/P_M \leq 0{,}528 \ .$$

In (6) μ_1, μ_2 – flow coefficients, S_{1d}, S_{2d} – areas of cylinder 1 chamber openings, P_M, P_C – pressure in the force and releasing lines of cylinder 1, k – adiabatic process coefficient.
By solving together equations (1) – (6) we find the speed, acceleration and forces on cylinder 1 and 2 piston rod, and also piston stroke cycle time. In the non-piston chamber of cylinder 2, the change of pressure results from air volume compression by the cylinder piston. For the closed chamber, let us put into equation (4) the equation $m_3 = Z_3 \rho V_3$ and find out the change of pressure of the compressed air in cylinder 2 chamber in time from the equation [1]:

$$dP_3 = \rho Z_3 R T_3 dt \ , \tag{7}$$

where: dP_3 – cylinder 2 chamber pressure, V_3 – cylinder 2 non-piston chamber volume, T_3 – compressed air temperature, Z_3 – air compression coefficient, ρ – air solidity at atmospheric pressure.

Compression coefficient can be found out from the volumes by the next equations

$$Z_3 = \frac{V_{03} + V_{3H}}{V_{3i} + V_{03}} \ , \tag{8}$$

where: V_{03} – tubing chambers volumes up to the check valves, V_{3H} – cylinder 2 chamber volume with the piston at its end position, V_{3i} – current volume of compressed chamber

$$V_{3H} = X_K S_3 , \ V_{03} = X_{03} S_3 \ , \ V_{3i} = (X_K - X) S_3 \ , \tag{9}$$

X_{03} – conditional reduced stroke of the tubing volumes.

Assuming the volumes, reduced to the movement, let us put conditions (9) in equation (8) and obtain the cylinder 2 chamber air compression coefficient in the form of:

$$Z_3 = \frac{(X_K - X_{03})}{(X_K - X + X_{03})} \ . \tag{10}$$

Cylinder 1 and 2 strokes are equal. Assuming equations (7) and (10) we obtain equations for finding out of cylinder chamber pressure when the piston moves:

$$dP_3 - \frac{\rho (X_K + X_{03}) R T_3 dt}{(X_K - X + X_{03})} \ . \tag{11}$$

The receiver, shown in Figure 4, is a chamber of a constant volume $V_4 = const$.

The pressure in the receiver at the supply of compressed air is generally continuous and is described as follows:

$$dP_4 = \frac{dt}{V_4} G_4 R T_4 \ , \qquad (12)$$

where: P_4, V_4, T_4 – pressure, volume and temperature of compressed air in the receiver, R – universal gas constant, G_4 – flow of compressed air which gets in the receiver.

Let us find out the mass flow of air which is supplied to the receiver, taking into account the flow condition [3]:

$$G_4 = \mu_4 S_{4d} P_3 \sqrt{\frac{2k}{k-1} \cdot \frac{1}{RT_4} \left[\left(\frac{P_4}{P_3} \right)^{\frac{2}{k}} - \left(\frac{P_4}{P_3} \right)^{\frac{k+1}{k}} \right]} \text{ , if } P_1 / P_M \geq 0{,}528 \ ,$$

$$G_4 = \mu_4 S_{4d} P_3 \sqrt{\frac{2k}{k+1} \cdot \frac{1}{RT_4} \left[\left(\frac{2}{k+1} \right)^{\frac{2}{k-1}} \right]} \text{ , if } P_1 / P_M \leq 0{,}528 \ . \qquad (13)$$

Be solving together (12), (13), we find out the time of receiver filling and the pressure inside. The air is supplied in the receiver in portions, by compressing it in the non-piston chamber of cylinder 2. Cylinder 2 chamber is a closed chamber and when piston is moving the volume and air pressure inside it are changing according to equations (7) – (11); with no emptying of the chamber. As soon as pressure P_3 in the compressed chamber of cylinder 2 gets higher than receiver pressure P_4 ($P_3 > P_4$), the check valve opens and compressed air from cylinder 2 chamber begins to flow into the receiver. From this moment we take the pressure in the chamber of cylinder 2 as constant up to the end of piston movement. The volume of compressed air, and accordingly the flow rate of the air which gets in the receiver, as well as forced out of cylinder 2 chamber volume and flow rate are equal. Assuming the fact that by one movement of cylinder 2 piston the portion of compressed air, equal to the volume V_{3H} of the cylinder 2 non-piston chamber, is supplied to the receiver we can find out the mass flow rate G_4 for portion supply to be defined by the next approximate equation:

