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3D printed robotic arm with elements of artificial intelligence

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Abstract

This article presents an example of a connection between three major modern disciplines of engineering: Artificial Intelligence, Robotic Engineering and Additive Manufacturing. The main focus is on developing the methodology for creating of a printable, low-budget and six degrees of freedom robotic arm, which can be used with external artificial intelligence system. The developed solution is based on a popular open source robotic arm project. The Article consists of three parts: introduction to 3D printing, short summary of printable robotic arm with emphasis on kinematics of the manipulator and presentation of available options for implementation of external control system based on artificial intelligence.

Keywords: Robotic Engineering; Additive Manucatruing; Robotic Arm, Artifiical Intelligence

1. Introduction

Rapid industrial growth and emergence of modern production machines causes significant need for more advanced automation of machinery parks. One of the possible options to increase efficiency of production systems is to use industrial robots [1] [2] [3] [4] [11]. The most popular type of the industrial robots are manipulators. They are relatively simple to build and have vast scope of applications. In general, the usage of industrial robots can minimize amount of human labor, significantly increase the safety and reduce the takt time, which is the key parameter in production economy. Despite the fact that a constant increase of the number of robots can be observed in industry, there is still a

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financial barrier for many companies to purchase advanced machines [1] [2] and increase their production flexibility. Moreover, a number of current production lines would need to be rebuilt in order to adapt to robotization.

A relatively new and dynamically developing branch of technology is additive manufacturing [5] [6][13][14][15], which is more widely known as 3D printing. This technology can significantly accelerate prototyping and production of desired mechanical elements. This technology is based on successive application of layers of material. Consequently, it minimizes or completely eliminates the need for further finishing of the model and allows for relatively simple and cheap production. Usually the printing technology does not require special rooms and can be used in generally available space. Broad accessibility of the additive technologies motivated the current study to investigate a possibility for creation of a relatively cheap and easily obtainable robotic arm.

The control systems of manipulators are commonly built using embedded systems [21]. The solutions developed by manufacturers are usually not open and their parameters are not accessible. Therefore, it might be desirable to develop a software that is open and easy to implement for a wide range of robot configurations. Such solution should be based on a widely available and low-cost microcontrollers with sufficient computing power. The current work presents an open-source solution, which can be used to control the robots and can be implemented at relatively low costs.

2. Additive Manufacturing

Additive manufacturing, known as 3D printing, is a technology based on successive application of layers of building material with simultaneous bonding of adjacent layers together [13][14][15]. The additive technologies use various methods of production including thermoplasticity.

The figure 1 presents the visualization of 3D printing methods. The additive manufacturing techniques can be divided based on the following [7]:

- extruding a molten or otherwise semi-liquid material,
- selectively solidifying a liquid resin – known as a 'photopolymer'
- selectively sticking together the granules of a very fine powder,
- lamination.

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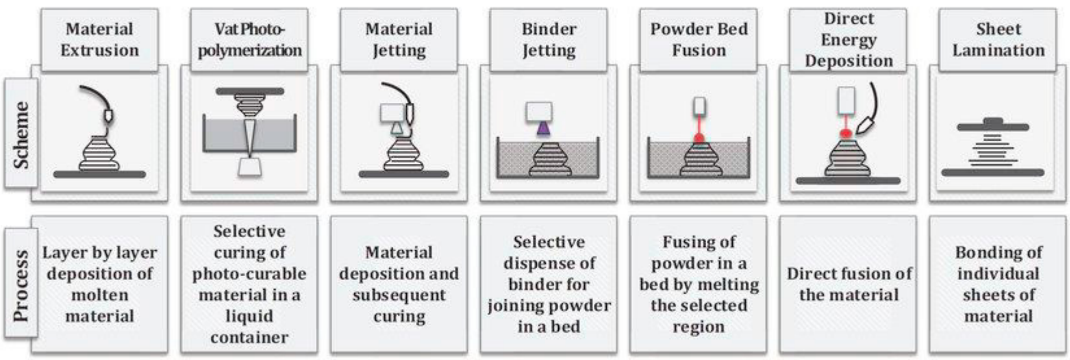

Fig. 1 Visualization of different 3D printing methods [8]

2.1. Fused deposition modeling/ Fused filament fabrication (FDM/FFF)

The FDM/FFF [12] is currently one of the most popular methods because it offers low production costs. The manufacturing process is based on extrusion of thermoplastic material through a heated nozzle. The element responsible for the material flow is the extruder, which is typically made of two moving rolls. By supplying the right amount of heat to the thermoplastic material it can leave the nozzle in semi-liquid form. Then the material cools down by natural convection or using cooling fan. The most popular solution is to use a single nozzle system. This solution is the simplest and most reliable. Unfortunately, the disadvantage of such application is the possibility of using only one type of material during the printing process. The alternative is a multi-nozzle system, which allows to achieve a complex detail characterized by heterogeneous properties.

