International Conference Cybernetics & Informatics 2022
Visegrád, Hungary, September 11th - September 14th, 2022

Implementation of Heterogeneous Multirobotic Cell Control Using Visualization Techniques

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***Abstract*—The article is focused on the use of progressive techniques in the process of design and implementation of a heterogeneous multirobotic cell control system. The task of visualization as a modern approach to the creation of applications for industrial automation is presented. The way of using the visual approach in the creation of the robotic cell workspace monitoring system and the identification of work parts based on machine vision is declared. Visual programming in the form of Stateflow diagrams is also used for the creation of a superior control system based on PLC. Visualization techniques are also used in the process of multirobotic cell operation control by a web-oriented application using augmented reality. The article provides a comprehensive view of the representation of visualization techniques in design process of applications for industrial automation on a specific implementation example.**

Keywords—heterogeneous multirobotic cell, control system, visualization, progressive design techniques

I. Visualization in the Process of Creating Control Systems for Industrial Automation

Today's modern industrial technologies are based primarily on the combination of modern computer information processing technologies with industrial automation control technology. Their advantages complement each other and thus create forms of management and control technologies designed for the field of industrial production. Computer control mainly concerns the presetting and control of each step in the industrial production process through elements of unified algorithmization. In this way, it is possible to ensure that all types of data in the production process can be collected and processed efficiently in a timely manner and thus improve production efficiency and, as a result, achieve a comprehensive technology benefit for the company [1].

Applying the principles of the Industry 4.0 concept is possible with two different approaches. One of the options is a comprehensive or partial renewal of technological equipment, which means a significant financial and energy investment. However, it is possible to apply the principles of the Industry 4.0 concept even without the need for significant investments in the revitalization of complete technical equipment. By appropriate use of available progressive methods and (often freely available) software tools in conjunction with existing technical equipment, it is possible to achieve full or at least partial coverage of the requirements arising from this concept.

A. Visualization as a Programming Technique for Industrial Logic Controllers

The rise of wireless industrial technologies, sensors and sensor networks or cloud computing has supported the emergence of new requirements for industrial applications. These PLC IoT applications require the ability to send notifications based on sensor status through various information channels (e-mails, SMS, push notifications), easy access to data via PC and mobile devices and increasingly sophisticated data analysis. All this means that access to the content and logic of the control code needs to be changed. Due to the simpler, faster, and more efficient multi-domain implementation, a change in the actual code creation process is also required.

Graphic programming methods have been used in the areas of production and automation for quite some time. Software tools such as LabView from National Instruments or Simulink from MathWorks, including many patented PLC programming tools, are ultimately very similar to classic text languages such as Cobol or C. However, a major difference is their graphical programming interface, also referred to as visual programming. This element has significant advantages in terms of the convenience of creating the program and is currently quite commonly used in the creation of automation and production IT systems.

Visual programming uses a variety of graphically represented objects, based on which the programmer creates, configures, and modifies programming schemes, which represent various concepts and algorithms of programming. After completing the visual representation, this diagram can be translated or compiled into a standard executable program and then deployed to a specific hardware element, or it can be directly performed as a simulation replacement for that hardware. Graphic tools are ideal for the description and programming of complex automation systems, from the level of specific production machines, through the layer of a complex production line to the level of MES. This approach makes it possible to combine various complex parallel,

This publication was written with the financial support of the VEGA agency in the frame of the projects 1/0176/22 "Proactive control of hybrid production systems using simulation-based digital twin" and 1/0193/22 "Proposal of identification and monitoring of production equipment parameters for the needs of predictive maintenance in accordance with the concept of Industry 4.0 using Industrial IoT technologies"

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sequential, and iterative tasks, which would not be possible using classical text-sequence programming approach.

