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INTERNET OF THINGS FOR ROBOTIC PROJECTS

The **subject** of research in the article is the application of IOT technology in flexible integrated robotic systems. The **goal** of the work is to integrate IOT technology with models and decision-making methods in order to create an adaptive control system for flexible robotic production. The article solves the following **tasks**: to analyze the application of IOT technologies in various fields, including in robotics, to consider the construction of an intelligent decision-making system as one of the key elements of automated control systems, to consider the development of an adaptive control system for a flexible robotic section and its individual modules. The following results were obtained: the main features of the IOT technology were analyzed, including those for implementation in flexible integrated systems of modern production; it is proposed to introduce intelligent production agents into the composition of technological systems, as means of transport and auxiliary assembly purposes, monitoring means and establish the basic requirements for them; from a formal point of view, the decision-making process is considered until the achievement of individual technological tasks. **Conclusions**: currently, there is a growing interest in the Industry 4.0 concept, in its implementation for the digital transformation of production systems, and one of these areas is the use of IOT technology, which will allow in production conditions to combine elements of flexible integrated production distributed in space, to ensure monitoring of production processes in real time, the functioning of an adaptive control system based on an intelligent decision-making system, which will improve the characteristics of control processes of a robotic system as part of a flexible integrated production.

Keywords: technology of the Internet of things; making decisions; mobile robot; flexible integrated system.

Introduction

While constant progress in communication and computer systems attracts the permanent interest to them from side of professionals, researchers and users, manufacturing systems cannot show such quick changes, because of technological problems and greater cost of equipment. Among the concepts, which describe the organization and control of manufacturing systems we still can see Flexible Integrated Systems (FIS) (fig. 1), currently improved by introduction of intelligent components and tools [1, 2, 4]. Such system usually consists of number of machine tools, manipulation a assembling cells and special equipment. The supplement of FIS is provided by robots [3].

Currently used FIS have several disadvantages. Their control systems of FIS are too centralized. The technological equipment simulation tools are obsolete. The tools of autonomous monitoring and control for workplaces are mostly at research stage. The intelligence of modules of technological tasks analyses for decision-making in particular workplaces on real-time monitoring results is not sufficient. There are no modules of decision-making adaptation to global of local changes of workspace of FIS states. The learning and self-learning tools are limited. The modern communication and integration modules between elements need for improvement. Such improvement can be achieved by application of intelligent systems, including manipulation and transport robots, integrated to distributed control system of FIS [5, 6].

Functioning of technological equipment in FIS for real conditions is affected by external factors of different nature: of static and moving workspace objects, of people, of robots, of other equipment. In such case, decision-making systems have the increasing role, making plans of FIS functioning for global and local tasks. This defines the task to develop the tools for intelligent decision-making of FIS control system, using AI-methods to improve the quality of manufacturing problems solution.

Currently we can see growing interest to Industry 4.0 concept, to its introduction for digital transformation of manufacturing systems. Production systems become the market, for which the most of projects of Industrial Internet of Things (IIoT) have their implementation. IIoT, with its base on Industry 4.0 and industrial Internet, is a key component of industrial development worldwide [7]. The Internet of Robotic Things is a new vision of problem, which unites the wide application of sensors and robotic objects. This concept can be effectively applied to solve problems of FIS, providing information support of decision-making components of FIS control system and more autonomous functioning of robots. Combination of industrial technologies and Internet of Things can potentially create perspective services [8].

Basic tasks of robotic iot concept

The initial idea of IIoT-robotics is traced from distributed, heterogenous paradigms of robotic control, for example from networking and clouding robotic systems. The term of "Internet of Robotics Things" (IoRT) was created to set the concept, according to which sensor data from different sources are received and processed with application of local and distributed data, then applied to control and manipulate the objects of physical world [7]. IoRT systems can be created by wide application of sensor systems and technologies of data analyses with final goal of best execution of tasks of industrial and other application.