The technique described above is the basis of operation of every machine which uses the FDM/FFF method. For its schematic see the figure 2. The main parameters of this technique are: type of the polymer used and its dimension (diameter). The diameter has been standardized and is either 1.75 mm or 3.00 mm. The dimension of 1.75 mm is much more popular. Examples of the materials used in this technology include: PLA, ABS, PET-G, PA-12, HIPS, ASA.

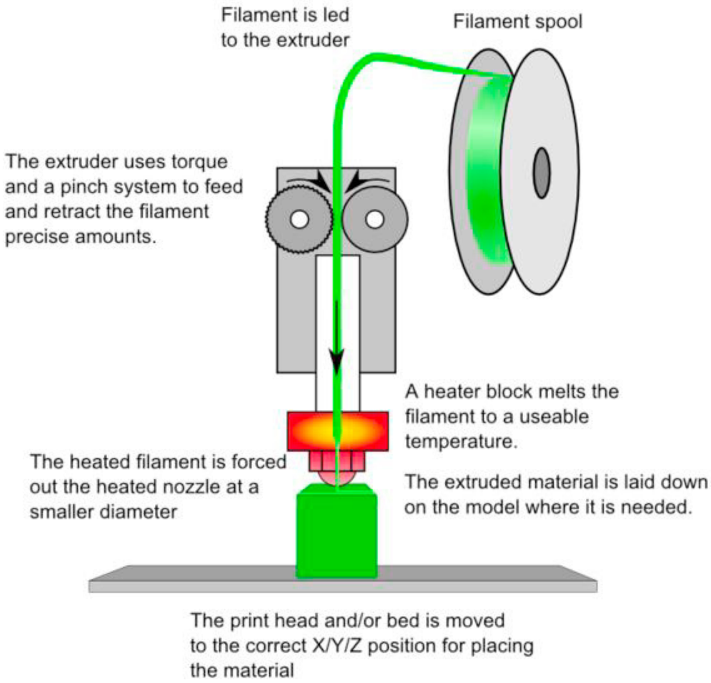

Fig. 2 Schematic of the FDM/FFF Technology [3].

3. The 3D printed robotic arm

Currently the most popular type of robotic arms are machines that have only rotational joints. For this reason, a 6xR (six rotational joints) type of the robotic arm is proposed in the present work. As a base for the current study a six-axis anthropomorphic manipulator, designed for printing with the FDM technology, was chosen. The project of this manipulator is available under the Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) license [10]. This project was adopted as the base structure and modified for the needs of this study. This could ensure an appropriate cooperation with generally accessible mechanical components and could improve the device operational parameters. The figure 3 shows the 3D model of the selected manipulator.

To manage the hardware, the control system based on the Atmega2560 microcontroller was chosen. In this system all the actuators were connected to the outputs mounted on the microcontroller board. The measuring elements, designed to control the position of the kinematic chain, were connected to the inputs of the microcontroller.

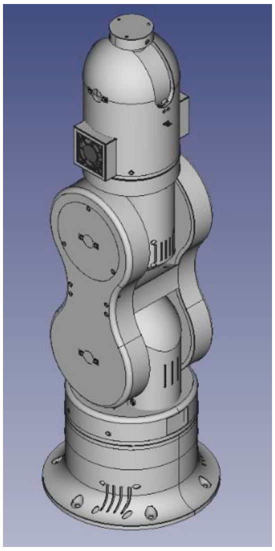

Fig. 3 Robotic arm designated to be printable with FDM technology

Main features of the investigated robotic arm were:

- maximum payload 750g,
- as many robot parts as possible should be manufactured using the additive technologies. The project consisted of 54 printable parts,
- it should be adapted for printing on FDM printers with a printing area of 200x200x200mm, the maximum range of the robot was about 620 mm,
- the cost of the whole device was about 350 €.

