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RESEARCH ARTICLE

Mechanical Engineering

Implementation of a fuzzy logic approach for a smart production system

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Abstract: This paper considers the monitoring of the entire process of an installation of a smart autonomous production system, and continuous analysis of its operation. The smart production system consists of an industrial robot and a computer numerical control (CNC) machine. Research is focused on the industrial robot subsystem; an implementation of a fuzzy logic method for end effectors is applied, and results regarding relevant clamping force are presented. The grippers and magnetic switches are described in more detail, and devices for measuring the clamping force are shown and analyzed. After installation and levelling of the machine, it is necessary to perform calibration – the correction of movement along the axis of the CNC machine. In theory, if the CNC machine is programmed to follow an ideal circular path, when the positioning accuracy of the machine and its tooling is perfect, then the actual curve that the machine produces, would correspond exactly to the ideally programmed circle. In practice, many factors affect CNC machine performance causing deviations from the ideal circuit. Factors influencing the accuracy are various, stemming from machine geometry, through the control system, to machine wear over many years of the operation. A possible upgrade of the existing system, in order to increase the autonomy, and reduce the need for a human operator, would include the installation of a 3D camera-sensor. The robot would take the correct pieces in accordance with production or assembly process, from the box next to it. The box is being filled with preparations from a conveyor belt.

Keywords: Artificial intelligence, automation, fuzzy logic, industrial computer systems, Industry 4.0.

INTRODUCTION

Complex working conditions and the size of machines are the key challenges facing modern industrial plants today (Mikić *et al*., 2022). Nowadays industrial production companies strive to make the transition from automation to digitization, and reach the requirements and exploit opportunities of Industry 4.0. Due to the necessity for modernization of the companies, reduction of production costs, increase of productivity, quality of service, improvement of working conditions, timely supply of material and parts, as well as finished products, it is crucial to develop methods for the achievement of these goals, and apply these appropriately in the real work environment (Günter *et al*., 2006; Novaković *et al*., 2021).

The aim of this paper is to examine and evaluate the possibility of successful installation of a smart production system of the latest generation, based on fuzzy logic implemented in the decision making, and to compare the results with the production systems of the previous generations. The research includes all the necessary conditions for the successful implementation of a flexible production cell in an automated production line in a modern factory. All conditions for the implementation of the Industry 4.0 are fulfilled, with the use of robots and

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intelligent control, as well as trends in their development and application.

A concrete example of the application of an intelligent autonomous system in the production of machine elements is explained. The HAAS CNC machine is chosen for an experiment (HAAS, USA) and the intelligent production is described in detail, with the flexible cell, robot and smart control.

Choosing the appropriate grippers, with respect to the grasping force, is presented and it is implemented by using an artificial intelligence technique – the SWARA method (Step-wise weight assessment ratio analysis).

In order to perform fusion of the computer numerical control (CNC) machine and industrial robot, it is necessary to:

- Install an experimental setup, consisting of a CNC machine, with work-piece plate - tilting table with two axes, the industrial robot as an active part of the clamping system and work-piece;
- Connect the devices into a network so that all can communicate with each other;
- Create a numeric control program for the HAAS CNC machine in computer aided manufacturing (CAM) software;

  Program a robot and synchronize it with the CNC machine program;
- Test whether pieces produced by the CNC machine are within the given tolerances.

The basic challenge is to connect these subsystems and ensure their mutual M2M (machine to machine) communication in order to determine whether the CNC cell system works well as a whole. There are many disturbances the robot is subjected to while being in operation – the weight it lifts can vary, as well as the dimensions of the work-piece, the tools are changing too, and the travel path is different from one task to another (Owen *et al.*, 2006; Chen & Dong, 2013; Cen & Melkote, 2017; Gualtieri *et al.*, 2021).

After the service department of the company had completed the installation of the components on the customer’s premises, it is necessary to perform leveling and calibration of the machine and the robot. The leveling of the CNC machine and the robot is performed with the help of a special digital measuring device. This measuring device has the ability to communicate to mobile devices and computers over the Bluetooth connection. Information on the position of the work-piece, plate, or some other reference part of the machine is sent in real time to the mobile phone of the service technician who performs the adjustment (Dumas *et al*., 2011; Tyapin *et al.*, 2014). That way, the service technician does not need to go to the device after checking each foot rate. To add to that, there is no need for another service technician who would constantly read the data during levelling (Lehmann *et al.*, 2012).

