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# IMPROVEMENT OF ROBOTIC SYSTEMS BASED ON VISUAL CONTROL

The **subject** of research in the article is the use of adaptive visual control in flexible integrated robotic systems. The **goal** of the work is the integration of visual control facilities into automated control systems for transport and handling operations of flexible integrated production. The article solves the following **tasks:** analyze the application of visual control methods in robotics, consider methods for improving adaptive visual work control systems, formulate the basic requirements for adaptive visual control systems, and develop a control model for a mobile robot in the space of a flexible integrated production systems and computer vision systems. To solve the set tasks, the **methods** of set theory, methods of automatic control theory, and methods of the theory of image processing were used. The following **results** were obtained: the analysis of visual control systems was carried out from the point of view of solving the problems of flexible integrated systems of modern production; the adaptive visual control scheme was improved by introducing a declarative workspace model and a functional model of a flexible integrated system; the main requirements and tasks of adaptive visual control systems are formulated; considered the main stages of processing visual information and their practical implementation, including multi-zone workspaces; a model of visual control of a mobile robot in a flexible integrated production workspace has been developed; the practical tasks of managing mobile platforms have been solved. **Conclusions:** the use of adaptive visual control in a production environment will allow combining the elements of flexible integrated production distributed in space, providing monitoring, control and refinement of control processes in real time, the functioning of intelligent control tools, which will improve the quality of control processes.

**Keywords:** visual control; making decisions; mobile robot; flexible embedded system.

## Introduction

The modern concept of development of production systems Industry 4.0 aims at the comprehensive implementation of information and communication tools and technologies by connecting all components of production (equipment, products) to a common network of data exchange [1]. The implementation of Industry 4.0 should result in the connection of all production facilities to the industrial Internet of Things, and the exchange of information between facilities should be carried out without direct human participation, will create a new scientific and technical environment dominated by mechatronic systems that synergistically combine mechanical and electronic components, intelligent control components. The key points of the new platform will be: big data and their analysis; autonomous works; virtual modeling of systems and processes; horizontal and vertical system integration; industrial Internet of Things; cybersecurity; cloud technologies; additive production; augmented (virtual) reality.

Special attention is paid to autonomous work in Industry 4.0. Capable of independent (without human intervention) performance of production and non-production tasks with, mainly, providing tasks of service and transport maintenance of basic technological equipment, autonomous work should be the basis of cyber physical systems, performing the functions of digital duplicates. As part of this forward-looking approach, today the concept of autonomous robot is formed, as a mobile platform with a manipulator installed on it and other executable devices, advanced sensor system, system of hardware and software drivers, means of communication and navigation, united by a single automated system on-board computer control.

Touch systems of mobile platforms must ensure the interaction of robots with the working environment and the objects that fill it, control the execution and planning of movements and manipulations. By analogy with the human senses, a significant share of information about the work environment, the autonomous robot should receive from the computer vision system (in the production prefer the term "technical vision"). In addition to monitoring the condition of objects in the environment, the computer vision system provides feedback in the robot control system, providing clarification of the position of the actuators. Thus, the functioning of the automated robot control system becomes significantly dependent on visual information, which is called visual-guided control [2, 3].

Based on the principles of visual control in a broad sense, you can build household mobile robotic platforms, industrial manipulators with self-calibration, humanoid work based on mobile platforms with onboard manipulators [2]. At the same time, studies of object manipulation based on visual control of gripping devices [4, 5], visual odometry [6], and even medical loporoscopy [7] remain relevant.

The aim of the work is to integrate visual control means into automated control systems for transport and handling of flexible integrated production.

The following tasks are solved in the article: to analyze the application of visual control methods in robotics, to consider methods of improving adaptive visual control systems, to form basic requirements for adaptive visual control systems, to develop a model of mobile robot control in a flexible integrated production system based on object information computer vision systems.

## 1. Improved system of robots adaptive visual control

Previously, researchers and practitioners used only classical approaches to the processing of computer vision information for the task of image processing and their interpretation. This approach needs to be updated today, including through the introduction of machine learning tools and neural networks. Solving the problems of recognition and identification of workspace objects provides an opportunity to build a model of description, in particular, on the basis of declarative representation. In

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turn, the declarative model can be the basis for building a functional model of the workspace and the implementation of the method of adaptive visual control.

The introduction of these models and methods allows to present the scheme of adaptive visual control in the form shown in fig. 1.