The motion of the described robotic arm was realized by seven bipolar stepper motors. The large number of motors were to achieve an optimal payload for the construction. The manipulator was mounted on the support structure to ensure its stability. The first four links were based on optical end-stops and the last two links were based on mechanical end-stops to ensure their correct alignment. As the working tool of the arm the gripper was chosen, which was moving by means of the servomotor. For the reference, the detailed BOM list and instructions of how to build a robotic arm can be found in [10].

3.1. Kinematics of the constructed robotic arm

The analytical description of the position of the manipulator was described by kinematics. The kinematics was used to determine the relationship between the configuration coordinates and the position of the gripper. The configuration coordinates were defined as the manipulator's coordinate system, which resulted from angular and linear movements in the respective joints. The previously mentioned dependencies were determined by means of two tasks [16] and their corresponding kinematics:

- The forward task: the known were the values of the vectors of configuration coordinates θ(t) for each of the joints and geometrical parameters of the links. The solution to the task was the position and orientation of the effector in the base coordinate system.
- The inverse task: the known were the position and orientation of the gripper and the geometrical parameters of all the links. The result of solving the task were all the possible vectors of the configuration coordinates.

The figure 4 shows the complete kinematic chain of the designed manipulator.

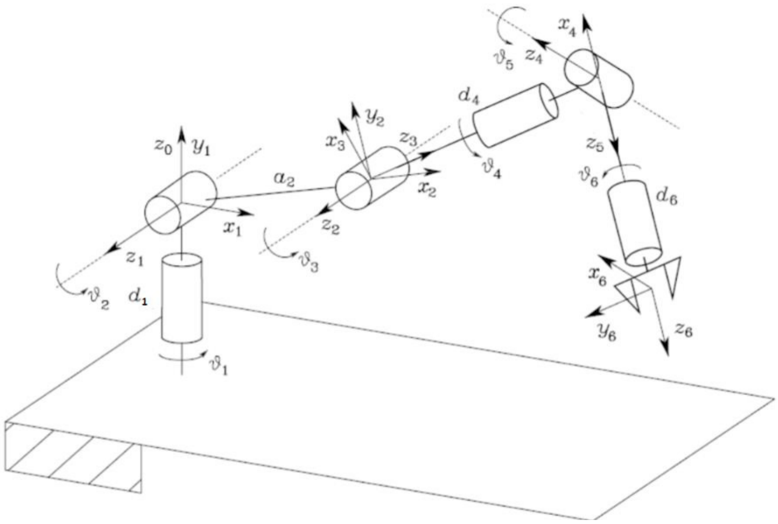

Fig. 4 The kinematic chain of the designed manipulator

The most common way to resolve the kinematics of the tasks was to begin with calculation of the forward task kinematics, which was based on Denavit-Hartenberg (D-H) parameters [19][20]. Table 2 shows all the D-H parameters of the constructed manipulator.

Table 2. The D-H Parameters of the constructed manipulator.

Link	θ_i	α_i	d_i	a_i
1	θ_1	90	L_1	0
2	θ_2-90°	0	0	L_2
3	θ_3	90	0	0
4	θ_4	-90	L_3	0
5	θ_5	90	0	0
6	θ_6	0	L_4	0

The obtained data was used to calculate all the transformation matrices. The final transformation matrix had the following form:

$$T = \begin{bmatrix} \eta_x & \varsigma_x & \alpha_x & d_x \\ \eta_y & \varsigma_y & \alpha_y & d_y \\ \eta_z & \varsigma_z & \alpha_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where:

$$\begin{aligned} \eta_x = cos_{\theta_6}\big[cos_{\theta_5}\{sin_{\theta_1}sin_{\theta_4} + cos_{\theta_4}(cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3})\} \\ + sin_{\theta_5}(cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3})\big] \\ + sin_{\theta_6}(sin_{\theta_4}\{cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3}\} - cos_{\theta_4}sin_{\theta_1}) \end{aligned} \tag{2}$$

