

Path Planning and Control of an Industrial Robot Used for Opening Tap Hole of an Electric Arc Furnace

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Abstract

The electric arc furnace (EAF) is one of the popular methods of steel production from steel scraps. The plasma arc is used in EAF to generate heat for melting scarp or direct reduced iron (DRI). The liquid metal is drained from the EAF through the tap hole. Nowadays, it is critical to use Automated/robotic tools for opening the tap hole with oxygen lancing. Because many workers have been blinded by spraying molten particles in opening operation. This study was aimed to simulate a robot manipulator with five degrees of freedom designed for opening the tap hole of an electrical arc furnace. The geometrical model of the robot was designed in Solid works software according to the real workplace and its expected path and obstacles. The Newton-Euler approach was employed to derive the dynamic equations and the resultant joint torques. The dynamic model is used to obtain the operating torques of the joints as well as in the simulation using the SimMechanic toolbox in Matlab software. The results of the simulation with SimMechanic show that the control system can follow the desired path of the robot with acceptable accuracy.

Keywords

Electric Arc Furnace, Industrial Robot, Path Planning, PID Control, SimMechanic

1. Introduction

The electric arc furnace is used to provide high-quality steels from raw materials of steel scarp [1]. The electric arc furnace which is used in steelmaking was invented in 1889 by Paul Héroult. The first-generation furnaces capacity was 1 to 15 tons. In the 1960s, with the advent of billet casting, the EAF occupied another niche: it was a choice for the melting so-called mini-mills. This mini mill was used for the production of rebar and wire rods [2]. In the following two decades, to decrease the tap-to-tap time required by the billet casters, the EAF reinvented itself as a melting-only unit. Steel refining was left for the recently introduced ladle furnace. Large transformers were introduced; ultrahigh-power furnaces developed, which were made possible by adopting foaming slag practice. In this way, tap-to-tap time became close to casting time. In 1985, a new niche for electric steelmaking began to be taken: flat products through thin slab casting and direct rolling. Also, this process route has achieved a significant role in world steel production. The development of EAF technology since 1965, including lower power consumption, reduced tap-to-tap time, and reduced electrode consumption, is shown in Figure 1 [1].

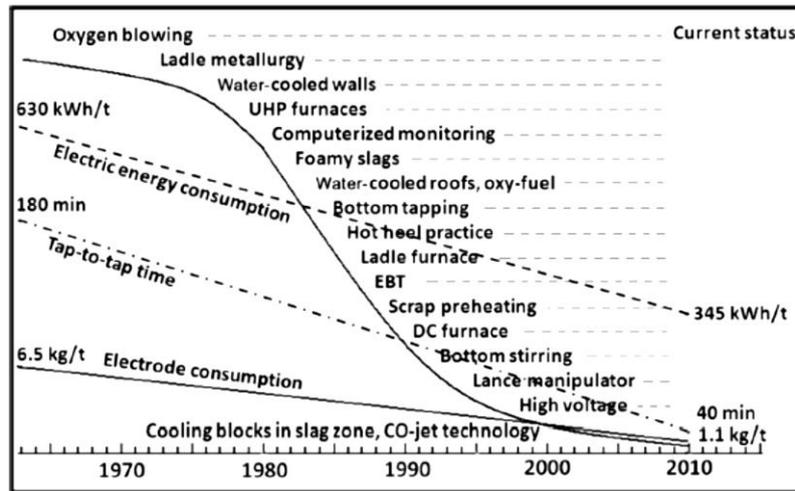


Figure 1. Revolution in the EAF [1]

The temperature of the arc column is approximately 3800°C. Manual tapping operation of the EAF in the hot environment around the furnace is a potentially dangerous and time-consuming task for the workers. There is a wide range of opening tap-hole methods, including manual oxygen lancing, Automated/robotic oxygen lancing, hydraulic drilling open, etc. Therefore, it is essential to open the tap hole with Automated/robotic oxygen lancing.

Robotics is concerned with the study of machines that can replace human beings [3]. Industrial robot manipulators are general-purpose machines used for industrial automation to increase productivity, flexibility, and product quality. Other reasons for using industrial robots are cost-saving, and elimination of hazardous and unpleasant work. Robot motion control is a key competence for robot manufacturers, and the current development is focused on increasing robot performance, reducing the robot cost, improving safety, and introducing new functionalities. The fact is that the motion control algorithms used in industry are sometimes considered a trade secret. Algorithms are rarely published due to the fierce competitive conditions among robot makers. Also, academic robot control researchers often use advanced mathematics, while robot industry researchers have to deal with all aspects of a complex system that the proposed advanced mathematics is not often used [4].