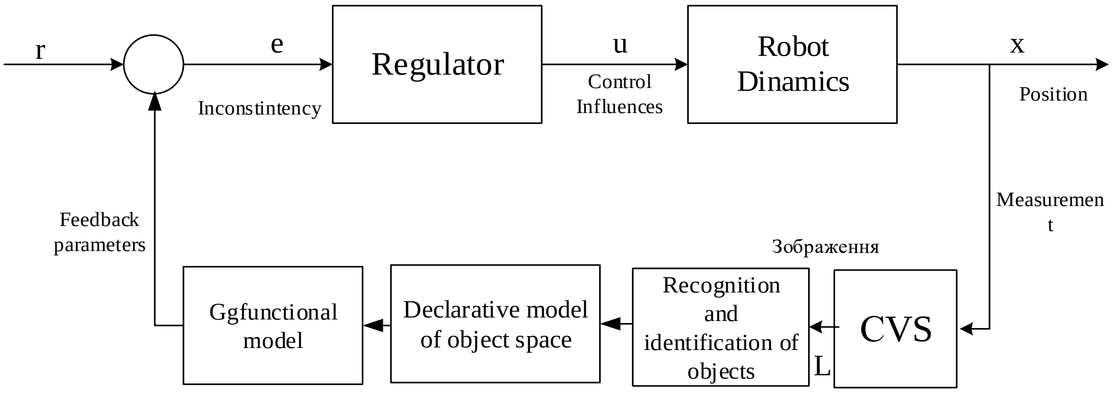


**Fig. 1.** Improved adaptive visual control approach

According to the dynamic nature of the robot workspace, the visual control system must provide a workspace analysis to move the robotic transport platform within a flexible integrated instrumentation system. The dynamic nature of the workspace is determined by the conditions of production, puts forward requirements for adaptation, which should increase the stability of a flexible integrated production system [8–9].

Thus, the current problem [10–11] of modern flexible integrated systems remains to ensure the performance of production functions aimed at improving production efficiency due to the continuity of the operation of the entire system.

Their significant disadvantage is the lack of the ability of robotic platform management systems to adapt to the changes in the workspace that can occur due to the dynamics of the performance of production tasks, the influence of the human factor, the need for changes in production technology, the emergence of various kinds of emergency situations, etc. [12]. The control system of the robotic platform, which will take into account changes in the working environment and states of the flexible integrated system, should monitor the conditions for the execution of technological tasks, monitor the movement of personnel and other mobile platforms, monitor the emergence of emergency situations and, if necessary, adapt the process of performing production functions in the GIPS as a whole. Adaptive visual control system is offered as such [13].

Consequently, adaptive visual control is a promising direction that can be used in modern automated manufacturing to manage mobile robots that perform transport operations and industrial robots to perform manipulations. The main advantage of such a system is its flexibility, which consists in high fitness and ability to quickly reconfigure production areas.

In order to create an adaptive visual control system, it is necessary to perform certain actions:

- to recognize and identify all workspace objects;
- simulate the working space with a description of the characteristics of objects and the links between them (declarative model);
- evaluate the functions performed by the objects and their relationship.

## 2. Basic requirements for adaptive visual control of robots

The control system, which will take into account changes in the working environment and the state of the flexible production integrated system, should monitor the conditions of the task and, if necessary, adapt the process of performing the production functions of RTS.

An adaptive visual control system can act as such a system. The introduction of such an adaptation system should significantly improve the performance of control systems for robotic systems that are part of SFIP.

The main problems of any flexible production today are automated transport operations, both within one shop (single-zone system) and between shops (multi-zone systems). These shops have a fairly wide distance between production equipment and wide ways to move goods. From this follows the possibility of integration for transport operations of flexible computerized production modules - intelligent robotic objects [13].

Such modules will consist of mobile robotic platforms and perception systems installed both object-wise (computer vision systems) and locally - on the robotic platform itself (GPS, rangefinders, etc.). The use of this type of system will significantly increase the speed of transport operations, which will have a positive impact on the production itself, too.

The advantages of using computer vision systems are the cheapness of the equipment used - no need to use to orient in the workspace a huge number of expensive sensors.

According to the dynamic nature of the working space of the intelligent robotic object (work), the visual control system should provide an analysis of the working space to move the transport and assembly robot,

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determined by the conditions of mechanical assembly, puts forward requirements for adaptation systems.

The visual control system of an intelligent robotic object must provide the following capabilities:

- work with the camera / cameras (connection and settings);
- image analysis and processing;
- classification of objects of the working area from the results of image analysis;
- formation of a model of movement of objects of the working area;
- forecasting the further trajectory of objects;
- allocation of impassable areas;
- route formation;
- submission of control influences;
- assessment of navigation errors;
- troubleshooting navigation errors.

Visual targeting will consist of:

- obtaining information about the workspace (geometric parameters);
- obtaining information about the working space of the camera (image parameters, reads using CVS);
- conversion of spatial coordinates into camera space coordinates (CVS);
- recognition and identification of the robot in space (both in the workspace and in the camera space);
- instructions of the starting point of movement on the image obtained with the help of CVS;
- indication of the end point of the movement on the image obtained using CVS.

Consider the simplest case when information about the parameters of the workspace is obtained using measuring devices. In the workspace, there is one static CVS (in this case, the CVS is a normal Web-camera), located objectively (the camera is fixed above the workspace of the robot).

From this, we can draw the following conclusions:

- the plane of the image of the work is parallel to the plane of motion;
- the camera can receive images from the entire work area;
- the camera can calculate the centers of mass of the mobile robot based on the recognition of certain physical characteristics;
- the camera can determine the orientation of the mobile robot, and thus the direction of movement of the MR by recognizing additional characteristics.

By image parameters, we mean its resolution (for example, 800x600 pixels).

Converting spatial coordinates to camera space coordinates (CVS) will be a mathematical comparison of the geometric parameters of the workspace with the dimensions of the image (for example, 1 meter of working space will correspond to 150 pixels of the image). Next, it is necessary to identify and identify the robot. In general, the process of recognition and identification will be as follows.

The process will be divided into several stages: initial recognition, collection of statistics, clustering of collected statistics, formation of standards (base of characteristics), and additional recognition.