One, already relatively well-established method of visual programming is the use of Petri nets. Petri net as a method of visual modeling represents graphical and mathematical formalism of work procedures and processes. Petri nets have been used for quite some time to model and simulate the behavior of various complex systems, especially where it is necessary to capture parallel processes. The problem, however, is the implementation of the Petri net directly in the PLC. The possibility is, for example, the implementation of logic outside the PLC itself, or the currently developed methodology of application and platform independent implementation [2, 3]. Petri nets are also widely used in automated production and development of MES systems. For example, Simatic IT software from Siemens, which is used to manage production operations, is based on the concept of the Petri net.

Impossibility of exchange code or the programmer dependence are well-known drawbacks of traditional programming. A new multilevel graphical and modular approach for programming industrial PLCs is one of possible solutions. The proposed paradigm exploits several object-oriented features, improving the re-use of code, develops objects to be used in a plug and play way understandable by so many developers. Hence this framework reduces the PLC brand and programmer dependence [4].

For complex automation tasks, state diagrams have been proposed for PLC programming. However, state diagram method has some limitations. A new PLC design approach to eliminate these limitations was proposed. In this method, identification of the functions of datapath and controller and the inputs/outputs of both is needed. Next, the Algorithmic State Machine (ASM) charts are used to draw the state transitions for the controller. Finally, a ladder diagram is designed from the ASM chart [5].

A different method of visual programming is used in Matlab software with toolboxes Simulink, Stateflow and Simulink PLC Coder (Fig. 1). The graphic language Stateflow combines state diagrams, flow diagrams, or transition and truth tables with continuous and discrete systems via Simulink.

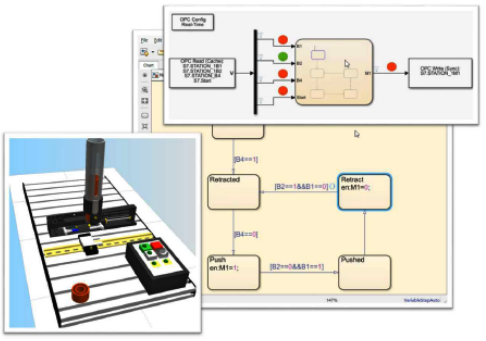


Fig. 1. Simulink Stateflow – Example of visual PLC programming.

The semantics of Stateflow are deterministic in this case because the user defines the order of system states processing. Stateflow enables the design and development of user interfaces, task scheduling, error management systems, control logic, communication protocols as well as hybrid systems. With the support of the Simulink PLC Coder toolbox, the result is a fully implementable code in the form of structured text according to the IEC 61131-3 standard for a wide range of PLC manufacturers [6-9].

B. Augmented Reality in Industrial Automation

Augmented Reality (AR) represents a direct or indirect view to a physically real scene, while certain elements can be enriched with additional digital information relevant to the object the user is looking at. So, it's a combination of the real world with a virtual environment. The virtual environment enriches the view of systems in the form of virtual models. The information presented through them is obtained from various information sources using off-line or on-line applications. Reality enrichment usually takes place in real time and in a semantic context with parts of the environment.

The engineering approach allows to superimpose virtual elements combined from CAD models and other additional data over views of real objects displayed on mobile devices, desktops, smart glasses, or specialized headsets. It is the superposition of the virtual environment over the real environment that distinguishes AR from Virtual Reality (VR), which gives the user access to a completely virtual environment created exclusively from digital elements.

With new advances in computer and manufacturing technology, there is a growing trend that allows users to directly access manufacturing information associated with manufacturing processes. Augmented and mixed reality has the ability to integrate responses to these requirements in real time into a real work environment, which is useful for specific production activities, especially assembly, as well as for training and maintenance.

There is a wide range of AR use in industrial environment, from intelligent predictive maintenance control using smart glasses [10], through control, monitoring and diagnostics of mechatronic devices using a mobile device [11] to modern alternative for control and monitor IoT devices using modern information and communication technologies, including virtual, augmented, and mixed reality [12].

