

## ALGORITHM FOR IMPROVING FEEDING RATES OF INDUSTRIAL WELDING ROBOT TA 1400

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**Abstract.** An algorithm for improving feeding rates of industrial welding robot TA 1400 of Panasonic with 6 degrees of freedom is presented. The kinematics and dynamics of the robot are calculated on MATLAB software. The proposed algorithm for improving feeding rates is mathematically analyzed and the performance of the system is evaluated in a simulation environment. The simulation results are used for proving the efficiency of the solution. Based on the achieved results, the algorithm can be applied for reducing time and improving the productivity of other industrial robots in the future.

**Keywords.** Robot TA 1400; Industrial welding robot; MATLAB program.

### 1. INTRODUCTION

Recently, industrial robots have been widely used for welding, cutting, 3D plastic printing and metal manufacturing additives due to their versatilities. Among them, the welding robots have been widely applied because of their flexibility. Studies on increasing productivity of welding robotics are still being researched to improve the competitiveness of industrial production. One of the most effective ways to increase productivity is to optimize the production process based on optimizing the feeding speed of the robot, especially for continuously and complex tool-paths. However, the accuracy of the head position and the limitation of dynamic variables such as velocity, acceleration and recoil of the joint must be ensured so that robots are not overloaded, avoiding undesirable vibrations, and tool-path errors.

Besides, the problem of inverse dynamics also plays an important role in analyzing dynamics and designing control systems of robots. These issues become more complex for the backup system due to the diversity. A number of methods have been developed to solve the inverse kinematic problems such as Pseudo-inverse [1,2], Jacobian transpose method [3], Damped Least Squares [4], Quasi-Newton and inter-gradient [5], Closed-loop inversion (CLIK) [6], offset modification method (OM) [7], Neutron Network algorithm [8], IK quick algorithms [9], the algorithm for adjusting the increments of generalized vector [10–12]. After that, [13] proposed an inverse kinematic solution of the 6-DOF industrial manipulator with Euler's wrist using the quaternary vector pair method. Furthermore, a new solution method to avoid general limitations, singularities, and obstacles to redundant robots is introduced in [14]. Dynamic model analysis solutions for welding and cutting robots are mentioned in [15]. The issues of reverse dynamics of excess robots are addressed in [16]. The inverse dynamics problems of the redundant robot are mentioned in the works [17]. The methods of planning the feeding speed by a processing robot are based on geometric parameter interpolation [18]. Additionally, the study in [19] for 5-axis computer numerical control (CNC)

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machines has solved the issues by a robotic combination system in the parameter domain based on the dynamic properties of the robot. It is said that the mathematical models of the system play an important role in the construction of the tool-path design for machining robots.

The problem of optimizing the feed rate is mainly considered when cutting on CNC machines. Only few works which research on optimizing the feed rate for industrial robots because the application of robots in machining has recently been of interest. The optimization of the feed rate for machining robots has only solved the kinematic problem and trajectory planning, not yet considering the dynamic problem and calculating the driven torque corresponding to the optimal machining parameters. Most of the previous optimization algorithms were quite complex, difficult to implement with machining robots and welding robots because most of them were redundant robots with a large number of degrees of freedom (DOF).

This paper presents a simple and effective algorithm for improving the feeding rates of industrial welding robots with 6-DOF. The paper has the following structure. In Section 2, the calculation of kinematics and dynamics is introduced. In Section 3, the algorithm for improving feeding rates of Panasonic 6-DOF welding robots TA 1400 is analyzed in details. Next, the simulation results for load speed parameters and torque values of industrial welding robot TA 1400 are given to prove the performance of the algorithm with the different values of kinematic and dynamic parameters such as position, velocity, acceleration, and recoil of the joints.

## 2. CALCULATION OF KINEMATICS AND DYNAMICS

The kinematics model of industrial welding robot TA 1400 with 6-DOF is depicted in Figure 1. The fixed coordinates system is  $(OXYZ)_0$  located at point  $O_0$  and  $(OXYZ)_i$ , ( $i = 1 \div 6$ ) are the local coordinate systems attached link  $i$ . The rotational joint variables are  $q_i$ .