Let’s define each of these stages:

- primary recognition means recognition of the entire work area.
- collection of statistics – the process of selecting reliably recognized objects, which will later make a training sample for the adaptive algorithm;
- clustering – division of the training sample into clusters (classes), with the help of such division the results of recognition obtained at the stage of primary recognition are specified, the statistical structure of the working area will be revealed;
- formation of standards is the creation of final, lifelong data sets (databases of characteristics), which will be carried out additional recognition;
- recognition – the second pass of recognition throughout the work area in order to clarify the results of the initial recognition, to set adequate estimates of accuracy, to recognize what was not recognized before, to mark unreliable objects.

Recognition and identification of the robot can be performed using, for example, the cascading Haar classifier, built by the method of Viola and Jones. The Haar Classifier has a format different from the rest of the machine learning library, as it was previously developed as a full-fledged face recognition application. To develop a robot detector, you need to look at the classifier in detail and show how you can learn to recognize objects in the robot's workspace.

Training is conducted on several hundred species of one sample of a particular object (mobile robot), which are called positive samples [14]. These images are reduced to one standard view (light parameters, object position and size). Negative samples are selected separately: arbitrary images of the same size that do not contain the target object.

Upon completion of the preliminary training of the classifier, it is possible to apply it to the area of interest (the size corresponds to the size of the training) in the input image.

The classifier takes the value 1 if the area, with a certain probability, is the target object (mobile robot), 0 - otherwise. The advantage of such a classifier is the ability to apply it to objects of different sizes without prior scaling. To do this, the scanning procedure must be performed several times with different weights. The classifier consists of a number of simple classifiers (preliminary stages of creating a classifier), which are consistently applied to the area of interest, until all stages are completed successfully. The main classifiers are a decision tree with at least 2 levels. This algorithm uses the following Haara-like characteristics.

Image normalization consists of scaling the object and bringing it to a specific size (the size of the photo on which the system was trained). Bilinear interpolation is most often chosen as a scaling algorithm.

Thus, this algorithm gives good image quality when scaling and requires a minimum of resources, which is important in solving this problem.

Another algorithm is to select objects of a certain shape in the image and track them. After receiving the video sequence from CVS, image capture (sequence of

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frames) is performed. This procedure is performed from a video capture device, during which it must be possible to control the recording parameters, namely the number of frames and frequency.

Then there are operations related to image processing, morphological operations, image analysis and improvement, image restoration and others. After reading, the image must undergo morphological processing. During the analysis, the coordinates of the center of the object (centers of mass) must be selected. On the basis of the center of mass is the construction of a minimum frame that limits the object (mobile robot).

In the first frame, the user specifies the object [14]. Having the value of the pixels of the selected object, the following frames are analyzed and the object is located - the active area is selected and the coordinates of the center of mass are calculated. For further work, the images are converted into binary, then fill the voids and delete those objects that do not match the search criteria. As a result, we get an image with a selected object; all other objects become the background.

When changing the position of the mobile robot using a computer vision system (CVS) we get an image that will need to be processed for further interpretation.

The following definitions can be understood as image processing with its further interpretation.

The main transformations used to select objects are:

- transformation of objects into halftone;
- filling holes in the original color image;
- approximation of the image by structural elements;
- tracking the external boundaries of objects in the image;
- measuring a specific set of characteristics for each area;
- calculation of centers of mass (centroid) elements;
- formation of minimum bounding rectangles / circles.

To more accurately select objects in the background, you need to convert the image from color to 8-channel - finding a sample of certain areas of the image that differ from others in brightness. The simplest way to encode an image point is binary (0, 1), ie the point can be in two states, black or white.

When turning objects into halftones, errors may occur - the appearance of holes in the objects themselves, so you need to fill them. This is done by filling the background pixels of the original image, starting from the points defined by the parameter. A hole is a set of background pixels that cannot be obtained by filling the background from the edge of the image.

Selecting the boundaries of objects in the image is possible with the Kenny algorithm [15], which consists of five separate steps:

- anti-aliasing - image blur to remove noise;
- search for gradients (boundaries are marked where the gradient of the image becomes the maximum value);
- suppression of non-maxima (only local maxima are marked as borders);
- double threshold filtration (potential limits are determined by thresholds);
- tracing the area of ambiguity (final boundaries are determined by suppressing all edges not related to the defined boundaries).

Next, the creation of flat, disc-shaped structural elements, where the parameter is the radius. It must be a non-negative real number. The parameter for the approximation must be 0, 4, 6 or 8. When it is greater than 0, then the structural element is approximated by a sequence of this number of periodically linear structural elements. When the parameter is 0, the approximation is not used and the structural elements are formed from all pixels spaced no more than a radius from the center. Threshold functions are used when selecting objects to determine the brightness threshold in the image.

Some image processing tasks are related to the conversion of halftone into binary. To reduce the information redundancy of the image, there is only the information needed to solve a particular problem. The binary image must retain details of interest (e.g. shapes of depicted objects) and exclude insignificant features (background).

Approximation of the contour allows without significant loss of information to reduce the number of points in the contour and significantly speed up the contour analysis. The approximation can be performed by the following algorithm:

- the two most distant points of the contour are located and the two parts of the contour between them are considered independently;
- for each obtained section of the contour is the point furthest from the line connecting the end points of the section;
- if the distance from the point found in step 2 to the line is greater than the specified threshold, then this part of the contour is divided by this point into two smaller sections;
- if the distance found is less than the threshold value, then instead of this part of the circuit in the resulting contour is a segment connecting the endpoints of the section.