Implementing augmented reality is usually more complex than implementing virtual reality because the AR system requires some mechanism to determine where the elements are in the real world so that the virtual elements can overlap as accurately as possible. Because many of these problems have already been addressed in the computer gaming industry, developers of AR applications, designed not only for the industrial sector, have adapted these principles and technologies to the gaming industry. For example, some applications use a headset equipped with a video camera with additional sensors, such as infrared sensors or radar. In addition to capturing regular video, these devices also measure depth and create perspective. The software, meanwhile, superimposes the virtual scene on the image of the real environment. Based on the evaluation of all information from the sensors, it is possible to draw a virtual model of the technical equipment in an adequate scale, position, and orientation with respect to the observer [13-17].

II. Heterogeneous Multirobotic Cell Configuration

The case study is focused on the implementation of a control system for a complex robotic workplace with a common shared dynamic workspace.



Fig. 2. Heterogeneous multirobotic cell.

The multirobotic cell, shown in Fig. 2, is part of the Laboratory of Control Systems of the University Science Park Campus Bottova (CAMBO) at the Faculty of Materials Technology STU in Trnava. The handling elements are represented by three autonomous robots of different manufacturers. The shared workspace is complemented by a conveyor belt and the entire space is equipped with a monitoring camera system. A programmable logic controller is used as a master control element. The complete list of technical elements of model heterogenous multirobotic cell is given in Tab. I.

TABLE I. Robotic Cell Hardware Configuration

Technical element	Specification
robot ABB IRB 120	control unit IRC5 Compact 6 axes payload 3 kg range 580 mm three-finger pneumatic gripper SMC MHSL3-16D solenoid valve SMC SY5120-5YO-C4F-Q rubber vacuum suction cup SMC B40 vacuum ejector SMC ZH13B solenoid valve VT307V
robot ABB IRB 140	control unit IRC5 Compact 6 axes payload 6 kg range 810 mm three-finger pneumatic gripper FESTO DHDS-16-A solenoid valve CPE10-M1BH-5L-M5 electromagnetic gripper E1AS 0111
robot Mitsubishi Melfa RV-2FB-D	control unit CR750-D 6 axes payload 3 kg range 504 mm two-finger parallel pneumatic gripper FESTO DHPS-16-A solenoid valve FESTO VUVG-L10-P53C-T-M5-1P3 optical sensor FESTO SOEG-L-Q30-P-A-S-2L
conveyor belt	width 300 mm length 1000 mm 3-phase asynchronous motor BONFIGLIOLI BN 63 A 4 3-phase frequency inverter SIEMENS SINAMICS 6SL3210-1KE11-8AB1 retroreflective photoelectric sensors TELEMECANIQUE SENSORS XUB1BPBNL2
vision system Cognex In-Sight 7050-01	monochromatic resolution 800x600 pixels RS-232C and Ethernet
PLC SIMATIC S7-1200	Ethernet and Profinet HMI panel Siemens SIMATIC KTP400 Basic 6AV2123-2DB03-0AX0

III. Design and Implementation of a Control System

A. Visualization in The Process of Control System Design - Identification of Components

The control system of the model robotic cell includes a control subsystem of the dynamic component of the shared workspace - conveyor belt, implemented by a Siemens SIMATIC S7-1200 programmable logic controller. The shared workspace is monitored by the Cognex IS 7050-01 sensor subsystem in combination with photoelectric sensors.

In the model case, the Cognex IS 7050-01 machine vision system is designed to identify the type, position, and orientation of the objects to be processed.

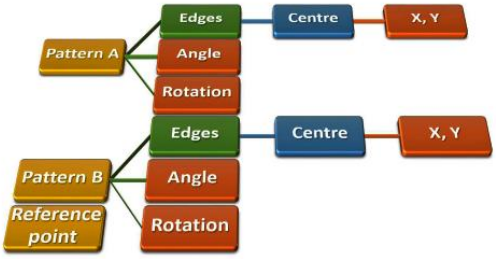


Fig. 3. Method of object parameter identification.