Cloud computations and IIoT are technologies, which not directly connected to robotics, but supply the creation of distributed robotic systems. Fig. 2 shows the scheme of this concept. Technologies of IIoT must be based on the next principal elements: wide application of sensors for robotic objects and workspaces; connection between intelligent mechatronic objects; analytic data tools with semantic technologies, transforming heterogeneous sensor data.

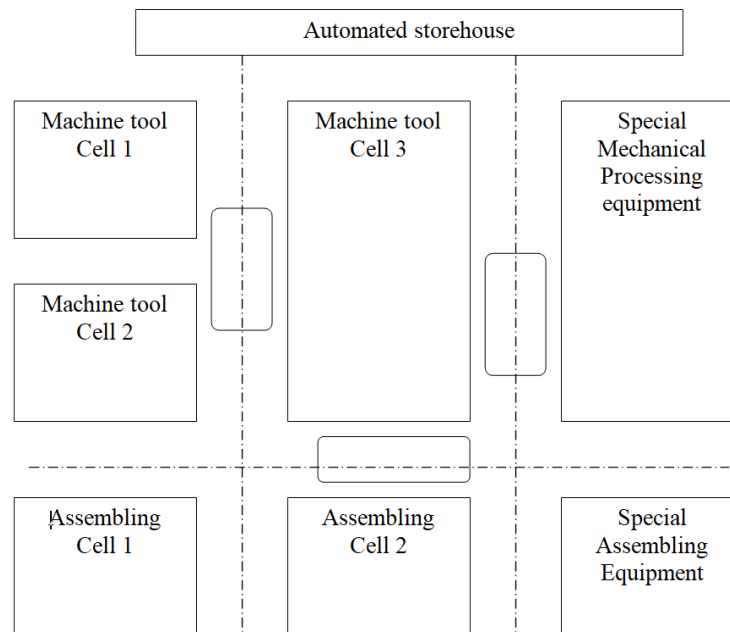


Fig. 1. Example of FIS composition

In structure of IoRT the real-time cloud computations supply the networking access (on requests) to virtualized hardware resources (of processing and storage) or to services of upper level. The cloud infrastructure is used by IoT tools for extraction of scaled services of IoT platform, providing an access for sensor data (not-processed, processed and mixed). The processing of data streams, generated by IoT-devices inside several centralized data processing centers, can be problem for real time systems in case of information processing delays [8].

The cloud paradigm was meet by robotic community as a tool to simplify tasks with abnormal consumption of resources, to exchange data and knowledges between robots, to supply function of robot's reconfiguration.

The technologies, based on application of sensors and analytic IoT tools, can give robots more wide possibilities in comparison to on-board system, especially from point of view of workspace, time and information type. Moreover, the application of in-build sensors allows their application in more flexible and dynamic way, possibility to use more complex strategies of active research in workspace.

The key challenge of IoRT is a distribution in time and in space. First, the methods to obtain data must be selected. In a part of works [3], there is proposed to use the local databases for every object. In this case data are organized in hierarchi of space, for example: robot has position in relation to robot, robot is positioned in a room etc. Other authors propose [6] robots to send requests to distributed centers on monitoring, for example of particular areas and objects of workspace.

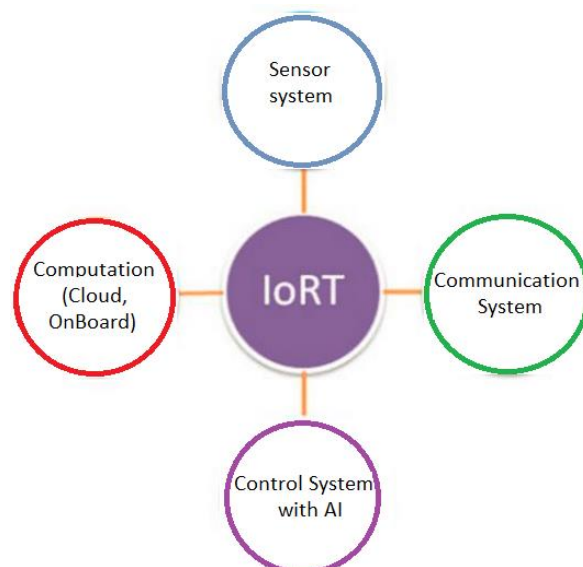


Fig. 2. Structure of IoRT [7, 8]

The systems of sensors can also be organized in distributed way. For example, the distributed cameras can help robot to find the charging station in a huge manufacturing workspace [5].