Threshold processing of halftone images is to divide all elements of the image into two classes on the basis of brightness, ie to perform element-by-element transformation.

One of the methods of threshold processing is the Otsu method [16]. This method allows you to calculate a threshold value where the variance between the object and the background of the results will be minimal.

Based on the already obtained contours of the images, it is possible to determine their contours - to form curves from the infinity of the selected edge points.

After defining the contours, we find the centers of mass of objects (centroids) in the image - geometric points that characterize the motion of a body or system of particles as a whole.

The last step is to select the resulting object with a rectangle or circle that will minimally delimit the object (objects will be inscribed in a rectangle / circle).

Consider the case when the workspace is very large and information about it is obtained from several cameras. Suppose there is a working space of an intelligent robotic

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object, equipped with a set of video cameras (computer vision systems), and the working spaces of all cameras intersect in some areas (fig. 2).

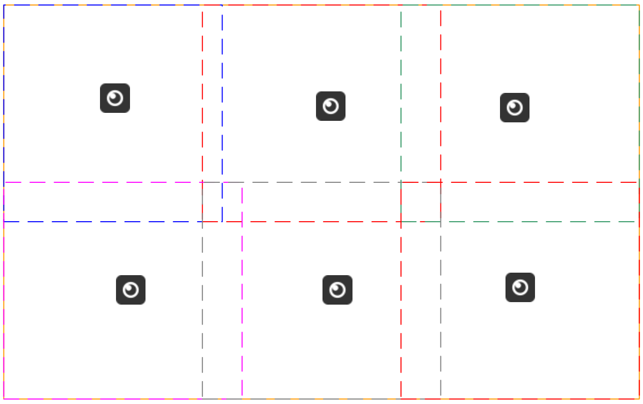

**Fig. 2.** Workspace with cameras located in it

Images obtained from the camera are stitched into a panoramic. There are several cameras in the workspace; the image of each of them may differ in several parameters, such as:

- matrix resolution;
- type of matrix;
- values of brightness and contrast;
- sensitivity;
- viewing angle;
- frame rate, etc.

It follows that the image or video stream from the cameras may have different parameters, which makes it difficult to stitch it into one image for further work.

The SIFT (Scale Invariant Feature Transform) algorithm was chosen as the stitching algorithm (panorama construction) [17]. The algorithm is to find special points in the image and their descriptors. Special points are those points that are most likely to be found in another image. Descriptors are the parameters of special points that distinguish them from others, the so-called uniqueness of each point. To find special points, it is necessary to calculate Gaussians (applying Gaussian blur to the image) and their differences.

For the SIFT method, the descriptor is a vector that is calculated on the Gaussian closest in scale to the key point, and, based on gradients, in some key point window. Before calculating the descriptor, this window is rotated to the angle of the key point, which achieves invariance with respect to rotation (fig. 3). The left part shows pixels marked with small squares, which are taken from the descriptor window, which is divided into four equal parts (regions). An arrow in the center of each pixel indicates the gradient of that pixel.

The center of the window is between the pixels. It is selected as close as possible to the exact coordinates of the key point. The circle indicates the convolution window with a Gaussian core (similar to the window for calculating the direction of the key point). For this kernel, a sigma equal to half the width of the descriptor window is defined. In the future, the value of each point of the descriptor window will be added to the value of the Gaussian nucleus at this point as a weighting factor.

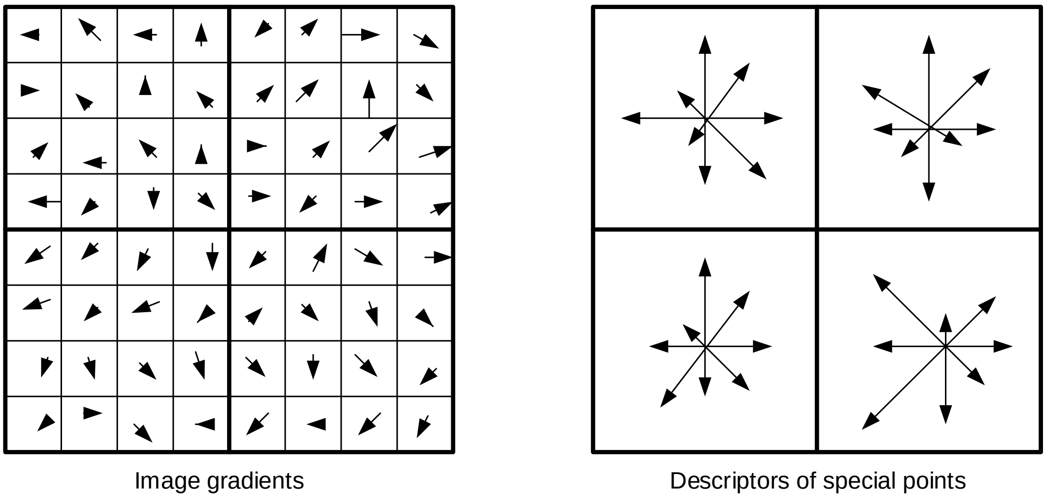


**Fig. 3.** Image and descriptor derived from it

In the right part of the image there is a descriptor of a special point, dimension 2x2x8, where 2x2 - the number of regions horizontally and vertically, and 8 - means the number of components of the histogram of these regions. Histograms of regions are calculated similarly to the histogram of directions with three conditions:

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- each histogram covers an area of 360 degrees and divides it into 8 parts;
- the value of the Gaussian nucleus, common to the whole descriptor, is taken as a weighting factor;
- three-line interpolation coefficients are taken as additional weights.