As shown in Fig. 3, the algorithm is based on the identification of the matching patterns representing the floor plan of the objects in the reference position. When the pattern is successfully identified, the object **type** is determined and the **angle** and direction of its **rotation** relative to the reference position is calculated. At the same time, shorter edges are identified in the areas, defined relative to the orientation of the object. Based on these edges, the **coordinates** of the center of the object with respect to the reference point are calculated.

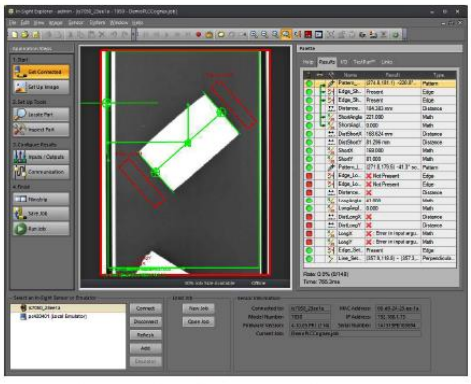


Fig. 4. Visual programming of the machine vision system using In-Sight Explorer.

The whole algorithm is created using the integrated software tool In-Sight Explorer utilizing a visual form of programming based on the creation and combination of algorithmic sequences of built-in functions (Fig. 4).

B. *Visualization in The Process of Control System Design - Workspace Control*

The PLC control subsystem, which ensures the movement of the conveyor belt based on information from the sensor subsystem as well as the control of the initialization of the identification algorithm in the machine vision system, is implemented with utilization of visual programming techniques - using the principles of state diagrams.

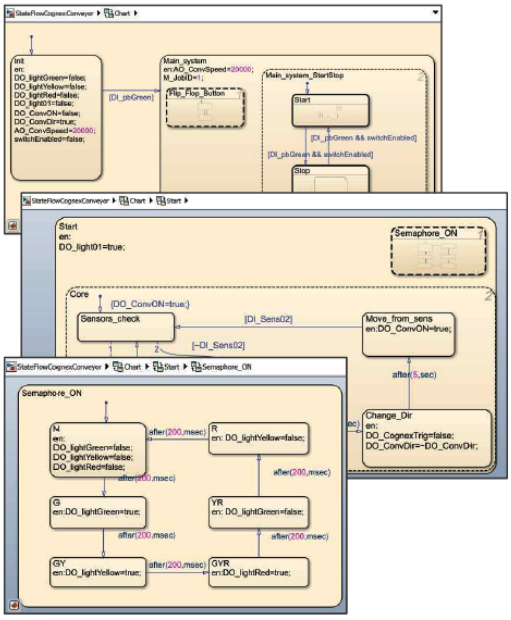


Fig. 5. Stateflow diagram of the PLC control subsystem.

The logic of the control system is designed in the form of states and transitions structured modularly and hierarchically. This method of logic controllers programming is supported by the Mathworks Matlab software with the Simulink and Stateflow toolboxes. The final implementation is realized with utilization of the Simulink PLC Coder toolbox, the result of which is a generated code in the SCL (Structured Control Language) format. This code can be used directly by uploading it to the SIMATIC S7-1200 PLC. The Stateflow diagram of the PLC control subsystem, used in model robotic cell is shown in Fig. 5.

C. *Visualization in the Robotic Cell Control Process*

The control system of the model robotic cell is complemented by a web-based interactive database application, which is used to visualize process and technical data using hybrid-marker-oriented augmented reality.

The implementation of the complementary system involves the use of several web-oriented technologies for sharing of process and technical information. The main purpose of the solution is to use the open-source technologies as much as possible, which means minimizing costs and at the same time maximizing the possibility of customizability of the system. A summary of used open-source technologies is in Tab. II.