$$G_4 = \frac{\rho S_3 X_K}{t_{c1}} \ . \qquad (14)$$

where: t_{c1} – one cycle of air compression time (stroke of piston with cylinders 1 and 2 rods), $S_3 X_K$ – volume of cylinder 2 non-piston chamber, ρ – air solidity at atmospheric pressure. The time t_{c1} is growing with every cycle.

Two methods of air compression in the receiver are available.

The first one – up to the maximum pressure, which depends on the pressure and amplifying coefficient of gas which is supplied to the first cylinder. In such a case the pump amplifier will stop to compress air in the receiver as soon as pressures in receiver and cylinder 2 chamber get to maximum, and the forces on the pistons of cylinders 1 and 2 are equal. The function of air compression in the receiver is close to the exponential rule. This is due to the fact that with every cycle the pressure and force actuating on cylinder 2 piston get higher, so – accordingly - the time of every next cycle gets longer. The first method is not efficient.

The second – when the stop of air compression process is maintained by means of pressure relay which is tuned on the necessary pressure. In such a case we can select the necessary pressure on the basis of the necessary conditions of compression time.

Usually, with this method, the time of compression up to the necessary pressure is 2…3 times lesser that with the first method. In other words – at compression up to the maximal values. The mentioned equations 1 … 14 provide the possibility of finding out the necessary parameters of compressed air pressure and flow rate for the "air-gas" pump amplifier.

The automatic opening and closing of valves, in spite of the quick work of pneumatic drives on the GDS, make it necessary to take into account the possibility of gas strike in the gas pipeline which may cause the damage of equipment.

3. CONCLUSION

The application of proportional pneumatic pressure valves in the role of master device for standard gas pressure regulators and controllers allows to automate the process of pressure regulation and to provide the remote control on the GDS. The results of modelling such a system shows that the accuracy of regulating at the pressure level up to 1,6 MPa at the pipelines with DU up to 80 mm reaches up to 2-3%, the value of over control is not larger than 8%, and the time of the over controlling process is not larger than 4-8 seconds.

In part 2 of the paper, the gas strike effect, which results in sudden pressure changes in gas pipeline during sudden change of gas flow velocity was presented. This effect appears when valve is rapidly opened or closed. The wave front of gas strike flow in gas pipeline was analyzed and equation of gas flow velocity in gas pipeline and pressure changes during direct and indirect non-full gas strike and direct and indirect full gas strike was introduced. The area of ball valve window covering is shown as well as pilot pressure regulator schematic and the maximum shift of elastic diaphragm equation. Three-stage gas pressure regulating model in consideration with technical characteristics of the proportional valve (third stage), allowing modelling of performance, accuracy, over-control of the remote control system was prepared.

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AUTOMATION OF GAS STATIONS THAT SUPPLY NATURAL GAS TO CUSTOMERS (PART 2)

Abstract:

The paper presents a concept developed for the automation of gas stations. The theoretical aspects of compressed air generation using natural gas energy are examined. Mathematical model of a pressure regulator created and approved by experimental studies and design projects are presented. A method for the design and use of pneumatic pressure regulators is proposed. Taking into account the process of gas strike in the pipelines, speed limits for opening and closing of gas valves are determined. Models to design gas pressure regulators and pump amplifiers for gas stations are presented. Technical data and results of studies of the pneumatic amplifiers are displayed. Amplifiers to use typical pneumatic automation in pipelines with low pressure of gas were developed.

1. INTRODUCTION

In Polivcev V., Polivcev Vl., Taranienko V., Świć A. Automation of gas stations that supply natural gas to customers (part 1) the application of proportional pneumatic pressure valves in the role of master device for standard gas pressure regulators and controllers allowing to automate the process of pressure regulation and to provide the remote control on the GDS were presented as well as three-stage gas pressure regulating model, in consideration with technical characteristics of the proportional valve (third stage), allows performance, accuracy, over-control of the system with remote control to be modelled.