$$\begin{aligned} \eta_y = cos_{\theta_6}\big[cos_{\theta_5}\{-cos_{\theta_1}sin_{\theta_4} + cos_{\theta_4}(sin_{\theta_1}cos_{\theta_2}sin_{\theta_3} + sin_{\theta_1}sin_{\theta_2}cos_{\theta_3})\} \\ + sin_{\theta_5}(sin_{\theta_1}cos_{\theta_2}cos_{\theta_3} - sin_{\theta_1}sin_{\theta_2}sin_{\theta_3})\big] \\ + sin_{\theta_6}(sin_{\theta_4}\{sin_{\theta_1}cos_{\theta_2}sin_{\theta_3} + sin_{\theta_1}sin_{\theta_2}cos_{\theta_3}\} + cos_{\theta_4}cos_{\theta_1}) \end{aligned} \tag{3}$$

$$\begin{aligned} \eta_z = cos_{\theta_6}\big[sin_{\theta_5}(cos_{\theta_2}sin_{\theta_3} + sin_{\theta_2}cos_{\theta_3}) + cos_{\theta_4}cos_{\theta_5}(sin_{\theta_2}sin_{\theta_3} - cos_{\theta_2}cos_{\theta_3})\big] \\ + sin_{\theta_4}sin_{\theta_6}(sin_{\theta_2}sin_{\theta_3} - cos_{\theta_2}cos_{\theta_3}) \end{aligned} \tag{4}$$

$$\begin{aligned} \varsigma_x = -sin_{\theta_6}\big[cos_{\theta_5}\{sin_{\theta_1}sin_{\theta_4} + cos_{\theta_4}(cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3})\} \\ + sin_{\theta_5}(cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3})\big] \\ - cos_{\theta_6}(sin_{\theta_4}\{cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3}\} - cos_{\theta_4}sin_{\theta_1}) \end{aligned} \tag{5}$$

$$\begin{aligned} \varsigma_y = -sin_{\theta_6}\big[cos_{\theta_5}\{-cos_{\theta_1}sin_{\theta_4} + cos_{\theta_4}(sin_{\theta_1}cos_{\theta_2}sin_{\theta_3} + sin_{\theta_1}sin_{\theta_2}cos_{\theta_3})\} \\ + sin_{\theta_5}(sin_{\theta_1}cos_{\theta_2}cos_{\theta_3} - sin_{\theta_1}sin_{\theta_2}sin_{\theta_3})\big] \\ - cos_{\theta_6}(sin_{\theta_4}\{sin_{\theta_1}cos_{\theta_2}sin_{\theta_3} + sin_{\theta_1}sin_{\theta_2}cos_{\theta_3}\} + cos_{\theta_4}cos_{\theta_1}) \end{aligned} \tag{6}$$

$$\begin{aligned} \varsigma_z = -sin_{\theta_6}\big[sin_{\theta_5}(cos_{\theta_2}sin_{\theta_3} + sin_{\theta_2}cos_{\theta_3}) + cos_{\theta_4}cos_{\theta_5}(sin_{\theta_2}sin_{\theta_3} - cos_{\theta_2}cos_{\theta_3})\big] \\ - sin_{\theta_4}cos_{\theta_6}(sin_{\theta_2}sin_{\theta_3} - cos_{\theta_2}cos_{\theta_3}) \end{aligned} \tag{7}$$

$$\begin{aligned} \alpha_x = sin_{\theta_5}\{sin_{\theta_1}sin_{\theta_4} + cos_{\theta_4}(cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3})\} \\ - cos_{\theta_5}(cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3}) \end{aligned} \tag{8}$$

$$\begin{aligned} \alpha_y = sin_{\theta_5}\{cos_{\theta_4}(sin_{\theta_1}cos_{\theta_2}sin_{\theta_3} + sin_{\theta_1}sin_{\theta_2}cos_{\theta_3}) - cos_{\theta_1}sin_{\theta_4}\} \\ - cos_{\theta_5}(sin_{\theta_1}cos_{\theta_2}cos_{\theta_3} - sin_{\theta_1}sin_{\theta_2}sin_{\theta_3}) \end{aligned} \tag{9}$$

$$\alpha_z = cos_{\theta_4}sin_{\theta_5}(sin_{\theta_2}sin_{\theta_3} - cos_{\theta_2}cos_{\theta_3}) + cos_{\theta_5}(cos_{\theta_2}sin_{\theta_3} + sin_{\theta_2}cos_{\theta_3}) \tag{10}$$