Each gradient in the descriptor window can be assigned three real coordinates (x, y, n), where x and y are the distances to the gradient horizontally and vertically, n is the distance to the direction of the gradient in the histogram.

Once the key point descriptors are obtained, the image can be stitched into a panoramic view.

To do this, we use the method RANSAC [19] – a method of fitting models to data that contains points that do not fit into the model. After determining the points included in the model (homography), it is necessary to superimpose all the images on a common plane. For example, create a large image filled with zeros, in a plane parallel to the central image; superimpose the entire image on it. The central image is filled with zeros on the right and left. Using homography, we determine from which side it is necessary to supplement the image [20].

The considered methods of image processing and stitching will be used to create models of recognition and identification, as well as models of mobile robot control in the space of a flexible integrated system.

## 3. Mobile robot control model in SFIP space based on information of the object system of computer vision

The construction of the mobile robot control model should be based on the presence of technical features of the MR chassis design, the presence of a sensor system of a certain level, the ability to perform manipulations with RP objects. Since it is assumed that the key element of the sensory system should be a computer vision system, the proposed model has feedback that is provided on the basis of obtaining visual information. To describe the functioning of the control system of the mobile robot using the object computer vision system (OCVS), a control scheme is proposed, which is shown in fig. 4.

The main difference between the systems is that a computer is used to control the OCVS, and the robot only executes control commands from it based on information from the object camera. LCVS performs all actions using the processor of the control board installed on it. This can be a Raspberry Pi, ASUS Tinkerboard and the like. The analysis of information and its interpretation, all calculations and formation of control influences are carried out by the computer $Computer$, and the robot $Rb$ only carries out these influences.

The initial information for the operation of the MR management system should be provided by the decision-making system – DMS. It must pre-generate a robot route as a sequence of destination points $Cp_i(x_i, y_i, z_i)$, or in the case of 2D projection – $Cp_i(x_i, y_i, z_i = 0)$.

The whole path will consist of the sum of the segments that need to be done by robot $Cp_i(x_i, y_i, z_i) = \sum_{j=0}^{N} Cp_i^j(x_i^j, y_i^j, z_i^j)$ .

The formation of the difference in coordinates $\varepsilon_x, \varepsilon_y$ forms the transition from point $Cp_i^0$ to point $Cp_i$ in the following way (fig. 5).

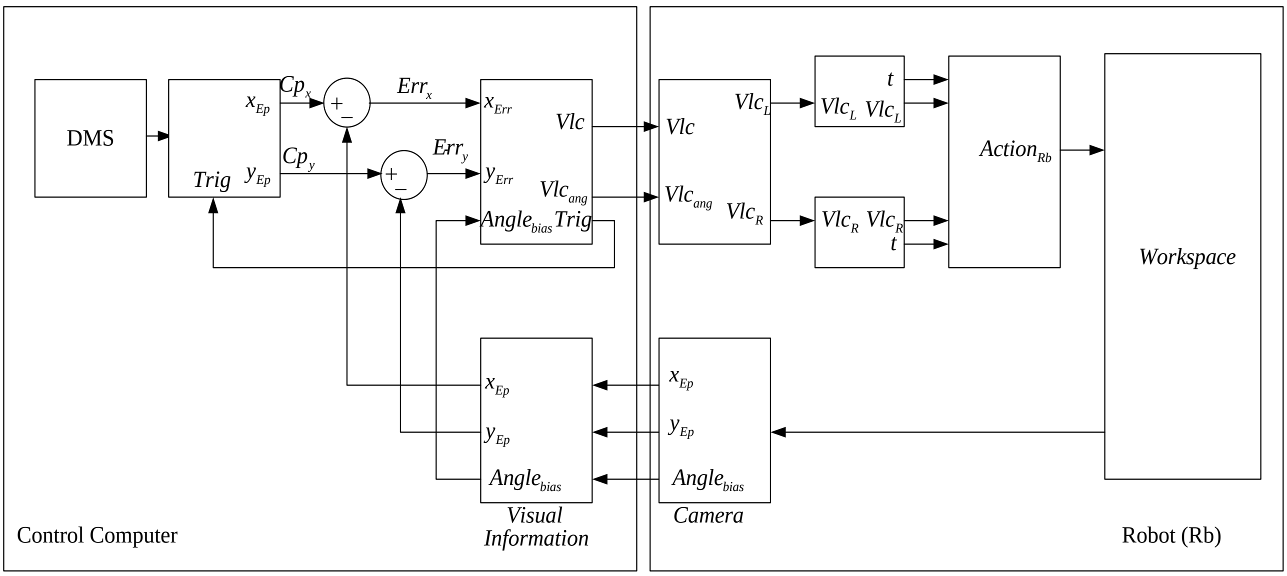


**Fig. 4.** Scheme of mobile transport control wheeled robot with feedback on visual position using OCVS

The robot positioning system compares the current coordinates of the robot $Cp_i^0(x_i^0, y_i^0)$ з $Cp_i^1(x_i^1, y_i^1)$ and finds the difference between them as $Cp_i^1 Cp_i^0(x_i^1 - x_i^0, y_i^1 - y_i^0)$. Thus there is a difference of coordinates $\varepsilon_x = (x_i^1 - x_i^0)$ , $\varepsilon_y = (y_i^1 - y_i^0)$ .