TABLE II. OPEN-SOURCE TECHNOLOGIES OF THE COMPLEMENTARY CONTROL SYSTEM

Name	Purpose
aFrame	3D virtual scene model
AR.js	marker-based reorientation of the virtual scene
QRCode reader	subsystem identification by QR code
php	application kernel scripting language
mysql	database system of the application
JavaScript	scripting language providing application dynamics
jQuery	library of additional JavaScript functions
w3.css	framework supporting responsive web-app design

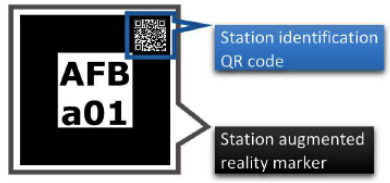


Fig. 6. Hybrid custom AR marker.

The sharing of data from the process level to the AR module is realized by the request of the application web server to the web server of the controlling PLC, as is shown on the communication diagram in Fig. 7. The supplementary part of the control system is designed universally for several possible control PLCs. A specific part of the cell, represented by a separate control PLC, can be identified by a QR code as a part of a hybrid AR marker (Fig. 6).

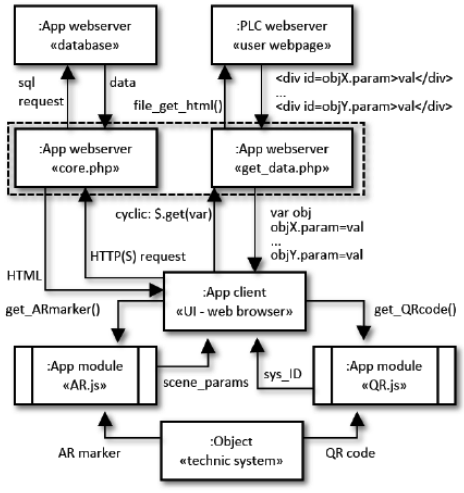


Fig. 7. Communication diagram of the visualization suplementary part of the cell control system.

After receiving the process information in basic form, it is processed on the application client's side (laptop, tablet, smartphone). This information is consequently displayed either on the information panel belonging to the object or in graphical form by changing the parameters of virtual objects (**position**, **color**, **scale**, **rotation**, **opacity**) directly representing a given element of industrial automation, as is shown in the application example in Fig. 8.

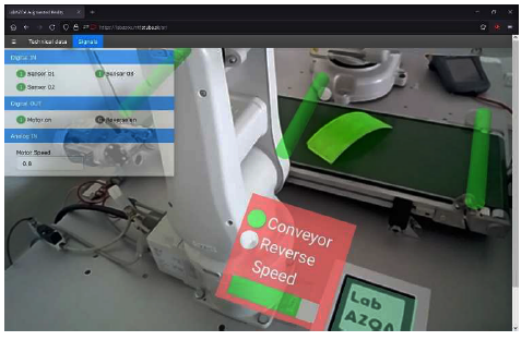


Fig. 8. Visualization suplementary part of the cell control system - visualization of process data.

Individual objects are implemented as interactive elements, where using the A-Frame object of the cursor type, the user is allowed to directly select the element of interest. The visualization part is supplemented by technical data of the selected element, which are read from the relational database located on the application server. The basic data are supplemented by references to the technical documentation of the object and subordinate elements in the hierarchical arrangement of the technical components of the robotic cell.

The modular concept of the application allows a very simple extension by any number of technological modules represented by individual elements:

- AR marker,
- identifier represented by QR code within the hybrid AR marker,
- virtual 3D model containing technical means of interest,
- list of input / output signals
- list of process variables,
- technical data / documentation stored in a relational database in a defined structure.

IV. Discussion and Evaluation of the Solution

The article focuses on the actual and currently much-discussed area of the fourth industrial revolution. From this issue, which includes a wide range of problems from various areas of industrial production, a view on the creation of control applications for industrial automation is selected. The main interest is focused on new, progressive approaches and methods of design and implementation of these applications.