CRITERIA

The end effectors are the crucial part of the robot subsystem, which is the focus of this project, and the appropriate choice is obtained by using a fuzzy logic approach (Pérez Armayor & Díaz Batista, 2010; Dihovični & Škrbić, 2020).

In robotics, the end effectors are devices at the end of a robotic arm designed to work with the environment. The exact nature of this device is determined by the application of the robot (Wan *et al.*, 2015; Wu *et al.*, 2015).

By strict definition, which comes from serial robotic manipulators, the end effectors represent the last connection (or end) of the robot. In a broader sense, the end effectors can be viewed as part of a robot that communicates with the work environment (Owen *et al.*, 2006).

End effectors can consist of a gripper, or a tool. In general, there are four categories of robotic gripping (Wan *et al.*, 2015):

- Impactive - jaws, or claws that directly physically grip an object;
- Ingressive - needles, or buttons that physically penetrate the surface of an object (used to handle textiles, carbon fibers, and glass fibers);
- Astrictive - attractive forces applied to the surface of an object (vacuum, magnetic, or electro adhesion);
- Contiguous - requires direct contact (such as gluing, surface tension, or freezing).

Most often, a mechanical gripper can have two, three, or even five grippers (fingers). In general, the gripping mechanism is operated by grippers, or mechanical fingers. Two-finger clamping is commonly used for industrial robots that perform specific tasks in less complex applications (Martinov *et al.*, 2012).

The mechanism used in gripping with two-finger grips is characterized by:

1) the shape of the surface to be gripped;
2) the force required to grip an object.

The shape of the grips can be selected according to the shape of the object being manipulated. For example, if the robot is designed to lift a round object, the shape of the gripper may have a concave contour.

Although there are numerous forces acting on a body raised by a robotic arm, the main force is the force of friction. The surface of the grip can be made of soft material with a high coefficient of friction, so that the surface of the object is not damaged. The robotic gripper must withstand not only the weight of the object, but also the acceleration caused by the frequent displacement of the object.

To determine the force required to grasp an object, the following formula is used:

$$F = \frac{m(a+g)}{\mu\, n}, \tag{1}$$

where:
F is a force required to grasp an object;
m is a mass of the grasped object;
a is an acceleration of the object;
μ is a coefficient of friction;
n is a number of grippers;
g is an acceleration of gravity.

The clamping force, in addition to acceleration, is also affected by the length of the grippers.

The diagram in Figure 1 displays how the clamping force is changing with respect to the length of the grippers.

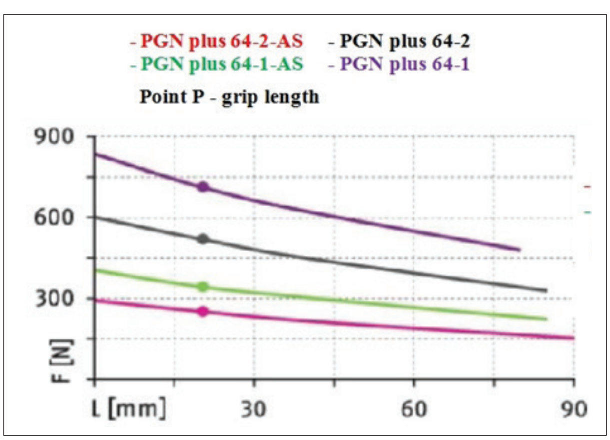

Figure 1: The diagram of the gripping force (F) with respect to the length of the grippers (L) (source: SCHUNK GmbH & Co. KG)

The grippers are pneumatically actuated. The opening and/or closing of the grippers is controlled with programmable magnetic switches SCHUNK MMS 22-PI1. A pneumatic nozzle between the grippers is installed, which is used for cleaning work-pieces and clamping accessories from sawdust and coolant.

DISCUSSION

Decision making in many areas can be very risky and difficult, affected by competing constraints and therefore cannot be individual. Multi Criteria Decision Making (MCDM) is a renowned methodology in decision making and evaluation. One of the famous MCDM tools is SWARA - Step-wise Weight Assessment Ratio Analysis method (Zolfani & Saparauskas, 2013).

Choosing end effectors can be enhanced by implementing the SWARA method in decision making. The objective of this study is to calculate relative weights of the average criteria by implementing the SWARA method (Merigó & Engemann, 2010; Zolfani & Saparauskas, 2013).

Based on their expected significances, the arithmetic mean values for the average clamping force in N are shown in the Table 1, sorted in descending order.