Given that the camera is object-oriented, the starting point $Sp_{Rb}$ has coordinates $(x_0; y_0)$. Since the entire path is discrete, intermediate points $Cp_i^0$ are defined between the start and end points.

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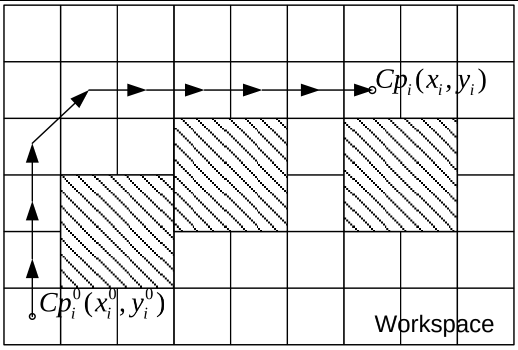


**Fig. 5.** Scheme of transition to the point of discrete RP

Next, the end point of the route $Ep_{Rb}$ is set with coordinates $(x_{Ep}; y_{Ep})$. During the implementation of the route almost always there are errors on the axes $Err_x$ and $Err_y$, therefore, the coordinates of the endpoint $Ep_{Rb}^{Err}$ with error will have coordinates $(Err_x, Err_y) = (Cp_{ix}^n - Ep_x, Cp_{iy}^n - Ep_y)$. The presence of errors should not exceed a certain level of discreteness of the working space, that is: $(Err_x < k \times D_x; Err_y < k \times D_y)$, where $k \in [0, 0.25]$.

Knowing the overall speed of the robot, we get the time $t$ that takes to move to the end point of movement. On the basis of the kinematic two-wheel model, the values of linear and angular speeds are calculated: $\dot{x} = \cos\alpha \times Vlc$, $\dot{y} = \sin\alpha \times Vlc$, $\dot{\alpha} = Vlc_{Ang}$, $Vlc = \frac{K}{2}(Vlc_1 + Vlc_2)$, $Vlc_{Ang} = -\frac{K}{2}(Vlc_1 - Vlc_2)$

where (*x*, *y*) are the coordinates of the wheel robot on the plane, $\alpha$ – the angle of rotation of the robot on the plane, $Vlc_{Ang}$ – the angular speed, $Vlc$ – the linear speed of the work, $Vlc_1$ and $Vlc_1$ are the linear velocities of the right and left wheels, $K$ – the drive transmission factor. Performing mobile robot displacements at specified speeds $Vlc_L$ and $Vlc_R$ at interval $t$ means performing actions $Action_{Rb}$ that interact with robot control commands and perform actions in the $Workspace$.

The computer vision system $Camera$ receives information from the working space $Workspace$, namely the position of the work on the axes $(x_{Ep}; y_{Ep})$, as well as the angle of its rotation $(x_{Ep}; y_{Ep})$ relative to the axes of the coordinates.

The visual control unit $Visual\ Information$ receives these coordinates and analyzes the position of the robot. These coordinates are compared to the necessary endpoints and the next moving point in the discrete workspace is calculated. If they are different, then the current coordinates $(x_{cur}; y_{cur})$ become the initial coordinates of movement and the whole process is repeated again until the robot arrives at the end point of movement. Next, move to the next point of the discrete space.

If there is no error, or it is compensated and the robot has reached the target point, a Boolean trigger $Trig$ is set to signal ($true$) for the execution of the task. The path that is required against the work between two points of discrete space is $L_{Rb}^i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$.

Then all the way will have the next look: $L_{Rb} = \sum_{i=0}^{n} L_{Rb}^i$. Route from point $Cp_i^0(x_i^0, y_i^0)$ to $Cp_i(x_i, y_i)$ can be defined in two ways:

- determination of the path that the robot must pass and the angle to which it needs to return;
- rectilinear movement, then movement by circumference.

The first method is the easiest in the absence of calculation of speeds and angular velocities, but only the turns of the wheel. The main parameters here are the radius of the robot wheel $R_w$, as well as the distance between the wheels, which will be the radius of rotation of the robot $R_{L_w}$. The wheel travels the distance $L_w = 2 \times \pi \times R_w$ in one full revolution. The robot passes $L_{L_w} = 2 \times \pi \times R_{L_w}$ in one full revolution (360 degree rotation) using one wheel.

Number of wheel revolutions $Q_{rot}$, the robot need to do will be equal to: $Q_{rot} = \frac{L_{Rb}}{L_w}$.