Artificial intelligence in Robotic IOT

The key element of robot's ability to perceive information is acquisition of knowledges on its location with ability to construct or renew workspace models. Despite the great progress in this area, the independent localization is still complex problem, especially for global or overcrowded workspace. In this view, the application of GPS-sensors is limited by specifications of GPS-standard (for civil systems) and by lacks for internal workspaces. In this way, application of IoT can essentially improve the quality of information about "robot's world".

The ability to move is one of fundamental characteristics of mobile robotic system. The existence of IoT supplies mobile robots with additional information on workspace, for example on possible control of automatic doors and lifts, on location of other mobile objects and equipment.

Services of IoT can simplify application of robots for such areas as logistics of object's supplement; agriculture; monitoring of environment; search and rescue in case of disasters when infrastructure is damaged or absent. In such case, mobile robots will possibly need extended communication at level of special networks, when every robot can be used as node in infocommunication system.

Manipulation of robots is also a key element of IoT. Industrial robots, supplied by manipulators, or mobile robots, equipped by on-board manipulators, can take, elevate, keep and move objects, using the system of on-board sensors.

The additional quality of IoT application for robotics is in possibility to get specifications of objects, including that of them, which are not observed by sensors, but, for example, have an effect for procedures of manipulation with objects like manipulations of assembling industrial robot.

The autonomy of robot's decisions belongs to ability of system to select the best solutions for goals and tasks. Here, more and more actual positions are for methods of motion planning on base of AI, for probabilistic models of workspaces and possible actions of robots in them.

The quality of plans is critically dependent of quality of these models and of estimation of initial state.

Other interesting feature of IoT for robotics is in ability of robot to interact physically, cognitively and socially to users, operators or other systems. Technologies of IoRT can improve interaction between human and robot on functional (command and software) and social levels, and be tool of interaction [3, 7].

The functional possibilities of IoT sensors can make more reliable the interaction of humans and robots. Here, the desired level can be in application of natural communication language, especially for non-professional users, while it is a base for various uncertainties and undeterminations. The other kind of communication is sign language, applied for example for pointing of objects.

In this case, the perspective way is in combination of computer vision system with sensors in-build on clothes of operative personal of factory [9, 10].

The responses of operative personal in a signs, voice of face mimics can be applied for estimation of emotion state of users and for initialization of robot's response for them. The integration to IoT sensors on operator's body or clothes can improve estimation of solution by measurement of physiological signals of heart rate, of skin conductivity. These estimations are bases for adaptation of robot's interaction strategy, f.e., implemented for development of robot-assistant for health-care or medical sphere.

The cognitive abilities of robots on base of IoT can be essentially increased if robots will "feel" the connection between them and surrounding workspace, will estimate possible their effect and results of actions. All these are bases for such aspects of cognition and multi-modal perception and social intelligence

Logical model for intelligent robot functioning

From point of view of robotic intelligent control system development, the decision-making process is in the functional strategies planning, which contains the definition of objective, executed by system, the description of all the alternative ways of objective achievement, solving methods for particular practical tasks [11, 12].