$$\begin{aligned} d_x = L_2cos_{\theta_1}sin_{\theta_2} - L_3(cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3}) \\ - L_4\big[cos_{\theta_5}(cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3}) \\ - sin_{\theta_5}\{cos_{\theta_4}(cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3}) + sin_{\theta_1}sin_{\theta_4}\}\big] \end{aligned} \tag{11}$$

$$d_y = L_2 sin_{\theta_1} sin_{\theta_2} - L_3(sin_{\theta_1} cos_{\theta_2} cos_{\theta_3} - sin_{\theta_1} sin_{\theta_2} sin_{\theta_3}) - L_4[cos_{\theta_5}(sin_{\theta_1} cos_{\theta_2} cos_{\theta_3} - sin_{\theta_1} sin_{\theta_2} sin_{\theta_3}) - sin_{\theta_5}\{cos_{\theta_4}(sin_{\theta_1} cos_{\theta_2} sin_{\theta_3} + sin_{\theta_1} sin_{\theta_2} cos_{\theta_3}) - cos_{\theta_1} sin_{\theta_4}\}] \quad (12)$$

$$d_z = L_1 - L_4[cos_{\theta_5}(cos_{\theta_2} sin_{\theta_3} + sin_{\theta_2} cos_{\theta_3}) - cos_{\theta_4} sin_{\theta_5}(sin_{\theta_2} sin_{\theta_3} - cos_{\theta_2} cos_{\theta_3})] - L_2 cos_{\theta_2} - L_3(cos_{\theta_2} sin_{\theta_3} + sin_{\theta_2} cos_{\theta_3}) \quad (13)$$

Calculation of the kinematics of the forward task could be described as straightforward linear algorithm, but calculation of the inverse task kinematics was more complicated. To calculate the inverse task kinematics the decoupling procedure [17] was used. This procedure allowed to calculate the joint parameters (q1, q2, q3) that placed the robot tip in the desired position and then calculated the joint parameters (q4, q5, q6) responsible for the wrist position and orientation. To determine the solution a graphical method was used. To calculate the first three articulated variables, it was assumed that the manipulator took the form of 3R (three rotational joints). Such dependence could ensure that the center position of the fifth link was determined. It should be emphasized that the position of the fifth link did not coincide directly with the position of the center of the effector. Therefore, it was necessary to use the following relation to determine the position of the fifth link:

$$P_m = Tx \begin{bmatrix} 0 \\ 0 \\ -L_4 \\ 1 \end{bmatrix} = \overrightarrow{P_n} - L4 * \vec{\alpha} \quad (14)$$

where P_m is the fifth link center vector, P_n is the effector position vector and $\alpha = (\alpha_x\ \alpha_y\ \alpha_z)^T$ represents the vector of O_1Z_1 axis direction in $O_0\ X_0\ Y_0\ Z_0$ system.

The figure 5 shows the kinematics of the 3-axis manipulator, on the basis of which the position of the center of the fifth link of the manipulator was determined.

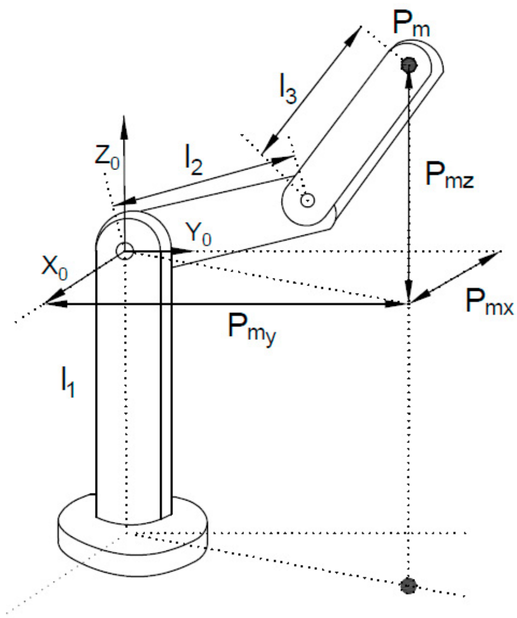

Fig. 5 3R Robotic arm configuration

The following formula could be derived from geometrical dependencies:

$$\theta_1 = arctg\left(\frac{P_{my}}{P_{mx}}\right) \quad (15)$$

where P_{my} is the projection on the Ox_0 axis position of Pm and P_{mx} is the projection on the Oy_0 axis position of Pm

$$\theta_2 = arctg\left(\frac{\pm\sqrt{1 - cos^2\theta_3}}{cos\theta_3}\right) \quad (16)$$

where:

$$cos\theta_3 = \left(\frac{{P_{mx}}^2 + {P_{my}}^2 + {P_{mz}}^2 - {L_2}^2 - {L_3}^2}{2 * L_2 * L_3}\right) \quad (17)$$