The angle of rotation of the robot $Angle_{bias}$ can be determined using the cosine theorem. It can be like that:

$$Angle_{bias} = \begin{cases} 0 - \arccos\left(\dfrac{(x_{Sp} - x_{Ep})^2 + (\sqrt{(x_{Sp} - x_{Ep})^2 + (y_{Sp} - y_{Ep})^2})^2 - (y_{Sp} - y_{Ep})^2}{2(x_{Sp} - x_{Ep})\sqrt{(x_{Sp} - x_{Ep})^2 + (y_{Sp} - y_{Ep})^2}}\right); & \text{якщо } x_{Ep} > x_{Sp}, y_{Ep} < y_{Sp} \\ -90 - \arccos\left(\dfrac{(x_{Ep} - x_{Sp})^2 + (\sqrt{(x_{Ep} - x_{Sp})^2 + (y_{Ep} - y_{Sp})^2})^2 - (y_{Ep} - y_{Sp})^2}{2(x_{Ep} - x_{Sp})\sqrt{(x_{Ep} - x_{Sp})^2 + (y_{Ep} - y_{Sp})^2}}\right); & \text{якщо } x_{Ep} > x_{Sp}, y_{Ep} > y_{Sp} \\ 180 + \arccos\left(\dfrac{(x_{Sp} - x_{Ep})^2 + (\sqrt{(x_{Sp} - x_{Ep})^2 + (y_{Ep} - y_{Sp})^2})^2 - (y_{Ep} - y_{Sp})^2}{2(x_{Sp} - x_{Ep})\sqrt{(x_{Sp} - x_{Ep})^2 + (y_{Ep} - y_{Sp})^2}}\right); & \text{якщо } x_{Ep} < x_{Sp}, y_{Ep} > y_{Sp} \\ 90 + \arccos\left(\dfrac{(x_{Ep} - x_{Sp})^2 + (\sqrt{(x_{Sp} - x_{Ep})^2 + (y_{Sp} - y_{Ep})^2})^2 - (y_{Sp} - y_{Ep})^2}{2(x_{Sp} - x_{Ep})\sqrt{(x_{Sp} - x_{Ep})^2 + (y_{Sp} - y_{Ep})^2}}\right); & \text{якщо } x_{Ep} < x_{Sp}, y_{Ep} < y_{Sp} \end{cases}$$

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Then in order to find out which way to go to work with one wheel $L_{Angle}$ at an angle $Angle_{bias}$ you need to use the formula: $L_{Angle} = \frac{L_{L_w}}{360} \times Angle_{Bias}$ .

For the second case, an intermediate point $Ip_{Rb}(x_{Ip} = x_i^0, y_{Ip} = y_i)$ is added, to which the robot makes a rectilinear motion, and then - in a circle (fig. 6). In order to obtain the speeds for the first and second motors (for the ideal case of a simple trajectory) you need to perform mathematical operations, which are shown in fig. 7.

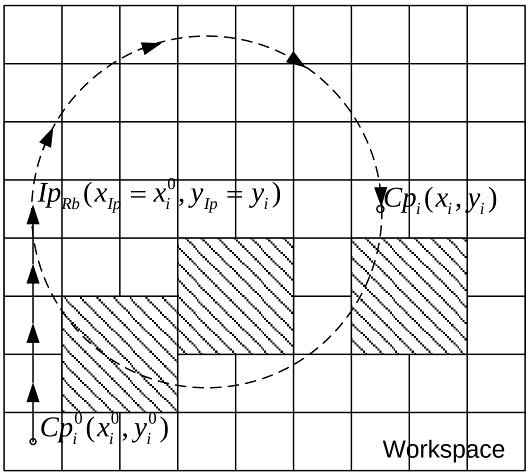


**Fig. 6.** Option with straight and then circular motion

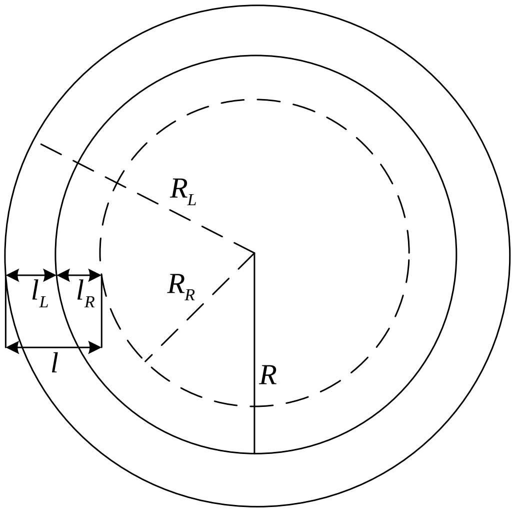


**Fig. 7.** Illustration of finding the speeds of the robot wheels for turns

In fig. 7, the distance between the wheels of the robot is equal $l$ , the distance from the left and right wheels to the center of the robot is $l_L$ and $l_R$ accordingly, provided that $l_L = l_R$ . From this condition, you can find the radius of turns of the left $R_L$ and right $R_R$ wheels. The radius of circular motion $R$ will be equal to: $R = \frac{x_i - x_i^0}{2}$ . Radius of rotation of left and right wheels respectively: $R_L = R - \frac{l}{2}; R_R = R + \frac{l}{2}$ . The path that the robot passes in one full circle, as well as the paths of the left and right wheels will be equal to:

$$\begin{cases} L = 2\times\pi\times R \\ L_1 = 2\times\pi\times R_L = 2\times\pi\times\left(R - \frac{l}{2}\right) \\ L_2 = 2\times\pi\times R_R = 2\times\pi\times\left(R + \frac{l}{2}\right) \end{cases}.$$

The velocity is going to be equal to:

$$\begin{cases} Vlc = \frac{L}{t} = \frac{2\times\pi\times R}{t} \\ Vlc_L = \frac{L_L}{t} = \frac{2\times\pi\times R_L}{t} = \frac{2\times\pi\times\left(R - \frac{l}{2}\right)}{t} \\ Vlc_R = \frac{L_R}{t} = \frac{2\times\pi\times R_R}{t} = \frac{2\times\pi\times\left(R + \frac{l}{2}\right)}{t} \end{cases}.$$

The proposed model of control of the robot allows, based on the information of the object system of computer vision, to calculate the route of movement of the mobile platform in SFIP space.