2. Path planning of the robot

This study is aimed to consider the path planning and control of a predesigned robot used in opening the tap hole operation. It is necessary to first give a brief description of the process of opening the tap hole. With the gradual melting of scrap, a molten pool is formed in the furnace. After the melting, it is ready to be discharged into the pan, the melting outlet (furnace tap hole) should be opened by the operator as shown in Figure 2 using oxygen gas blowing or so-called lance (oxygen supply pipe). Then the furnace tilted and melt is drained into the pan.



Figure 2. An arc furnace and an operator opening the tap hole

The process of opening the tap hole is very dangerous for the operator and in many cases leads to burns and even blindness of the person. To increase furnace efficiency and to decrease the tap to tap time, a manipulator robot with five degrees of freedom (5R) is designed by modeling industrial robots and the dynamic equations of the robot obtained [5]. This dynamic model will be used to simulate the robot motion path. The robot control problem has two parts: in the first part, the robot only moves the lance in a well-designed path from the starting point and has no contact with the environment. Therefore, in this part, the control problem can be defined in the space of joint variables. The block diagram of the control problem in the first part is as shown in Figure 3.

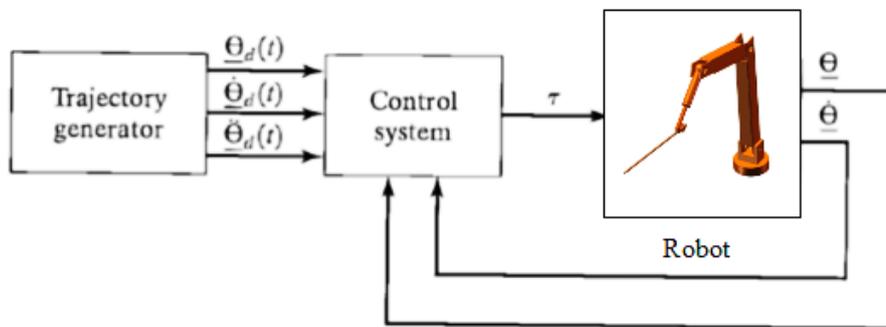


Figure 3. The robot control system in the first part of the path [6]

In the second part, the robot engages with the path through the lance and the precise control of the robot is very important despite the changes and uncertainties in the work environment. A constant force is used to model the lance contact with the tap hole.

The Denavit – Hartenberg method was used to model the mechanism of the robot. In this method, the attachment of local coordinate frames to the link was precisely specified. Figure 4 gives a clear view of the manipulator and its degrees of freedom. The manipulator has a total of five revolute joints.

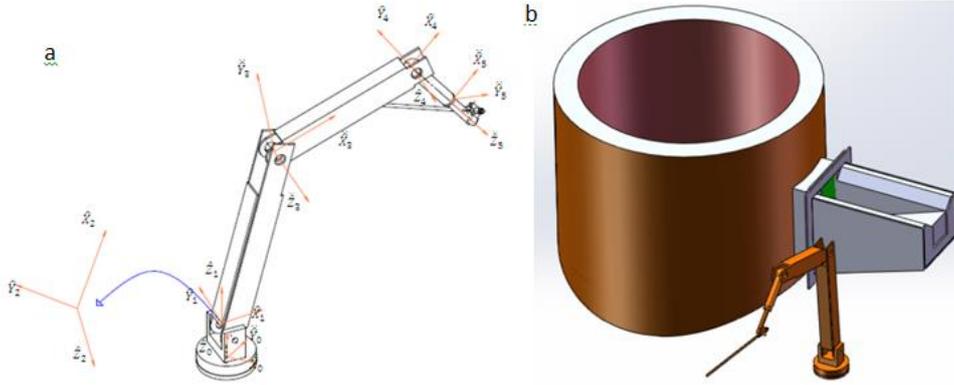


Figure 4. (a) Robot manipulator with 5 degrees of freedom. (b). shell and tap hole of EAF

The Denavit – Hartenberg parameters (link parameters), describing the geometry and relative displacement, was shown in Table 1.