Where P_{mz} is the projection on the Oz_0 axis position of Pm

The determination of the articulated variables θ1, θ2, θ3 and the solution of the forward task kinematics allowed for determination of the exact position and orientation of Pm. According to the initial assumptions the other configuration variables were responsible for the proper orientation of the effector. This resulted in another task of defining the orientation matrix that could be used to determine θ4, θ5, θ6. The orientation matrix for this problem took the form:

$$R_0^1(\theta_1) * R_1^2(\theta_2) * R_2^3(\theta_3) * R_3^4(\theta_4) * R_4^5(\theta_5) * R_5^6(\theta_6) = \begin{bmatrix} \eta_x & \varsigma_x & \alpha_x \\ \eta_y & \varsigma_y & \alpha_y \\ \eta_z & \varsigma_z & \alpha_z \end{bmatrix} \quad (18)$$

After transformation, the above dependence took the form:

$$R_3^6(\theta_4, \theta_5, \theta_6) = R_0^3(\theta_1, \theta_2, \theta_3)^T * \begin{bmatrix} \eta_x & \varsigma_x & \alpha_x \\ \eta_y & \varsigma_y & \alpha_y \\ \eta_z & \varsigma_z & \alpha_z \end{bmatrix} \quad (19)$$

Equation (19) is a system of 3 equations that could determine the values of the other joint variables:

$$\begin{aligned}\theta_5 = arcos\Big[-\big\{\alpha_x\big(&cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3}\big) \\ &+ \alpha_y\big(sin_{\theta_1}cos_{\theta_2}cos_{\theta_3} - sin_{\theta_1}sin_{\theta_2}sin_{\theta_3}\big) + \alpha_z(cos_{\theta_2}sin_{\theta_3} \\ &+ sin_{\theta_2}cos_{\theta_3})\big\}\Big]\end{aligned} \quad (20)$$

$$\begin{aligned}\theta_4 = arcos\Big[\big\{\alpha_x\big(&cos_{\theta_1}cos_{\theta_2}sin_{\theta_3} + cos_{\theta_1}sin_{\theta_2}cos_{\theta_3}\big) \\ &+ \alpha_y\big(sin_{\theta_1}cos_{\theta_2}sin_{\theta_3} + sin_{\theta_1}sin_{\theta_2}cos_{\theta_3}\big) + \alpha_z(sin_{\theta_2}sin_{\theta_3} \\ &- cos_{\theta_2}cos_{\theta_3})\big\}/sin_{\theta_5}\Big]\end{aligned} \quad (21)$$

$$\begin{aligned}\theta_6 = arsin\Big[\big\{\eta_x\big(&cos_{\theta_1}cos_{\theta_2}cos_{\theta_3} - cos_{\theta_1}sin_{\theta_2}sin_{\theta_3}\big) \\ &+ \eta_y\big(sin_{\theta_1}cos_{\theta_2}cos_{\theta_3} - sin_{\theta_1}sin_{\theta_2}sin_{\theta_3}\big) + \eta_z(cos_{\theta_2}sin_{\theta_3} \\ &+ sin_{\theta_2}cos_{\theta_3})\big\}/sin_{\theta_5}\Big]\end{aligned} \quad (22)$$

4. Control system with elements of artificial intelligence

The previous section showed the calculation method of all the variables depending on the chosen kinematics task. This procedure allowed to obtain the parameters which could be used to control the robotic arm. However, there was still a need to manually program the robot to perform the pick and place task. Usage of an external sensor system would allow to achieve a more independent solution, which could automatically trigger the robot to move to the desired position. The solution for such problem could be solved on an external computer system using an image recognition algorithm. In such situation the control system in the computer would recognize the external object and then compute the inverse kinematics algorithm. After obtaining the solution the postprocessor would have to translate the acquired variables for the control commands, which would be used by the microcontroller to move all of the links. Such solution could be used in factories to perform sorting of different objects moving along the conveyor. The figure 6 shows the block diagram of the proposed solution. This solution could be relatively easily implemented in the ROS [18] (Robotics operating system) software, which is an open source Unix oriented software made for robots' control. Another program which can be used to implement mentioned solution can be MATLAB by MathWorks.