2. THREE-STAGE GAS PRESSURE REGULATING MODEL, TAKING INTO ACCOUNT THE GAS STRIKE EFFECT IN GAS PIPE

The gas strike is something equal to the hydraulic strike and is characterized by quick change of pressure in the line in terms of sudden gas movement speed change, which is the

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consequence of the quick opening or closing of valve and so on. If the pressure increases, this is a positive gas strike, if it decreases – a negative one. The strike can be full when the movement of gas completely stops after facing a barrier, or it can be non-full when the speed of gas flow changes to a certain level.

The strike can be direct, when the valve is opened or closed quickly, or indirect, when the valve is opened or closed slowly. The most dangerous strike is the positive, full, direct one, when first there occurs the breakdown of measuring devices, other equipment, valves, and the final result may even be the break of a pipeline. The change of pressure spreads all over the length of the pipeline L with great speed C, called the speed of strike wave front spread (fig. 5).

The value of speed C of gas strike wave front spread is defined by equation [4]:

$$C = \sqrt{\frac{nRT}{\rho}} \ , \tag{15}$$

where: n – index of polytropic process, R – universal gas constant for natural gas, T – temperature of natural gas, ρ – solidity of natural gas.

The value of C cannot exceed the speed of sound spreading in natural gas.

The gas strike is full when the gas completely stops its movement after the strike in the barrier ($W_0 = 0$ – speed of gas that moves in the pipeline after the strike wave front) and not full, when the speed of gas that moves in the pipeline W_0 by striking a barrier, after it changes to a certain value W.

The gas strike is direct when opening and closing of valve (or other units) happens fast enough $t_3 < t_f$, or indirect – when the slowing down of gas flow at the barrier happens on the condition of $t_3 > t_f$.

The increasing of pressure with (positive) direct gas strike could be found be N.E. Jukovsky equations for liquid [2]:

At direct strike $\Delta p = \rho_1 C W_0$, (16)

At indirect strike $\Delta p = \rho_1 C (W_0 - W)$, (17)

where: W_0 – speed of gas that moves in the pipeline after the strike wave front, W – speed of gas after the gas strike, ρ_1 – solidity of gas with pressure P_{M1} in the pipeline after the strike wave front at the moment of strike (Fig. 5).

The increase of pressure with (positive) indirect gas strike can be found by equations:

At direct strike $\Delta p = \dfrac{\rho_1 2 L W_0}{t_3}$, $t_3 < t_f$. (18)

At indirect strike $\Delta p = \dfrac{\rho_1 2 L (W_0 - W)}{t_3}$, $t_3 > t_f$. (19)

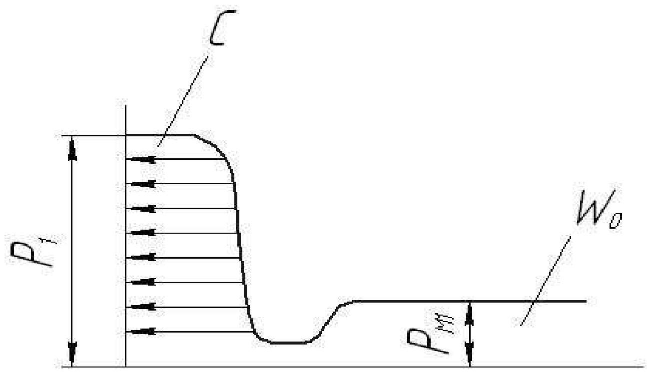

Fig. 5. The front of gas strike wave spreading in the pipeline

where: t_3 – tome of valve actuation, L – length of gas pipeline in which the strike wave is spreading.

The full pressure, when the gas strikes the barrier (Fig. 5), is equal to the pressure of gas that is after the strike wave front plus the pressure jump from equations (16), (17), (18), (19):

$$P_1 - P_{M1} + \Delta P \ .$$

The doubled phase or one period (cycle) of the strike wave $t_{\text{ф}}$ is defined as:

$$t_f = 2L / C \ . \qquad (20)$$

Gas, in comparison to a liquid, is a compressed medium and the solidity of gas increases with growing pressure. Let us find out natural gas solidity change as a function of pressure change for the common case – polytropic process [3].