Table 1. Link parameters

Joint i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0.3m	θ_1
2	90°	0	0	θ_2
3	0	1.75m	0	θ_3
4	0	1.370m	0	θ_4
5	90	0	0.52 m	θ_5

By the use of link parameters, rotation matrixes and Homogeneous transforms could be calculated. The position and orientation of the robot joints were specified with rotation matrixes and Homogeneous transforms. For the derivation of dynamic equations of motion of robot the Newton-Euler formulations were used, they yield a dynamic equation that can be written in the below form

$$\tau = M(\theta)\ddot{\theta} + V(\theta, \dot{\theta}) + G(\theta) \quad (1)$$

Where $M(\theta)$ is the 5×5 mass matrix of the manipulator, $V(\theta, \dot{\theta})$ is a 5×1 vector of centrifugal and Coriolis terms, and $G(\theta)$ is a 5×1 vector of gravity terms. Each element of $M(\theta)$ and $G(\theta)$ is a complete function that depends on θ , the position of all the joints of the manipulator. Each element of $V(\theta, \dot{\theta})$ is a complex function both θ and $\dot{\theta}$. Equation (1) gives expressions for the torque at the actuators as a function of joint position, velocity, and acceleration. The closed-form equations for a manipulator with six degrees of freedom will be quite complex. the controller design is performed using the dynamic equations in the Simulink environment of Matlab software. SimMechanic is a very powerful physical modeling toolkit in Simulink. Using SimMechanic toolbox, geometric simulation of robot movement in two directions is performed .Then, the geometric simulation of the robot's motion is performed in both parts of robot motion.

3. The initial part of the robot motion

In this part, the tool frame must reach the contact point of the tap hole from its original location in the desired period of 19 seconds. The goal here is to find the joint angles as a function of time to perform this motion. By obtaining the path functions, the location of the robot joints can be calculated according to the movement of the end effector in 3D space over time. The desired path includes seven intermediate points. The joint angle functions are then obtained based on connecting

the intersections of each joint smoothly. Here, the angles of each intermediate point are obtained by Solidworks software, and inverse kinematics are not used. The path functions of the robot joints for the entire movement time are listed in Table 2.

3.1 Control of the robot in the initial part of its path

PID controllers are widely used in industrial control systems. A PID controller calculates the error value between the measured value and the desired value. The controller tries to keep the error to a minimum by setting process control inputs. The PID controller algorithm consists of three parameters, proportional, integral, and derivative, which are abbreviated as P, I, and D. These values can also be defined in terms of time as P depends on the error of the present, I refers to the error of the past, and D predicts the error of the future [6]. The PID control rule to obtain the controller torque τ_c is a bellow

$$\tau_c = k_p e(t) + k_i \int_0^t e(t) dt + k_d \frac{de(t)}{d(t)} \tag{2}$$

Joint angle error is $e(t)$. PID coefficient of the robot joint angle controllers as declared in Table 3

Table 2. The joint angle functions in the initial part of the robot motion

Joint number	Joint angle function
1	$\theta_1(t) = \begin{cases} 0 & 0 \leq t < 2 \\ 20.414(t - 2)^2 - 2.722(t - 2)^3 & 2 \leq t \leq 7 \\ 170.12 & 7 < t \leq 19 \end{cases}$
2	$\theta_2(t) = \begin{cases} 86.73 + 9.952t^2 - 3.317t^3 & 0 \leq t \leq 2s \\ 100 & 2 < t < 15s \\ 100 - 32.25(t - 15)^2 + 10.75(t - 15)^3 & 15 \leq t \leq 17s \\ 57 & 17 < t < 18s \\ 57 - 5.01(t - 18)^2 + 1.67(t - 18)^3 & 18 \leq t \leq 19s \end{cases}$
3	$\theta_3(t) = \begin{cases} -69.05 + 10.537t^2 - 3.512t^3 & 0 \leq t \leq 2s \\ -55 & 2 < t < 13s \\ -55 + 28.98(t - 13)^2 - 9.66(t - 13)^3 & 13 \leq t \leq 15s \\ -16.36 & 15 < t \leq 19s \end{cases}$
4	$\theta_4(t) = \begin{cases} 33.57 & 0 \leq t < 10 \\ 33.57 - 22.19(t - 10)^2 + 4.931(t - 10)^3 & 10 \leq t \leq 13 \\ -33 & 13 < t \leq 17 \\ -33 - 23.55(t - 17)^2 + 15.7(t - 17)^3 & 17 < t \leq 18 \\ -40.85 & 18 < t \leq 19 \end{cases}$
5	$\theta_5(t) = \begin{cases} 42.8 & 0 \leq t < 7 \\ 42.8 + 43.477(t - 7)^2 - 9.661(t - 7)^3 & 7 \leq t \leq 10 \\ 173.23 & 10 < t \leq 19 \end{cases}$