## Conclusions

In the conditions of changing the concept of production systems development, their focus on compliance with the Industry 4.0 standard, there are tasks of developing new software and hardware, including mobile robotic platforms and advanced manipulation systems. At the same time, the tasks of developing and improving automated control systems for individual facilities and production in general increasingly depend on the volume and methods of obtaining information about the working space in which robotic systems operate. Implementation of adaptive visual control systems is a step that will allow to integrate into automated control systems new software and hardware methods of visual information processing, combine them with decision support systems and, based on methods of forming and processing knowledge about the subject area to ensure intelligent control systems.

The practical significance of the results obtained in this article is the development of a mobile transport robot control system, which practically provides the analysis of the workspace with the help of computer/technical vision, recognition and identification of workspace objects and robotics, obtaining their spatial coordinates, supporting the visual targeting of the mobile robot route and the functioning of the intelligent decision support system. The results obtained are the basis for further research that should focus on the wide implementation of neural methods for implementing robot control systems.

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# ВДОСКОНАЛЕННЯ РОБОТИЗОВАНИХ СИСТЕМ НА ОСНОВІ ВІЗУАЛЬНОГО КЕРУВАННЯ

**Предметом** дослідження в статті є застосування адаптивного візуального керування у гнучких інтегрованих роботизованих системах. **Мета** роботи – інтеграція засобів візуального керування у автоматизовані системи керування транспортними та маніпуляційними роботами гнучкого інтегрованого виробництва. В статті вирішуються наступні **завдання:** провести аналіз застосування методів візуального керування в робототехніці, розглянути методи вдосконалення систем адаптивного візуального керування роботами, сформувати основні вимоги до систем адаптивного візуального керування, розробити модель керування мобільним роботом у просторі гнучкої інтегрованої виробничої системи на основі інформації об`єктової системи комп`ютерного зору. Для вирішення поставлених завдань були використані **методи** теорії множин, методи теорії автоматичного керування, методи теорії обробки зображень. Отримано наступні **результати:** проведено аналіз систем візуального керування з точки зору розв'язання завдань гнучких інтегрованих систем сучасного виробництва; вдосконалено схему адаптивного візуального керування за рахунок впровадження декларативної моделі робочого простору та функціональної моделі гнучкої інтегрованої системи; сформульовано основні вимоги та завдання систем адаптивного візуального керування; розглянуто основні етапи обробки візуальної інформації та їх практична реалізація, в тому числі для багатозонових робочих просторів; розроблено модель візуального керування мобільним роботом у робочому просторі гнучкого інтегрованого виробництва; розв'язано практичні завдання керування мобільними платформами. **Висновки:** застосування адаптивного візуального керування у виробничих умовах дозволить об`єднати розподілені в просторі елементи гнучкого інтегрованого виробництва, забезпечити моніторинг, контроль та уточнення процесів керування в режимі реального часу, функціонування засобів інтелектуального керування, що дозволить покращити якість процесів керування роботизованих систем гнучкого інтегрованого виробництва.

**Ключові слова:** візуальне керування; прийняття рішень; мобільний робот; гнучка інтегрована система.

# УСОВЕРШЕНСТВОВАНИЕ РОБОТИЗИРОВАННЫХ СИСТЕМ НА ОСНОВЕ ВИЗУАЛЬНОГО УПРАВЛЕНИЯ

**Предметом** исследования в статье является применение адаптивного визуального управления в гибких интегрированных роботизированных системах. **Цель** работы – интеграция средств визуального управления в автоматизированные системы управления транспортными и манипуляционными работами гибкого интегрированного производства. В статье решаются следующие **задачи:** провести анализ применения методов визуального управления в робототехнике, рассмотреть методы усовершенствования систем адаптивного визуального управления работами, сформировать основные требования к системам адаптивного визуального управления, разработать модель управления мобильным роботом в пространстве гибкой интегрированной производственной системы. системы компьютерного зрения. Для решения поставленных задач были использованы **методы** теории множеств, методы теории автоматического управления, методы теории обработки изображений. Получены следующие **результаты:** проведен анализ систем визуального управления с точки зрения решения задач гибких интегрированных систем современного производства; усовершенствована схема адаптивного визуального управления за счет внедрения декларативной модели рабочего пространства и функциональной модели гибкой интегрированной системы; сформулированы основные требования и задачи систем адаптивного визуального управления; рассмотрены основные этапы обработки визуальной информации и их практическая реализация, в том числе многозоновых рабочих пространств; разработана модель визуального управления мобильным роботом в рабочем пространстве гибкого интегрированного производства; решены практические задачи управления мобильными платформами. **Выводы:** применение адаптивного визуального управления в производственных условиях позволит объединить распределенные в пространстве элементы гибкого интегрированного производства, обеспечить мониторинг, контроль и уточнение процессов управления в режиме реального времени, функционирование средств интеллектуального управления, что позволит улучшить качество процессов управления.

**Ключевые слова:** визуальное управление; принятие решений; мобильный робот; гибкая встроенная система.

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