Be using the polytropic equation $\dfrac{P_{M1}}{\rho_{M1}^n} = \dfrac{P_M}{\rho_M^n}$, the equation for gas condition $P_M \cdot V = mRT_M$ and gas solidity $\rho = m / V$, let us obtain the final value of solidity with the polytropic process:

$$\rho_{M1} = \frac{P_M}{RT_M} \left(\frac{P_{M1}}{P_M} \right)^{\frac{1}{n}} , \qquad (21)$$

where ρ_{M1}, ρ_M - current value of gas solidity with the pressure of gas in pipeline P_{M1} after the valve and the solidity of gas with the pressure P_M before the valve, V – gas volume, m – gas mass, R – universal gas constant, T_M - temperature of gas in the pipeline, n – the criteria of polytropic process.

Let us find out the speed of gas movement in the pipeline W_0 (after the valve has been opened) at the moment of strike, using Bernulli equations [3]:

$$\frac{W_0^2}{2}+\frac{n}{n+1}\left(\frac{P_{M1}}{\rho_{M1}}-\frac{P_M}{\rho_M}\right)+\xi\frac{W_0^2}{2}=0\ , \tag{22}$$

where ξ – local resistance coefficient.

Let us solve the equation (22) by W_0 and obtain a new equation

$$W_0=\frac{1}{\sqrt{1+\xi}}\sqrt{\frac{2n}{n-1}\left(\frac{P_{M1}}{\rho_{M1}}-\frac{P_M}{\rho_M}\right)}\ . \tag{23}$$

Assuming the polytropic process for correlation of pressures, gas solidity and gas conditions equations mentioned above, let us transform equation (22) and obtain an equation for speed:

$$W_0=\frac{1}{\sqrt{1+\xi}}\sqrt{\frac{2nRT}{n-1}\left[1-\left(\frac{P_{M1}}{P_M}\right)^{\frac{n-1}{n}}\right]}\ . \tag{24}$$

Depending on switching speed and level of valve opening (closing), the shutoff element of the pressure regulator takes a direct full strike - equation (16), or indirect full strike - equation (18). Let us put ρ_{M1} from equation (21) and speed W_0 from equation (24) in the equations (16), (18) and obtain the next equations:

For direct full strike

$$\Delta P=\frac{CP_M}{RT_M}\left(\frac{P_{M1}}{P_M}\right)^{\frac{1}{n}}\frac{1}{\sqrt{1+\xi}}\sqrt{\frac{2nRT}{n-1}\left[1-\left(\frac{P_{M1}}{P_M}\right)^{\frac{n-1}{n}}\right]}\ . \tag{25}$$

For indirect full strike

$$\Delta P=\frac{2LP_M}{t_з RT_M}\left(\frac{P_{M1}}{P_M}\right)^{\frac{1}{n}}\frac{1}{\sqrt{1+\xi}}\sqrt{\frac{2nRT}{n-1}\left[1-\left(\frac{P_{M1}}{P_M}\right)^{\frac{n-1}{n}}\right]}\ . \tag{26}$$

The measuring system 7, represented at figure 1, gets under the direct non-full and indirect non-full strikes which are described by equations (3), (5). The same way, let us put ρ_{M1} from equation (21) and speed W_0 from equation (24) in equations (17), (19) and obtain the next equations:

For direct non-full strike

$$\Delta P = \frac{CP_M}{RT_M}\left(\frac{P_{M1}}{P_M}\right)^{\frac{1}{n}}\left\{\frac{1}{\sqrt{1+\xi}}\sqrt{\frac{2nRT}{n-1}\left[1-\left(\frac{P_{M1}}{P_M}\right)^{\frac{n-1}{n}}\right]}-W\right\} . \tag{27}$$

For indirect non-full strike

$$\Delta P = \frac{2LP_M}{t_з RT_M}\left(\frac{P_{M1}}{P_M}\right)^{\frac{1}{n}}\left\{\frac{1}{\sqrt{1+\xi}}\sqrt{\frac{2nRT}{n-1}\left[1-\left(\frac{P_{M1}}{P_M}\right)^{\frac{n-1}{n}}\right]}-W\right\} . \tag{28}$$