To solve the tasks of intelligent system decision-making support for flexible integrated robotized system (FIRS) there is proposed the following concept on adaptation of functionality [13]:

- a) there are the subject (subjects) of strategies planning – the mobile or manipulation robot (robots), equipped by automated control system;
- b) there are the objects of FIRS, for which the decision is made and decision can be implemented;
- c) there is the workspace, which includes the subjects and object of strategies planning, also other objects, having effect to strategies planning process, the nature of FIRS workspace is given and can be determined or stochastic;
 - d) properties of strategies planning subject are:
 - technical (ability for decision execution);
 - functioning strategies development according to current state of workspace;
 - strategies execution by way of movements in space or manipulation with objects as to developed strategy;
 - strategy adaptation for cases of manufacturing task changes or changes in workspace;
 - plan execution adaptation according to strategy;
 - e) Intelligent system of decision-making support of executing subject's control system, correspondently consists of the following parts:
 - workspace information storage unit (for simplest case – database, for more complex cases is connected to sensor system of executive subject);
 - the unit of operative schemes with standardized description of particular problem solutions (in other word, the knowledge base of robot's ACS);

- strategies search unit, which on base of particular strategies planning stage or global goal proposes the hypothesis (in general case) for functional strategy;

- strategies planning unit, which on base of sensor system interaction must monitor the workspace changes and, therefore, change (in other terms modify or adapt) the solution implementation plan;

- target formulation unit;

- ACS results verification unit;

- movements and manipulation formation unit.

The actual problem of modern flexible integrated system (FIS) is still in supplement of execution of production functions, directed to production efficiency [15].

The selection of logical model as a base for strategies planning isn't accidental. The planned actions of robot may look ordered, checked and logical for common sense. Other feature of accepted solution is it's verification for current conditions of WS, so the decision, accepted for space S is true at time moment t and can be false at $t+1$, but decision always has the value of variety.

Logical model gives possibility to use designations similar to standard theory set model.

Suppose, there are sets X, D, S of robotic system (RTS) states, its decisions, states of workspace (WS), correspondently.

Then $x_i \in X, d_i \in D, s_i \in S$ are the atomic expressions in model describing RTS and WS activity.

For element of sets, X, D, S operations $\neg, \wedge, \vee, \rightarrow, \leftrightarrow$ are introduced.

In this way the Right-Constructed Formulas are $\neg x, x \wedge y, x \vee y, x \rightarrow y, x \leftrightarrow y$.

To describe the theory sets X, D, S the functions and predicated are introduced.

Function of RTS state's transition: $x_i = f(x_0, \dots, x_{i-1})$,

Function of WS state's transition: $s_i = f(s_0, \dots, s_{i-1})$.

Also there is introduced the predicates connecting elements of sets X, D, S : $pt(x_i), pt(s_i), pt(d_i), pt(x_i, s_i), pt(x_i, d_i), pt(d_i, s_i), pt(x_i, d_i, s_i)$, supplying the description of RTS and WS properties, their interaction and connection.

Among the predicates:

$pr(x_i, s_i) \subset pt$ – set of RTS descriptions in WS,

$ps(x_i, s_i) \subset pt$ – set of WS states,

$pa(x_i, s_i) \subset pt$ – set of RTS actions in WS,

$pg(pr, ps) \subset pt$ – set of RTS goals in WS.

The goal of RS is defined as a new (or existing) state of RS or of WS: $pg(pr, ps) \leftarrow (pr(x_i, s_i) \vee ps(x_i, s_i))$.

RS database is defined as a set of declarations of type $pr(), pt(): pr(x_i), pr(x_i, s_i), ps(s_i), ps(x_i, s_i)$.

RS knowledge base is depicted as definition of possible actions $pa(x_i, s_i)$ of RTS in WS.