Table 3. PID coefficient of the robot joint angle controllers

Joint Controller	P	I	D
PID 1	5430.4	42.8	62696.3
PID 2	21311.4	5574.7	7473.3
PID 3	29741.1	10534.9	582.9
PID 4	422.6	201.3	62.84
PID 5	6884	0.175	59913073

The desired and actual path is taken by the five joints of the robot is shown in Figure 5.

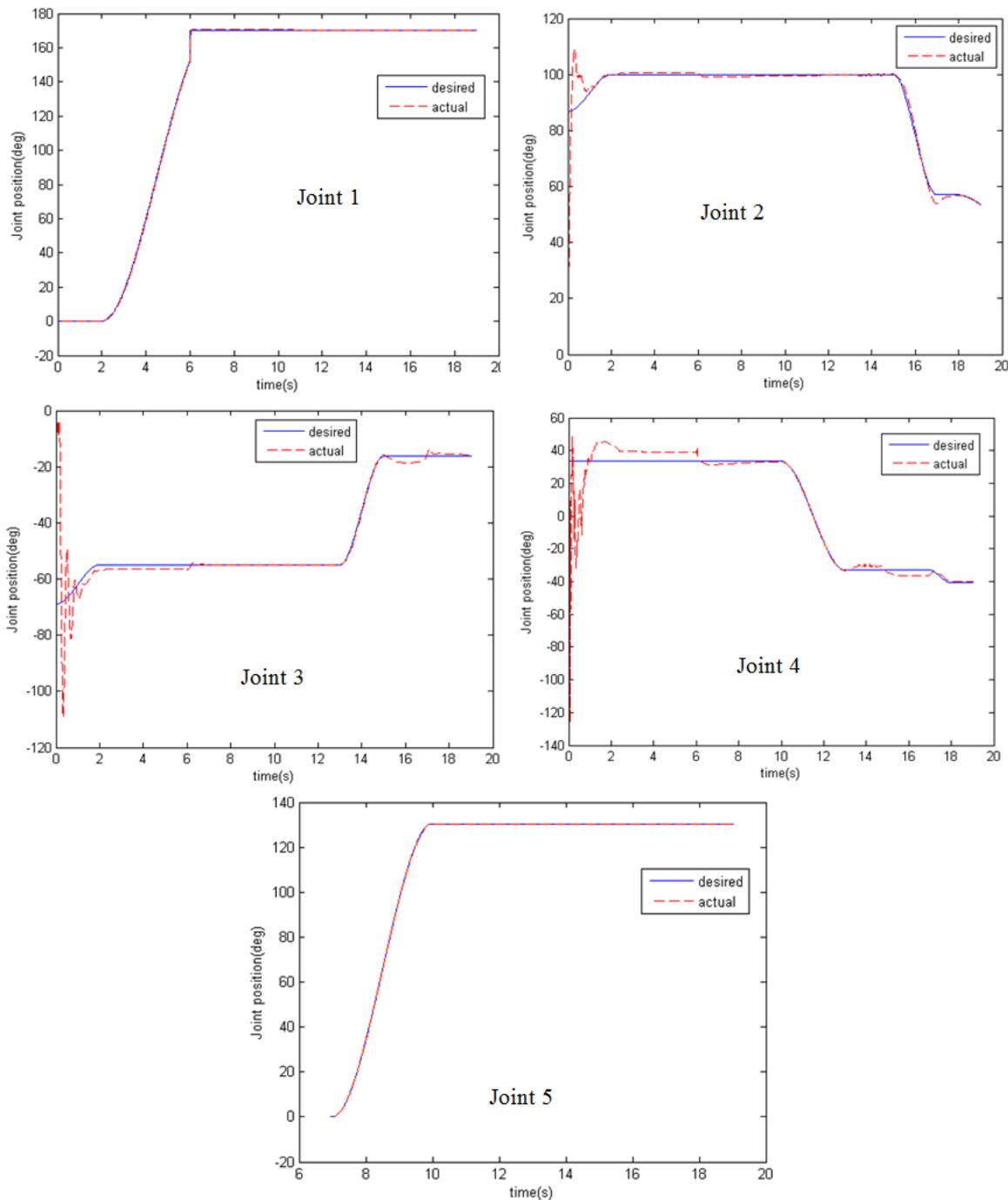


Figure 5. The optimal path and the actual path taken by the joints

As can be seen from the joints angle graphs in Figure 5, the simulation results show that the angle errors remain small when tracking the desired path.

3.2 Geometric simulation of the robot moving in the initial part of its path

First, the 3D model drawn by Solidworks software was inserted into the SimMechanic model. Then, using the symbolic library, PID controllers, sensors, and actuators are designed for each joint. The result is the simulation of the initial path of the robot using the PID coefficients obtained in section 3.2 and the result is shown in Figure 6.

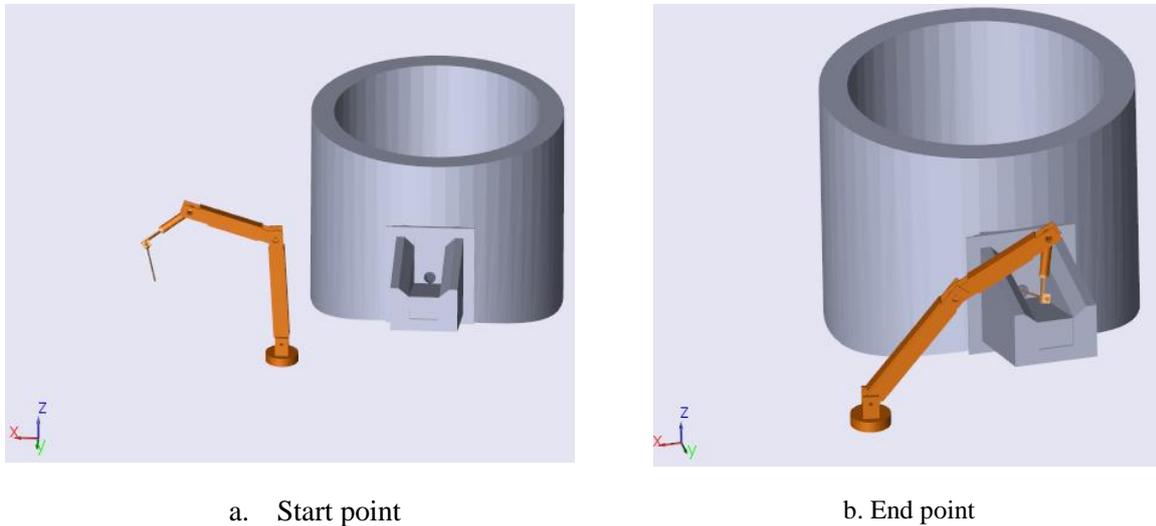


Figure 6. Simulation of the robot's movement in the first part of its motion

4. The second part of the robot motion

The starting point of the second part of the robot path is the end point of the previous part of the path. The second part has three intermediate points. In this path, all the joints of the robot must move at the same time in such a way to prevent the robot from colliding with the furnace body. Therefore, this part of the path is independent of time and the time parameter did not involve in the control algorithm directly. To simulate this part with Simulink, the Lookup Table command is used. Also, the values related to the settings of this command are according to Table 4.

4.1 Robot control in the second part of its path

In the second part of the desired path, the robot collides with the tap hole. The design of the control system according to the first part of the path is done using Simulink and based on the dynamic model. The dynamic model in the second part has two differences: 1- In this case, the robot does not move in free space and it is in contact with the tap hole, so the contact force in the dynamic model is non-zero. 2- The path is independent of time and all the joints of the robot must move at the same time. The adjusted PID coefficients are obtained according to Table 5.