In equation (24), the speed of strike wave spreading (speed of gas flow) cannot exceed the speed of sound and depends on some critical value of pressure correlation $\beta_{KR} = P_{M1} / P_M$. The critical value of pressure is found from the equation [3]:

$$\beta_{KR} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} . \tag{29}$$

With the value $P_{M1} / P_M < \beta_{KR}$ the speed of gas flow is close to the speed of sound, and the critical value of pressure is acquired from equation (29). With the value $P_{M1} / P_M > \beta_{KR}$ the speed of the strike wave is defined from equation (24). In other words, it is necessary to take into consideration, for equations (25), (26), (27), (28), the critical correlation of pressures before and after the valve from equation (29).

The speed of opening and the area of the open section of valve 2 define the value of pressure P_{M1} after the valve and the speed of gas flow W_0 (the speed of strike wave spreading) in the section of pipeline up to the gas pressure regulator 5 (Fig.1)

For defining the mass flow rate G of gas that passes through the ball valve 2 let us use the equations of Sen-Venan and Vanzel for sub-critical flow of gas: [3]:

$$G = \mu S_3 P_M \sqrt{\frac{2n}{RT(n-1)}\left[\left(\frac{P_{M1}}{P_M}\right)^{\frac{2}{n}} - \left(\frac{P_{M1}}{P_M}\right)^{\frac{n+1}{n}}\right]} , \quad P_{M1} / P_M > \beta_{KR} , \tag{30}$$

where μ – flow rate coefficient, S_3 – area of valve opening window, P_M, P_{M1} –pressures before and after the valve. The above-critical flow of gas is not taken into consideration, as the speed of gas movement before the valve cannot exceed the speed of sound, or - in other words - the speed of sound spreading in the gas $a_{зв}$.

The flow rate coefficient can be defined as follows:

$$\mu = \frac{Z}{\sqrt{1+\xi}} \ ,$$

where: Z – coefficient of gas jet compression after the passing of valve window, ξ – coefficient of local losses in the valve.

Assuming that the flow rate which is supplied to the valve is a constant value for a certain time period (at the moment of valve opening), let us reorganize the equation (30) by P_{M1} and write it as follows:

$$A(P_{M1})^{n+1} + B(P_{M1})^2 - C = 0 \ , \qquad (31)$$

where: $A = -\frac{1}{(P_M)^{n+1}}$, $B = \frac{1}{(P_M)^2}$, $C = \left(\frac{G^2 RT[n-1]}{\mu^2 S_3^2 2n}\right)^n (P_M)^{2n}$.

By solving equation (31) we can find the pressure P_{M1} after valve opening. Pressure P_{M1} in equation (31) greatly depends on the area S_3 of the window opening and the time t_3 of activation of valve 2. The time of valve activation is defined by the rule by which the cylinder 3 rod and the drive of valve 2 move, and the area of window opening - by geometric characteristics which depend on the design of shutoff part and the value of its movements.

In the gas industry branch valves with ball shutoff part are extensively employed. The process of opening and closing of such a valve is presented in Figure 6. The maximal area of window opening (the valve is fully opened) is:

$$S_3 = \pi r^2 \ .$$

The minimal area of window $S_3 = 0$ (the valve is fully closed). The intermediate positions of shutoff part of the ball valve as well as the areas of window are defined by the following equation:

$$S_3 = r_1\left(\frac{\pi\alpha_1^\circ}{180} - \sin\alpha_1^\circ\right) + r_2\left(\frac{\pi\alpha_2^\circ}{180} - \sin\alpha_2^\circ\right) \ , \qquad (32)$$

where: r_1 – radius of shutoff part ball valve window, r_2 – radius of let-through part of valve housing, $\alpha_1^\circ, \alpha_2^\circ$ - central angle (degrees) of valve window area segments which are found from the next equations:

$$\alpha_1^\circ = 2\arccos\frac{r_1 - h_1}{r_1} \ ,$$

$$\alpha_2^\circ = 2\arccos\frac{r_2 - h_2}{r_2} \ .$$

where: h_1, h_2 – arrows of valve window area segments, $x = h_1 + h_2$, x – movement of valve drive shutoff part, $h_1 / h_2 = r_1 / r_2$.