Table 1: The presentation of arithmetic mean of clamping force in [N] for different gripper types

Criteria – Gripper type	Mean clamping force [N]
PGN-plus 64-1	633
PGN-plus 64-2	450
PGN-plus 64-1-AS	322
PGN-plus 64-2-AS	225

Table 2 displays the relative importance of the mean criteria for average clamping force. The relative importance of the mean criteria j, denoted as $\tilde{s}_j$ to previous criteria (j-1), is given in the Table 2.

Solving the weight q of the j-th criteria, denoted by $\tilde{q}_j$, is given by Equation 2 (Keropyan & Gil-Lafuente, 2010):

$$\tilde{q}_j = \begin{cases} 1, j = 1 \\ \dfrac{\tilde{x}_{j-1}}{\tilde{k}_j}, j > 1 \end{cases} \tag{2}$$

Table 2: The relative importance of the mean criteria for average clamping force

Criteria – Gripper type	$\tilde{s}_j$
PGN-plus 64-1	
PGN-plus 64-2	0.710
PGN-plus 64-1-AS	0.705
PGN-plus 64-2-AS	0.698

The relative weight of the evaluation criteria j is determined in Equation 3 (Nicolas, 2004; Pérez Armayor & Díaz Batista, 2010), and is given in the rightmost column of the Table 3:

$$\tilde{w}_j = \frac{\tilde{q}_j}{\sum_{k=1}^{n} \tilde{q}_k} \qquad (3)$$

Table 3: The relative weight of the evaluation criteria

Criteria – Gripper type	$\tilde{s}_j$	$\tilde{k}_j$	$\tilde{q}_j$	$\tilde{w}_j$
PGN-plus 64-1		1	1	0.470
PGN-plus 64-2	0.710	1.710	0.584	0.274
PGN-plus 64-1-AS	0.705	1.705	0.342	0.160
PGN-plus 64-2-AS	0.698	1.698	0.201	0.096
			2.127	1.000

The SWARA method is often applied for two reasons. Firstly, SWARA's perspective is different from other similar methods – this method gives the chance to decision makers to select their priority based on the current situation of environment and economy. Secondly, the role of the experts is very important in the SWARA method. Experts have a key role in process of decision making on very important projects. Finally, SWARA has the advantage of more logical calculation of weights and relative importance of criteria (Zolfani & Saparauskas, 2013).

The summary of resulting weight of the mean criteria for the clumping force for all of the four selected types of grippers is shown in Figure 2.

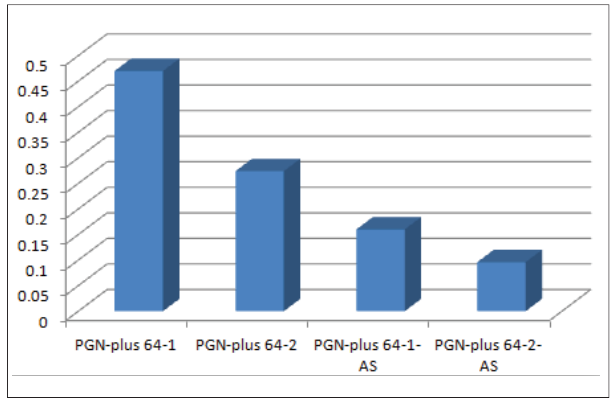

Figure 2: Graphical representation of resulting weight of the mean criteria for average clumping force

Two universal parallel grippers such as SCHUNK PGN-plus 64-1 grippers are chosen as the end effectors. The maximum force of external clamping of the work-piece is 135 N, and the step is 4 mm per grip.

The grippers are pneumatically actuated, where the control of opening and closing of the grip is done via programmable SCHUNK MMS 22-PI1 magnetic switches. A pneumatic nozzle is installed between the grippers, which is used to clean the work-pieces and clamping accessories from sawdust and coolant (Ma *et al*., 2007).

Two universal parallel grippers, with two grippers SCHUNK PGN-plus 64-1, in Figure 3 are presented. The grippers are made of aluminum bars having a profile that corresponds to the shape of the work piece, and the profiles are oriented towards the gripping position. The grippers are manufactured by the custom design and machined on a CNC machine on the customer's premises, in the customer's plant.

The solution with two grippers placed perpendicularly on the fork, at an angle of 90° to each other, is chosen (as shown in Figure 3) in order to save time. While the robot brings the preparation in one gripper, with the other it takes and lifts-up the finished work-piece. After that the robot pulls the work-piece out of the clamping accessories and rotates the last joint by 180° to swap the places of both grippers. This way, the double stroke of the robot arm from the clamping accessories to the pallet is eliminated (Ezugwu *et al.*, 2009).

