

A Model of Using Computer Vision to Monitor the Environment of a Collaborative Manipulator Robot

Vladyslav Yevsieiv¹, Nataliia Demska¹

1. CITAR Department, Kharkiv National University of Radio Electronics, UKRAINE,
Kharkiv, Nauki Ave. 14., e-mail: vladyslav.yevsieiv@nure.ua

Abstract: The paper considers a model of using computer vision to monitor the environment of a collaborative manipulator robot in the context of Industry 5.0. The sequence of stages of image processing is described, including detection, tracking and classification of objects, which allows the robot to respond adaptively to changes in the environment and ensure safe interaction with a person. The model contributes to increasing the flexibility and efficiency of robotic systems in modern production processes.

Keywords: Industry 5.0, Computer vision, Collaborative manipulator robots, Image processing, Environmental monitoring.

I. Introduction

Modern trends in the development of Industry 5.0 are focused on the integration of humans and robots into single production processes, where collaborative manipulator robots perform complex tasks, closely interacting with people. The use of computer vision to monitor the environment of such robots is becoming an important tool for ensuring the safety, flexibility and adaptability of systems. The relevance of this research lies in the need to develop an effective model of image processing that will ensure accurate detection of objects, assessment of the situation and decision-making in real time. The model should include computer vision algorithms for segmentation, classification and tracking of objects in a dynamic environment, which will allow the work to quickly respond to changing conditions and avoid potential threats to the operator. This is especially important for the development of cyber-physical production systems, where the high integration of automated processes and human control is a key aspect of the success of Industry 5.0.

II. COMPUTER VISION MODEL FOR ENVIRONMENTAL OBSERVATION

Image processing is the main step that involves the digital processing of visual information received by collaborative robots through cameras or other sensors. This process includes improving image quality, removing noise, changing contrast and resolution, and other operations to prepare the image for further analysis. Image processing in the context of Industry 5.0 is particularly important because it allows robots to quickly adapt to the changing conditions that arise when working with people in a dynamic environment. Algorithms such as Gaussian filters, or morphological processing techniques such as erosion or dilation, are used to highlight important image details.

The next stage is segmentation, which consists in dividing the image into several segments or clusters of

pixels for a better understanding of the structure of the image. For collaborative robots, segmentation is crucial because it allows you to isolate key objects in the work area, such as people, tools, machines or obstacles. Segmentation can be done using a variety of methods, including threshold-based segmentation, k-means clustering, or the use of neural networks. Within the concepts of Industry 5.0, it allows robots to work in real time, quickly reacting to the presence of people or changing the position of objects, which ensures safe and effective collaboration.

Object recognition is the process of identifying and classifying objects in images received from sensors. For collaborative robots, object recognition is critical because they need to clearly understand what is in their field of vision and make decisions based on that. Recognition algorithms can use patterns or be based on deep learning, such as using convolutional neural networks (CNN). In the context of Industry 5.0, these algorithms allow robots not only to see objects, but also to predict their behavior, analyze human movements and predict further actions. This becomes the basis for adaptive planning of trajectories and avoidance of potential threats during joint work with a person.

Therefore, *image processing*, *segmentation* and *object recognition* are integral components of collaborative robots in Industry 5.0. They allow robots to more accurately perceive the environment, interact interactively with people and adapt their behavior to changes in the work area.

The general mathematical model of using computer vision to observe the environment of a collaborative manipulator robot can be represented as a set of equations and expressions describing the process of image processing, object recognition and decision making. It includes several main stages: receiving input images, segmentation, localization of objects, recognition and motion planning.

The process begins with the collection of images from the camera. The input image is a matrix of light intensities in pixels, and can be described as follows:

$$I(x, y) = f(x, y, t), \quad (1)$$

where $I(x, y)$ – pixel intensity at coordinates (x, y) ;
 $f(x, y, t)$ – a function that describes brightness changes depending on spatial coordinates x and y , as well as time t .

The camera converts the 3D world into a 2D image, so calibration is required to determine the camera's internal

and external parameters. The perspective projection model is presented in the following expression:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{z} \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad (2)$$

where (X, Y, Z) – coordinates of a point in space;

(u, v) – coordinates of a point on the image;

f_x, f_y – focal lengths;

c_x, c_y – coordinates of the optical center of the camera.

Segmentation is the process of selecting objects in an image. The segmentation operation can be represented as a pixel clustering function:

$$S(x, y) = \begin{cases} 1, & \text{if the pixel belongs to an object} \\ 0, & \text{otherwise} \end{cases}, \quad (3)$$

where $S(x, y)$ – binary segmentation function that determines whether a pixel belongs to an object.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = K^{-1} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} Z, \quad (4)$$

where K – matrix of internal parameters of the camera;

(X, Y, Z) – three-dimensional coordinates of the object;

(u, v) – coordinates of the object in the image.

Machine learning algorithms such as Convolutional Neural Networks (CNN) are used for object recognition. Formally, the recognition process can be described as:

$$P(c|I) = f_{\theta}(I), \quad (5)$$

where $P(c|I)$ – the probability that the object belongs to class c in the image I ;

$f_{\theta}(I)$ – a neural network model with parameters θ that predicts the class of an object.

Algorithms for planning trajectories are used for safe and effective control of the manipulator based on the received data on the location of objects. This can be represented as the minimization of the cost function for the movement:

$$J(\tau) = \int_0^T L(x(t), u(t)) dt, \quad (6)$$

where $J(\tau)$ – trajectory cost function τ ;

$L(x(t), u(t))$ – the instantaneous cost of movement depending on the state $x(t)$ and management $u(t)$;

T – task completion time.

This is minimized under the constraint of robot dynamics:

$$\dot{x}(t) = f(x(t), u(t)), \quad (7)$$

where $\dot{x}(t)$ – changing system state over time;

$f(x(t), u(t))$ – robot dynamics model.

Multiple data sources (cameras, sensors, LiDAR, etc.) are used for a more accurate understanding of space. Data integration is done by merging (Data Fusion):

$$X_f = w_1 X_1 + w_2 X_2 + \dots + w_n X_n, \quad (8)$$

where X_f – result of data fusion;

X_1, X_2, \dots, X_n – data from various sources;

w_1, w_2, \dots, w_n – weighting factors of each source.

Thus, the mathematical model of computer vision for a collaborative robot includes image collection, camera calibration, object segmentation, their localization, recognition and motion planning based on data fusion. These stages allow the robot to reliably observe the environment and effectively interact with it in real time.

III. Conclusion

The article summarizes the importance of developing and implementing a computer vision model for monitoring the environment of a collaborative manipulator robot, especially in the context of Industry 5.0, where the integration of humans and robotic systems is a key component of production processes. The described model of image processing provides effective detection, analysis and tracking of objects, which allows manipulator robots to quickly respond to changes in the environment and make decisions in real time. Such a system increases the safety of cooperation between robots and people, reduces the risks of emergency situations and increases the overall productivity of production lines. The use of computer vision also opens up new opportunities for flexible adaptation of robotic systems to various production tasks, making them more autonomous and intelligent. In the context of Industry 5.0, the proposed model increases the level of automation and personalization of processes, contributing to the development of cyber-physical systems and the harmonious coexistence of humans and robots on the same production site.

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