By using the necessary rule for the control of valve drive (the size of movement x, its speed, and time of opening) it is possible to obtain, for the gas regulator, the indirect full, and for the measuring equipment – indirect non-full gas strike that allow to reduce (or completely eliminate) the possibility of breakdown for regulated shutoff equipment and measuring devices. Assuming equations (26), (31) and (32) or (28), (31) and (32), as well as t_3 which is obtained from the speed of shutoff part movements, we can obtain the rule for valve control (when opened, closed) for the safe regulating maintenance of the shutoff part and measuring devices on the gas distributing stations. The equations (25) and (27) can be used for cases when the valve is fully opened and the time of its opening and closing for practical cases of $t_3 < 0.1 \ldots 0.5$ seconds. In that case there happens a direct gas strike, and the speed of strike wave spreading in the pipeline may reach the speed of sound in the gas medium. This mode does not guarantee safe operation of the GDS.

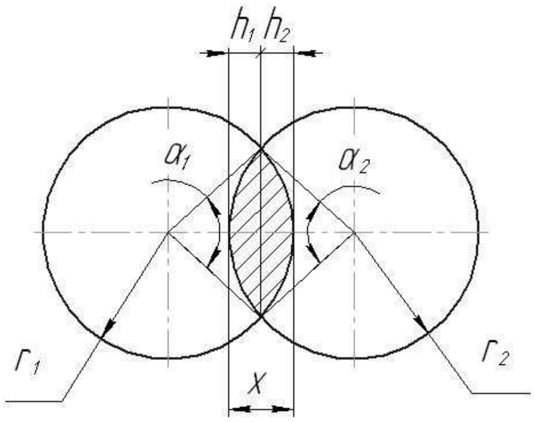

Fig. 6. Area of ball valve window covering

Let us consider a 3-stage model for gas pipeline pressure regulation which allows to choose the necessary control rule for automatic remote control by operator. The first and second stages are pressure regulators 6 and 5 (Fig. 1), and the third – proportional pneumatic pressure valve 7.

Be it the design that the pilot gas pressure regulator is a diaphragm drive with a shutoff element and a saddle, with four chambers A, B, E,O, and a housing (Fig. 7).

` Let us represent the equation of forces acting on the diaphragm of the pilot regulator [1] as:

$$m\ddot{X} = S_e P_2 + SP_1 + cX + F_n - S_e P_y \ , \tag{33}$$

where: m – mass of the moving parts (rod and gate valve), $\ddot{X}$ - acceleration of the moving parts of diaphragm drive, S_e - effective area of diaphragm, S – area of gate element, P_1 – gas pressure at the pilot regulator input and chamber O, P_2 – gas pressure at the pilot regulator output and chambers B, E, c - spring force, X – value of diaphragm rod and gate element shift, F_n – value of spring pre-tension, P_y – compressed air pressure (control) fed into chamber A.

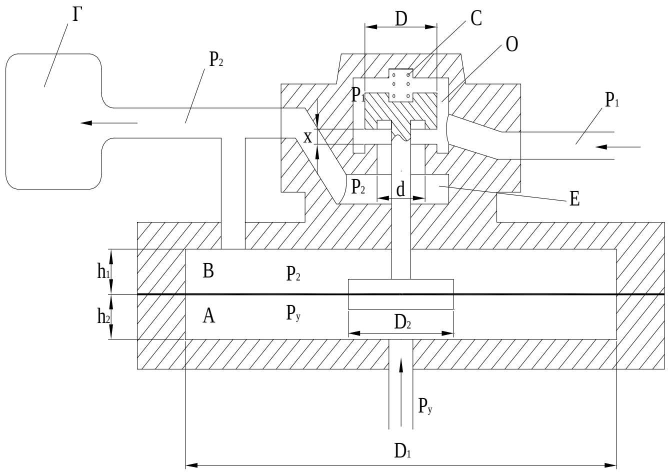

Fig. 7. Pilot pressure regulator schematic

The effective area of elastic diaphragm is found from the Liktan equation [5] on the basis of (Fig. 8):

$$S_e = \frac{\pi D_1^2}{12}\left[1+\gamma+\gamma^2 - \frac{x(1-\gamma)\sqrt{4+7\gamma+4\gamma^2}}{\sqrt{5(x_{\max}^2 - 5x^2)}}\right]. \quad (34)$$

The maximum shift of elastic diaphragm:

$$x_{\max} = \frac{x_0\sqrt{5(1+\gamma+\gamma^2)+(1-\gamma)(4+7\gamma+\gamma^2)}}{(1+\gamma+\gamma^2)\sqrt{5}}, \quad (35)$$

where: $\gamma = D_1 / D_2$, x_0 - shift of elastic diaphragm without load, x - actual coordinate of diaphragm centre shift.