Table 4. Robot joints angle in the second part of the path

Joint number	Start point	VP1	VP2	VP3	End point
1	170.12°	172.12°	175.12°	180.12°	188.12°
2	50.32°	48.65°	48.89°	57.40°	68.91°
3	-16.37°	-14.89°	-15.35°	-36.62°	-62.51°
4	-40.85°	-44.12°	-43.9°	-27.67°	3.26°
5	173.27°	176.86°	179.82°	183.29°	183.76°

Table 5. PID coefficients of the robot joint controllers in the second part of the path

Joint controller	P	I	D
PID 1	543	42	626.3
PID 2	21311	5574	7430
PID 3	85258	1245	532
PID 4	431	94	436
PID 5	1554	121	438

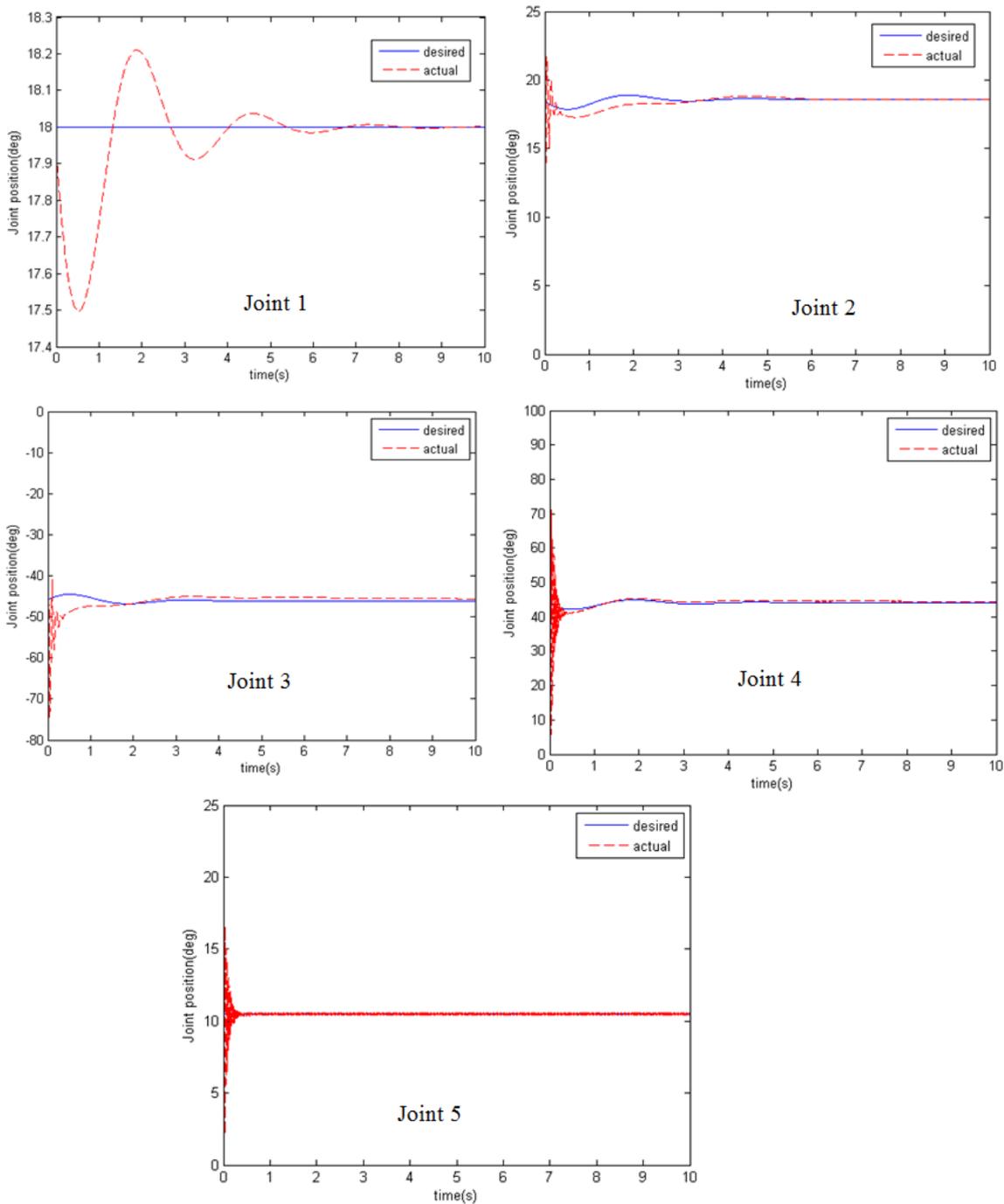


Figure 6. The desired and the actual path taken by the robot joints

The result of geometric simulation of the robot motion path using the SimMechanic toolbox is given in Figure 7.