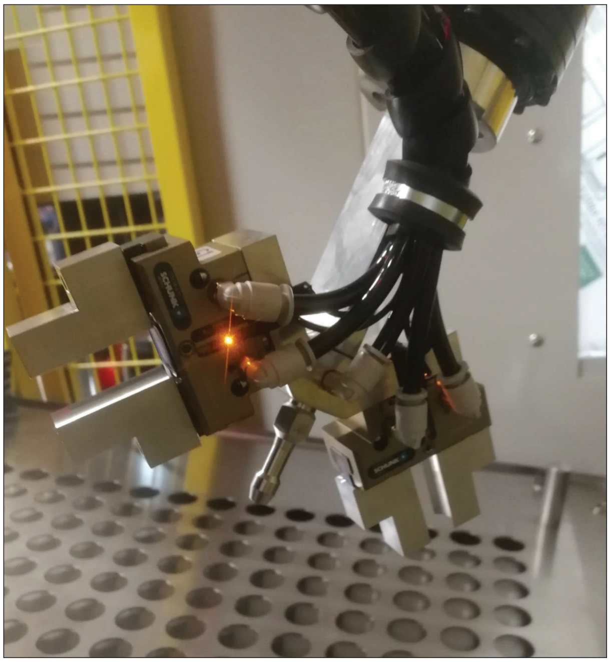

Figure 3: Parallel grippers with two grippers SCHUNK PGN-plus 64-1

The programmable magnetic switches SCHUNK MMS 22-PI1 has the function of sending the information to the robot in order to close the feedback.

The sensor is mounted on the body of the catcher, and connected with the channels provided. The sensors can also be programmed using special programming tools (plug-in or magnetic). The sensors have LED lights that send signals to operator by varying the number and frequency of flashes. The sensors also send the information to the robot via cable.

In case of any physical problem while catching the work piece (jamming, incorrectly placed work piece, etc.), the robot receives a signal to stop further execution, and signals the stop by turning on the red light on its signal traffic light, as well as by sending a message with a description of the error to the control panel. If the light signal on the robot's traffic light fails, the CNC machine recognizes that the waiting time is longer than the usual cycle (the allowed value of time delay expressed in seconds previously entered in the programme).

After reporting an error on its control unit and turning on its traffic light, the CNC machine sends an SMS (Short Message Service) with a description of the problem to the mobile phone of the responsible person, and a message to the predefined e-mail addresses. All this is provided via the HaasConnect application. The ability to equip grippers of the robotic arm of the CNC machine with inductive sensor systems, magnetic switches, or work-piece-specific grips, improves their functionality, while increasing both the reliability and productivity of the process. The quality control of machining of the parts (with measuring and checking dimensions) is automated and performed using WIPS – Wireless Intuitive Probing System. A WIPS measuring probe manufactured by RENISHAW (RENISHAW mark - OMP40) is delivered with the CNC machine, as displayed in Figure 4. This probe enables fast and precise calculation (within the accuracy of the CNC machine) of the machined work piece on the CNC machine.

Figure 4: Measuring probe RENISHAW OMP40

The CNC machine manufacturer HAAS offers a complete system with WIPS equipment as a standard option. Considering the growing demands regarding precision and reduction of cycle time, as well as reduction of scrap, it is almost impossible to use a machining centre without this device.

Programming of a CNC machine for a cycle of inspection and quality control is done directly on the machine's control unit. The WIPS probe communicates with the CNC machine over transceiver located in the workspace in the vicinity of the machine using an infrared (IR) radiation connection (Figure 6). The probe can be programmed to find the zero point of the work-piece, measure the dimensions of the work piece, touch the holes on the piece, tactilely scan the work piece, etc.

Communication between the measuring device and the CNC machine is shown in Figure 5.