$S = \frac{\pi D_1^2}{4}$ - primary area of flat diaphragm.

The change of gas mass in the chamber with volume V and for adiabatic process is found out from the equation:

$$M = \frac{P_2}{RT}V \quad , \tag{36}$$

where: $V = V_0 + V_1$, V_0 – constant volumes of chambers $V_0 = V_{01} + V_{02} + V_{03}$ (for chamber E - V_{01}, chamber G - V_{02}, connection pipes - V_{03}), V_1 – volume of diaphragm chamber B, which includes constant volume ($Sh1-Sx0$) and variable one - $S_e x$, by means of diaphragm shift (fig. 3) $V_1 = S(h_1 - x_o) - Sex$.

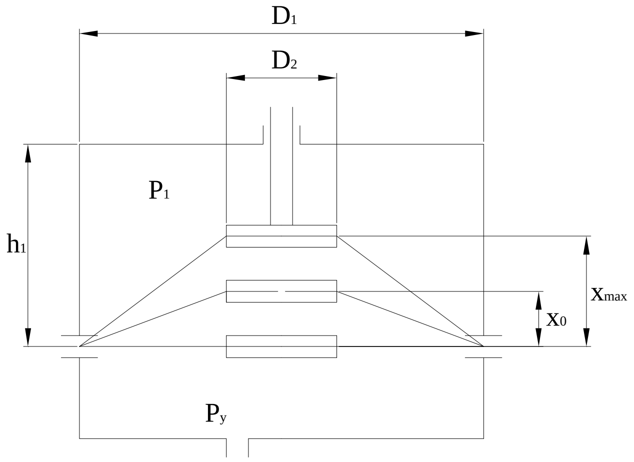

Fig. 8. Diaphragm drive principle of work

Let us differentiate by time the equation (4) and transfer it by $\frac{dP_2}{dt}$:

$$\frac{dP_2}{dt} = \frac{1}{V_0 + S(h_1 - x_0) - S_e x}\left(RTG - P_2 S_e \dot{x}\right) \ , \tag{37}$$

where $\frac{dP_2}{dt}$ is the change of pressure on the regulator output in the corresponding chambers with common volume V (fig. 1), R – universal gas constant, T – gas temperature, $G = \frac{dM}{dt}$ - mass usage of gas coming in volume V, P_2 – pressure at the regulator output, $\dot{x}$ - speed of diaphragm centre shift.

Taking in consideration the sub-critical and above-critical flow condition of gas through the gate part of pressure regulator we can find out the mass flow of gas:

$$G = \mu\pi dxP_1\sqrt{\frac{2}{RT}\frac{k}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{k}} - \left(\frac{P_2}{P_1}\right)^{\frac{k+1}{k}}\right]} \text{ by } P_2/P_1 > \beta_{KR}\ , \tag{38}$$

$$G = \mu\pi dxP_1\sqrt{\frac{2}{RT}\frac{k}{k+1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k}}} \text{ by } P_2/P_1 < \beta_{KR}\ , \tag{39}$$

where: d – diameter of saddle opening of pressure regulator, x – shift of diaphragm centre and gate element of pressure regulator, k - ratio of specific heats for natural gas, β_{KR} – critical factor defining the sub-critical and above-critical flow condition of gas:

$$\beta_{KR} = \left(\frac{P_1}{P_2}\right)_{KR} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} .$$

In automated GDS the role of master pressure control is played by proportional pressure valve which provides continuous signal in the form of compressed air pressure coming in the upper part of chamber A. Then, the proportional pressure valve obtains a continuous electrical signal in the form of voltage or current level from the controller. The controller is controlled remotely by means of dispatcher control centre. Equations 33…39 describe the gas pressure control of the pilot part of the scheme.