Description $pa(x_i, s_i)$ is a strategy to reach goal $pg(pr(x_i, s_i), ps(x_i, s_i))$, if conjunction of RTS actions, which supplies $pg(pr(x_i, s_i), ps(x_i, s_i))$ is:

$$pg(pr(x_i, s_i), ps(x_i, s_i)) \leftarrow pa^0(x_i, s_i) \wedge pa^1(x_i, s_i) \wedge \dots \wedge pa^{n-1}(x_i, s_i),$$

or $pg(pr(x_i, s_i), ps(x_i, s_i)) \leftarrow \bigwedge_{i=0}^{n-1} pa^i(x_i, s_i)$,

and besides:

$$\exists f, f \in F : x_i = f_i(x_{i-1}, s_{i-1}),$$

$$\exists \psi, \psi \in \Psi : x_i = \psi_i(x_{i-1}, s_{i-1}).$$

$$\text{Therefore, } pa(x_i, s_i) = T \left\| f_i + \psi_i \right\|.$$

The decision-making process is sequential set of m -alternatives to reach the goals of the system:

$$pg^0(pr, ps) \leftarrow pg_0^0(pr_0, ps_0, pa_0) \wedge pg_1^0(pr_1, ps_1, pa_1) \wedge \dots \wedge pg_{n-1}^0(pr_{n-1}, ps_{n-1}, pa_{n-1}) = \bigwedge_{i=0}^{n-1} pg_i^0(pr_i, ps_i, pa_i)$$

$$pg^m(pr, ps) \leftarrow pg_0^m(pr_0, ps_0, pa_0) \wedge pg_1^m(pr_1, ps_1, pa_1) \wedge \dots \wedge pg_{n-1}^m(pr_{n-1}, ps_{n-1}, pa_{n-1}) = \bigwedge_{i=0}^{n-1} pg_i^m(pr_i, ps_i, pa_i).$$

In this way the global goal is describes as follows:

$$pg^{total}(pr, ps) \leftarrow \bigvee_{j=0}^{m-1} \bigwedge_{i=0}^{n-1} pg_i^j(pr_i, ps_i, pa_i).$$

For conditions of RTS goal formulation there is developed the initial plan with next state's transformations:

$$pr(x_1, s_1) \leftarrow pa_0^0(pr(x_0, s_0) \vee ps(x_0, s_0)),$$

$$pr(x_n = Y, s_n) \leftarrow pa_{n-1}^0(pr(x_{n-1}, s_{n-1}) \vee ps(x_{n-1}, s_{n-1})).$$

But for case of dynamic state of WS the achievement of particular $pg(pr(x_i, s_i), ps(x_i, s_i))$ becomes impossible:

$$pr(x_i, s_i) \neq pa_i^0(pr(x_{i-1}, s_{i-1}) \vee ps(x_{i-1}, s_{i-1})).$$

For such case, the scheme needs for modification:

$$pr(x_i, s_i) \leftarrow pa_i^*(pr(x_{i-1}, s_{i-1}) \vee ps(x_{i-1}, s_{i-1})),$$

$$pr(x_{i+1}, s_{i+1}) \leftarrow pa_{i+1}^*(pr(x_i, s_i) \vee ps(x_i, s_i)),$$

what, as result, gives the strategy decision modification:

$$pg^{m*}(pr, ps) \leftarrow pg_0^{m*}(pr_0, ps_0, pa_0) \wedge pg_1^{m*}(pr_1, ps_1, pa_1) \wedge \dots \wedge pg_{n-1}^{m*}(pr_{n-1}, ps_{n-1}, pa_{n-1}) \text{ Defi} = \bigwedge_{i=0}^{n-1} pg_i^{m*}(pr_i, ps_i, pa_i).$$

$$\text{ne } X = \{X^0, X^1, \dots, X^{n-1}\} \text{ as a set of RTS states.}$$

Therefore, there is developed the logical model of adaptive strategies planning for intellectual control systems of FIS, which uses the predicates logics and describes the relationships between robot and objects in WS, formulates the goals of control system as needed states of workspace and supplies the constructions of logical inference. This model is tested in Robotic Lab of CITAM dept in KhNURE.

Proposed model is applied for realtime decision-making as a part of complex industrial system, including mobile, manipulation robots and other equipment, united by wireless integrated control system, combining all the parts under concept of IoRT. From other hand IoRT part supplies the information support for predicate-based decision-making.