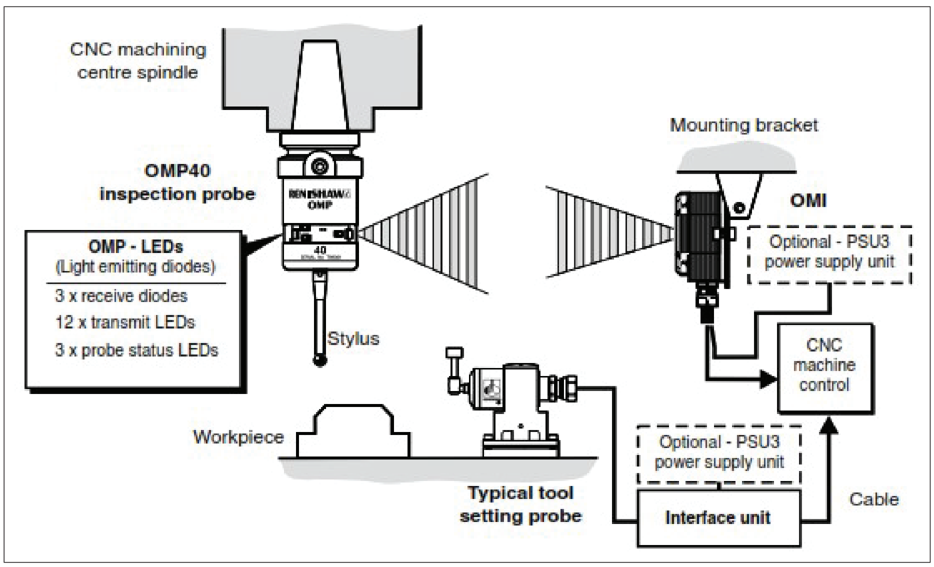

Figure 5: Communication of the measuring device with the CNC machine

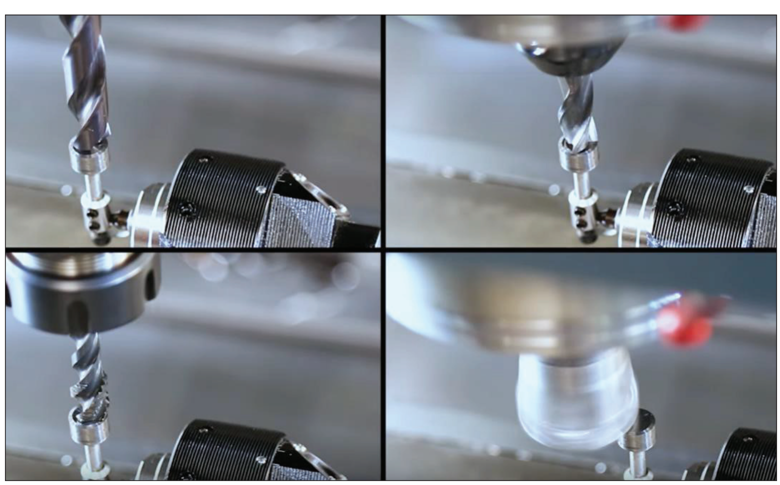

Figure 6: Measuring the tool dimension on the CNC machine

When the tool sizing cycle is started, the tool itself approaches the hard metal cylinder located on the top of the device and after touching the tip of the probe sends a signal to the machine control unit (Figure 6). At that moment, the machine compares the difference in the lengths of the axis of the movement and the previously calibrated (known) length at which the tip of the probe is located. Thus, the exact length of the tool is obtained, which is measured from the tip of the tool to the front of the spindle, and the machine automatically saves the measurement – it enters value in the tool table.

The same process is repeated along the second axis in case it is necessary to measure the diameter of the tool. Then the tip of the probe approaches the cylinder of the tool sideways, with the spindle rotating the tool in the opposite direction then while performing cutting or turning.

Measuring the tool dimension on the CNC machine is presented in Figure 6.

This measuring device is very useful in series production, because it has the ability to detect tool breakage. The tool check cycle and repetition interval are set on the machine control unit in the tool table. The principle of the operation is such that the machine has a predefined allowable path length that can be travelled when the tool approaches the measuring probe. If there is no contact between the tool tip and the measuring probe within this range, the machine signals a fault on the control unit. The cycle can be repeated periodically in predefined equal time intervals (after the tool has been in the grip for a certain period of time), or after each change of the tool.

The use of automated measuring devices for the machining quality control and inspection process reduces significantly the occurrence of scrap in automated production, where the human presence is not perpetual. The initial investment in systems of this type returns rather quickly through the decrease of the preparation time, which includes adjusting the position of the part or preparation and defining the dimensions of the cutting tools.

The classic calibration methods last approximately 11 minutes for the preparation, with 8 tools stacked to be ready to work. This system reduced that time to less than 2 minutes.