The main purpose of the article is to point out to the fact, that the application of the principles of the Industry 4.0 concept is possible without requirement of significant investments in revitalization of complete technical equipment. By appropriate use of available progressive methods and (often freely accessible) software tools in conjunction with current technical equipment, it is possible to achieve full or at least partial coverage of the requirements arising from this concept.

In the case of the deployment of an industrial machine vision system as well as a superior control PLC, modern visual programming techniques are used. This approach eliminates the disadvantages of classical command programming such as parallel branches or multilayer nesting. An additional, but by no means less important part of the complex cell control system is a web-oriented application used to visualize the entire process, which in combination with a relational database and the use of augmented reality brings a completely different view on the production process.

The main qualitative indicators that prove the advantage of the described implementation method of the robotic workplace design, can be considered:

- independence from knowledge of a specific programming language,
- easy-to-applicable virtual commissioning,
- user-endpoint-hardware-independent no-installation marker-based augmented reality web-application,
- robot-brand independent communication framework,
- OPC UA ready.

A summary of techniques and technologies used in the process of design and implementation of the model solution is given in Tab. III.

TABLE III. Visualization Techniques and Technologies Used in the Control System Design

Technique / Technology	**Purpose**	**Tool**
Visual programming Edge computing	Identification of handling objects on the conveyor belt using Cognex IS 7050-01	In-Sight Explorer 6.1.3
Visual programming	Control algorithm of PLC Siemens SIMATIC S7-1200	Matlab 2019a Simulink 9.3 Stateflow 10.0 Simulink PLC Coder 3.0 TIA Portal V13
Visualization WebApp	Web application interface	Php7.2 MySQL 5.5 jQuery 3.2 w3.css 4.1
Visualization WebApp	Identification using a QR code via a web interface	Instascan QRCode reader
Visualization WebApp	Virtual 3D model of the cell for web browser	aFrame 1.0.4
Visualization WebApp	Augmented reality in the web interface	AR.js 3.3
Visualization Remote control	Communication between PLC Siemens SIMATIC S7-1200 and web application	TIA Portal V13 S7-1200 webserver Simplehtmldom 1.9.1 Portforwarding
Visualization Cloud solution	Display of the result of machine vision in the virtual control system Matlab Stateflow Offline image processing	In-Sight Explorer 6.1.3 ImageMagick-7.0.8 FileZilla Server 0.9 FTP

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His research interests include identification, modeling and simulation of dynamic systems, analysis and synthesis of control systems with utilization of software tools like Matlab, Simulink or VRML. His next field of professional interest is oriented to design and implementation of information systems, including data modeling and functional modeling, together with their implementation by SQL, Oracle PL/SQL, php, html, css, javascript, Object Pascal or C #. In last years he deals with modeling and control of industrial robots (tool like ABB Robotstudio, CIROS Studio, RoboGuide or Mitsubishi MELFA Basic in combination with TIA Portal) with focus on robot-robot collaboration and communication in heterogeneous multirobotic workcells.



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Her research and activities are focused in the areas of software engineering and control systems. In the field of software engineering she is specialized to analysis, identification, definition and design of information systems with focus to software architecture. In this area she has skill in using software tools like Er-Win ERX, Enterprise Architect or Oracle SQL Developer – Data Modeler. Her next field of professional interest, control systems, is oriented to modeling and simulation of systems with utilization of software tools Matlab and Simulink.



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He is dealing with the problems of control of production systems and especially flexible production systems with focus on the design of various control strategies, or the optimization of control goals, mainly with the utilization of discrete event-driven simulation and simulation optimization, mostly from the point of view of its use; for example, in the proposal of an alternative procedure for determining the optimal size of the production batch, or the problem of the impact of priority rules in the scheduling of operations on production goals. Currently with proactive control of production systems using simulation-based digital twin.