Conclusion

Growing interest to Industry 4.0 concept, to its introduction for digital transformation of manufacturing systems. Production systems become the market, for which the most of projects of Industrial Internet of Things (IIoT) have their implementation. IIoT, with its base on Industry 4.0 and industrial Internet, is a key component of industrial development worldwide.

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ІНТЕРНЕТ РЕЧЕЙ ДЛЯ РОБОТОТЕХНІЧНИХ ПРОЄКТІВ

Предметом дослідження в статті є застосування технології ІОТ у гнучких інтегрованих роботизованих системах. **Мета** роботи – інтеграція технології ІОТ з моделями та методами прийняття рішень з метою створення адаптивної системи керування гнучким роботизованим виробництвом. В статті вирішуються наступні **завдання**: провести аналіз застосування технологій ІОТ в різних галузях, в тому числі, в робототехніці, розглянути побудову інтелектуальної системи прийняття рішень як одного з ключових елементів автоматизованих систем керування, розглянути розробку адаптивної системи керування гнучкої роботизованої ділянки та її окремих модулів. Отримано наступні **результати**: проаналізовано основні особливості технології ІОТ, в тому числі, для реалізації у гнучких інтегрованих системах сучасного виробництва; до складу технологічних систем пропонується впровадження інтелектуальних виробничих агентів, як засобів транспортного і допоміжного складального призначення, засобу моніторингу та встановлюються основні вимоги до них; з формальної точки зору розглядається процес прийняття рішень до досягнення окремих технологічних завдань. **Висновки**: в даний час спостерігається зростання інтересу до концепції Industry 4.0, до її впровадження для цифрової трансформації виробничих систем і одним з таких напрямків є застосування технології ІОТ, що дозволить в виробничих умовах об'єднати розподілені в просторі елементи гнучкого інтегрованого виробництва, забезпечити моніторинг виробничих процесів в режимі реального часу, функціонування адаптивної системи управління на основі інтелектуальної системи прийняття рішень, що дозволить поліпшити характеристики процесів управління роботизованої системи в складі гнучкого інтегрованого виробництва.

Ключові слова: технологія інтернету речей; прийняття рішень; мобільний робот; гнучка інтегрована система.

ІНТЕРНЕТ ВЕЩЕЙ ДЛЯ РОБОТОТЕХНИЧЕСКИХ ПРОЕКТОВ

Предметом исследования в статье является применение технологии ИОТ в гибких интегрированных роботизированных системах. **Цель** работы – интеграция технологии ИОТ с моделями и методами принятия решений с целью создания адаптивной системы управления гибким роботизированным производством. В статье решаются следующие **задачи**: провести анализ применения технологий ИОТ в различных областях, в том числе, в робототехнике, рассмотреть построение интеллектуальной системы принятия решений как одного из ключевых элементов автоматизированных систем управления, рассмотреть разработку адаптивной системы управления гибкой роботизированной участка и его отдельных модулей. Получены следующие **результаты**: проанализированы основные особенности технологии ИОТ, в том числе, для реализации в гибких интегрированных системах современного производства; в состав технологических систем предлагается внедрение интеллектуальных производственных агентов, как средств транспортного и вспомогательного сборочного назначения, средства мониторинга и устанавливаются основные требования к ним; с формальной точки зрения рассматривается процесс принятия решений до достижения отдельных технологических задач. **Выводы**: в настоящее время наблюдается рост интереса к концепции Industry 4.0, к ее внедрению для цифровой трансформации производственных систем и одним из таких направлений является применение технологии ИОТ, что позволит в производственных условиях объединить распределенные в пространстве элементы гибкого интегрированного производства, обеспечить мониторинг производственных процессов в режиме реального времени, функционирования адаптивной системы управления на основе интеллектуальной системы

принятия решений, что позволит улучшить характеристики процессов управления роботизированной системы в составе гибкого интегрированного производства.

Ключевые слова: технология интернета вещей; принятие решений; мобильный робот; гибкая интегрированная система.

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