A possible plan for future work is to upgrade the existing system, described here, by installation of a 3D camera-sensor, which would provide an even higher level of autonomy and eliminate the need for a worker who serves the machine. Succesful implementations of artificial vision systems exist (Roberti *et al.*, 2009). Instead of a human worker who places preparations on the pallet matrix and transports the finished pieces the robot would take the pieces from the box next to it, which would be filled with preparations by a conveyor belt. The robot would also place the finished pieces on another conveyor belt that would take these to the next operation (inspection and packaging). If this is the case, it would not be necessary to place the workpieces in the proper position on the pallet. This aproach would be a significant improvement towards Industry 4.0.

In recent years fuzzy logic has provided advances in the design and control of hybrid intelligent systems based on nature-inspired optimization. Applications of fuzzy and hybrid intelligent systems in areas such as intelligent control and robotics, pattern recognition, medical diagnosis, time series prediction, and optimization of complex problems have been explored (Melin *et al.*, 2018).

Dumitrescu *et al.*, (2021) introduced a concept of distributed intelligent control (DIC) and applied fuzzy logic to the control of an autonomous robot (vehicle). From the point of view of the DIC concept, three types of components can be defined and fuzzified (Dumitrescu *et al.*, 2021):

- Fuzzy sensors, which provide a representation of measurements as fuzzy subsets;
- Fuzzy actuators, which can act and operate in a real world; depending on the fuzzy subsets they receive;
- Fuzzy components of inference, also received by the fuzzy actuators, which can perform distributed fuzzy logic.

Fuzzy components can be integrated for different applications into a compact model of components, called the fuzzy cell. The configuration of the cells in the network is done through a specific programming language (Dumitrescu *et al.*, 2021).

Increasing the variety of products that market needs impose on manufacturers requires high adaptability of production systems that can be achieved through the introduction of flexible production systems composed of interoperable devices with variable architecture. Control and management of such a complex system requires fast and reliable real-time virtualization of real-world applications, as well as real-time feedback from real-world virtual (cyber) models (Wan *et al.*, 2015). The boundary line between the real production system and its cyber-representation is characterized by extremely high information throughput, combining these two systems into a single system, the Cyber-Physical Manufacturing System (CPMS). Recent advances in the fields of Cyber-Physical Systems (CPS) and the Internet of Things (IoT) have enabled the creation of CPMS.

CONCLUSION

In this study the SWARA method was applied on given data for the clamping force, obtained from the SCHUNK manufacturer. For the chosen criteria such as clamping force, the resulting weight was calculated. The degree of importance is presented in the appropriate tables, as well as in graphs. Taking into account the relative weight, the SCHUNK PGN-plus 64-1 grippers are chosen for the end effectors out of group of four types of the grippers.

In order to achieve adequate grip and capture of the object, the positioning and orientation of the grippers play a very important role. The industrial robot must achieve the precise relative positioning and orientation of the catcher with respect to the object, which in the case of hierarchical intelligent control can be placed in an arbitrary position.

Movement of an autonomous industrial robot in accordance with the recognized object, initiates many difficulties during completion of other defined phases of object manipulation. Thanks to visual feedback and learning based on artificial neural network systems, the robot catcher can determine and take a proper position and orientation with respect to the recognized object. This can be obtained in different ways, primarily by using systems with adaptive flexibility.

Smart behavior, which involves an autonomous industrial robot, is provided through adequate coordination between visual information about the object and surrounding space obtained from the sensor-camera and the control system. The smart control of the robot, realized by using sensor-cameras and artificial neural networks, has proven to be effective in overcoming the problems of modeling and the emergence of uncertainty in the real environment (*e.g.*, changing the position of objects).

The successor of the contemporary CNC machine could be called the ICNC machine (intelligent computer numerical control). In the future, there will be more flexible production cells controlled by artificial intelligence which will be able to ‘learn’, and the human presence will be decreased further and reduced only to assigning tasks.

Two decades ago, there were less than 700,000 industrial robots worldwide; however nowadays the number is over 3 million. In developed countries, there has been a simultaneous increase in production and a decrease in employment, and one, but not the only, cause is the development of technology. Today, 3D printing is used in the production of cars and airplanes, biotechnology is changing the way we grow crops and produce food, and the further development of nanotechnology and artificial intelligence will greatly reshape numerous economic activities, probably faster than we expect.

Currently the need for unskilled laborers whose work can be automated shows a downward trend and this is expected to continue, while the need for experts having skills to develop, launch and maintain highly automated systems is growing year by year.

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