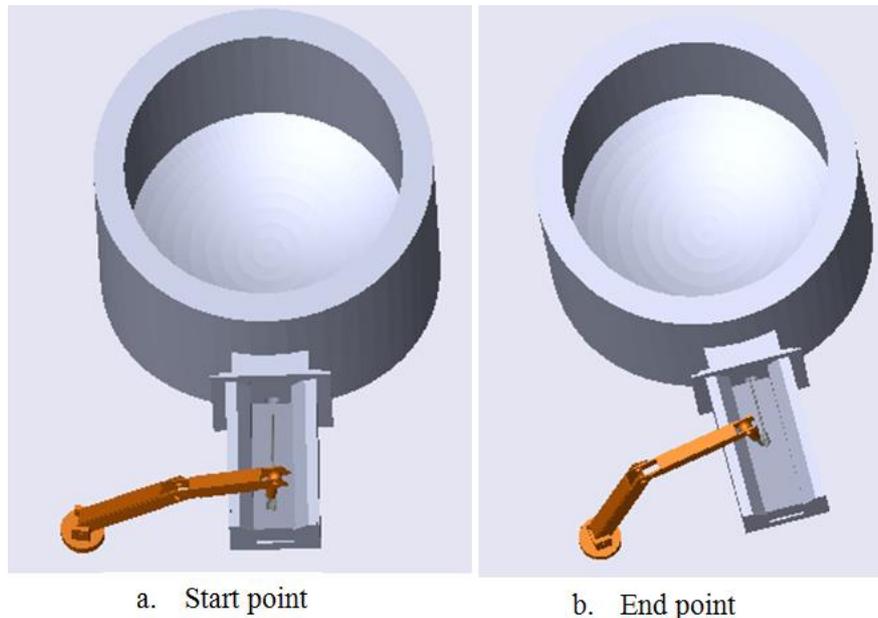


Figure 7. Geometric simulation of a robot in the second part of the path

5. Conclusion

A predesigned robot manipulator used in the tap hole opening is considered. The path planning of the robot and its control in the designed desired path discussed. The dynamic model was used to design the PID controller and to simulate the system with the SimMechanic toolbox. The simulation results show that the designed robot can follow the desired paths to open the furnace tap hole with the least error. The diagrams of the actual path and the desired path of the robot joints show that its overshoot and settling time are acceptable for the desired paths with ignorable steady state error.

6. References

- [1] Labar, H., Djeghader, Y., Samira, K. M. and Kamel, B. 2009. Closely parametrical model for an electrical arc furnace. *World Academy of Science. Engineering and Technology*. 40: 96-100.
- [2] Seetharaman, S., Mclean, A. and Goodwill, J. E. 2014. *Treatise on process metallurgy: industrial processes*. Royal Institute of Technology. Stockholm, Sweden.
- [3] Moberg, S. 2010. *Modeling and control of flexible manipulators*. Ph.D. Thesis. Department of Electrical Engineering Linköping University, SE-581 83 Linköping, Sweden.
- [4] Høifødt, H. 2011. *Dynamic modeling and simulation of robot manipulators*. MSc Thesis, Department of Engineering Cybernetics. Norwegian University of Science and Technology
- [5] Esmaeili, M., Saadat, M. 2019. *Dynamic Modeling of a Robot Manipulator for Opening the Tap Hole of an Electric Arc Furnace*. *Journal of Modern Processes in Manufacturing and Production*. 8(4): 17-24.
- [6] Tenova. 2015. *Melt shops top charge EAF with an anthropomorphic temperature and sampling Robot*. URL: <https://www.youtube.com/watch?v=7Yr5qYZUpso>

Path Planning and Control of an Industrial Robot used for Opening Tap Hole of an Electric Arc Furnace, pp. 5-14

[7] Craig, J. J. 1989. Introduction to Robotics: Mechanics and Control .2nd. Ed. Addison-Wesley Longman Publishing Co., Inc., USA.