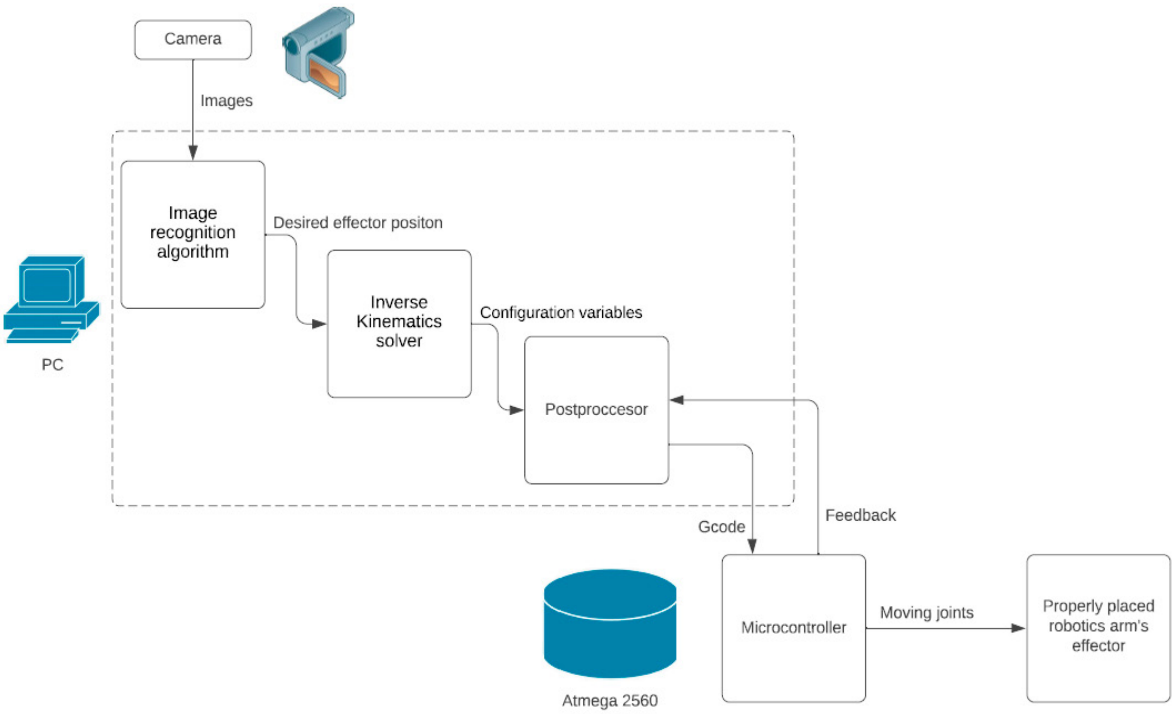

Fig. 6 Block diagram of control system with AI

5. Summary and Conclusions

Detailed description of the usage of the FDM technology to make a manipulator was presented. The work described the structure of the manipulator and specified the most important machine parameters. The main aspect of the machine description was the detailed derivation of the manipulator kinematics. The achieved results could be directly translated into the control algorithm and implemented to perform kinematics of the forward and backward task.

In order to solve the kinematics of the forward task the method using Denavit-Hartenberg parameters was adopted. Consequently, the diagram of kinematics of the created robot was plotted and the table of D-H parameters was constructed. The article provided also the final transformation matrix with all its components. The decoupling procedure was used to solve the task of the inverse kinematics. It allowed to propose an example of an intelligent control system, which could be based on an image recognition algorithm. The proposed control system should consist of an external control unit coupled with a microcontroller.

The main result of the presented work is a short description of how to create a budget and open source solution for the 6DOF manipulator. The proposed solution could be used for educational purposes to illustrate practical aspects of robotics.

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