The force pressure regulator installed directly on the gas pipeline almost fully repeats in its design the design of the pilot regulator and differs only in its size and relative opening.

Let us represent the equation which describes the action of forces on the diaphragm and gate element of the regulator in such a way:

$$m_1\ddot{x}_1 = S_{E1}P_3 + S_1P_1 + c_1x_1 + F_{\Pi 1} - S_{E1}P_2\ , \tag{40}$$

where: m_1 – mass of the moving parts (rod and gate valve), $\ddot{x}_1$- - acceleration of the moving parts of diaphragm drive, S_{E1} - effective area of diaphragm, S_1 – area of gate element, P_1 – gas pressure at the pilot regulator input, P_2 – gas pressure in chamber G, P_3 – pressure level on the pilot regulator output, c_1 - spring force, x_1 – value of diaphragm rod and gate element shift, $F_{\Pi 1}$ – value of spring pre-tension.

Taking into consideration the design properties of regulator 5 (Fig.1), gas at its output flows through the flow chamber with the volume V_3. Let us write the equation of pressure change in this chamber in the following way:

$$\frac{dP_3}{dt} = \frac{G_3RT_3}{V_3}\ , \tag{41}$$

where: G_3 – mass usage of gas in the flow chamber with volume V_3, T_3 – gas temperature.

Taking in consideration the sub-critical and above-critical flow condition of gas through the gate part of pressure regulator we can find out the mass flow of gas:

$$G_3 = \mu_3 \pi d_1 x_1 P_1 \sqrt{\frac{2}{RT_3}\frac{k}{k-1}\left[\left(\frac{P_3}{P_1}\right)^{\frac{2}{k}} - \left(\frac{P_3}{P_1}\right)^{\frac{k+1}{k}}\right]} \text{ by } P_3/P_1 > \beta_{KR}, \quad (42)$$

$$G_3 = \mu_3 \pi d_1 x_1 P_1 \sqrt{\frac{2}{RT_3}\frac{k}{k+1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k}}} \text{ by } P_3/P_1 < \beta_{KR}. \quad (43)$$

The above described three-stage gas pressure regulating model (equations 33…43), in consideration with technical characteristics of the proportional valve (third stage), allows performance, accuracy, over-control of the system with remote control to be modelled.

3. CONCLUSION

The modernization of standard gas equipment on Ukrainian GDS by the proposed method allows the process of regulation of natural gas pressure and its supply to the customers to be automated, at costs 2 to 4 times less than in the case of complete replacement of gas equipment with foreign one. Such a kind of method gives possibility to implement remote control by operator in the online mode, thus increasing the efficiency and safety of the GDS work. Elements of pneumatic automation were use for the automation of gas valves and pressure regulators. These elements work from the energy of compressed air which is the most safe source of energy. In the proposed method, the compressed air for the elements of pneumatic automation is obtained from the energy of flowing natural gas by means of a “gas-air” pump-amplifier. Such a kind of energy transformation allows only source of energy to be used – compressed natural gas.

The application of proportional pneumatic pressure valves in the role of master device for standard gas pressure regulators and controllers gives possibility to automate the process of pressure regulation and to provide remote control on the GDS. As the main results of modelling such a system show, the accuracy of regulating at the pressure level up to 1.6 MPa at the pipelines with DU up to 80 mm is 2..3%, the value of over-control is not larger then 8%, and the time of the process over-controlling is not larger than 4..8 seconds. The increase of pressure regulation precision and thus of flow rate, increases the possibilities of GDS in supplying natural gas to the customer, dependently on his specific requirements at the present moment of time. The accuracy of gas consumption metering increases.

The obtained technical characteristics of modernized gas pressure regulators are equal to the finest world analogues in this field and their modernization requires less investments compared to analogous elaborations. The suggested model for opening and closing of gas valves at different pressures in the pipelines allows control rule that eliminates gas strike to be implemented, which in turn increases the safety and efficiency of gas equipment.

Such a kind of method for GDS automation and remote control gives possibility to modernize the gas-distributing industry of Ukraine in shorter times and with less capital investments.

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