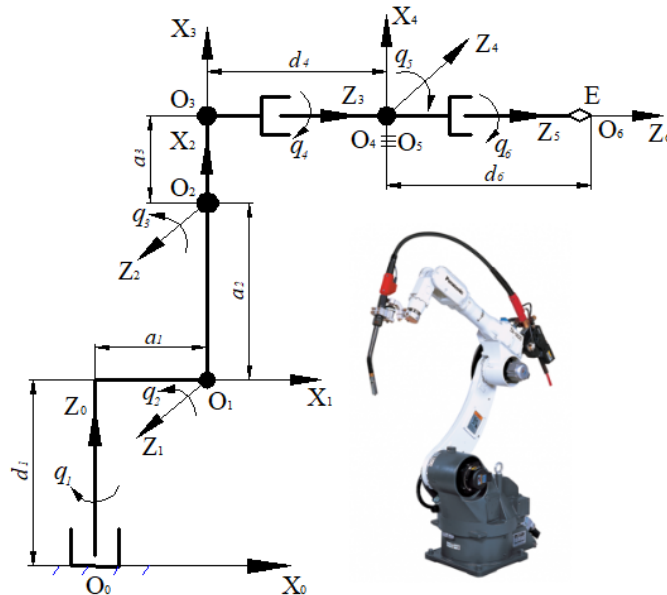


Figure 1. Kinematics model of the welding robot TA 1400

The kinematic parameters according to the D-H rule [2] are shown in Table 1. Based on the kinematic D-H parameters, the transformation homogeneous matrices  $H_i$ , ( $i = 1 \div 6$ ) are able to be determined easily.

Table 1. Kinematic parameters D-H

Links	$\theta_i$	$d_i$	$a_i$	$\alpha_i$
1	$q_1$	$d_1$	$a_1$	$\pi/2$
2	$q_2$	0	$a_2$	0
3	$q_3$	0	$a_3$	$\pi/2$
4	$q_4$	$d_4$	0	$\pi/2$
5	$q_5$	0	0	$-\pi/2$
6	$q_6$	$d_6$	0	0

The position and direction of the end-effector point (EE) are determined from the  $\mathbf{D}_6$  matrix related to a fixed coordinate system as mentioned in [2]. In details, the transformation homogeneous matrices of EE point of the welding torch are calculated as follows

$$\mathbf{D}_6 = \mathbf{H}_1\mathbf{H}_2\mathbf{H}_3\mathbf{H}_4\mathbf{H}_5\mathbf{H}_6. \quad (1)$$

Define  $\mathbf{q} = [q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6]^T$  as the generalized joint vector and  $\mathbf{x} = [x \ y \ z]^T$  is the coordinate vector of EE. The forward kinematics equations can be written as

$$\mathbf{x} = f(\mathbf{q}), \quad (2)$$

where  $f$  is a vector function representing the robot forward kinematics. The derivative of (2) with respect to time supports the relation between the EE velocity parameters and the joint velocities as follows

$$\dot{\mathbf{x}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}, \quad (3)$$

where  $\mathbf{J}(\mathbf{q})$  is the Jacobian matrix of size  $3 \times 6$ . The acceleration of EE can be given by the derivative of (3) as follows

$$\ddot{\mathbf{x}} = \dot{\mathbf{J}}\dot{\mathbf{q}} + \mathbf{J}\ddot{\mathbf{q}}. \quad (4)$$

The derivative of (4), the jerk of EE is determined as

$$\ddot{\mathbf{x}} = \ddot{\mathbf{J}}\dot{\mathbf{q}} + 2\dot{\mathbf{J}}\ddot{\mathbf{q}} + \mathbf{J}\ddot{\mathbf{q}}. \quad (5)$$

The inverse kinematics equations of robots are written as

$$\mathbf{q} = f^{-1}(\mathbf{x}). \quad (6)$$

The values of vector  $\mathbf{q}$  have been determined from (6), the joints velocity is determined as

$$\dot{\mathbf{q}} = \mathbf{J}^+(\mathbf{q})\dot{\mathbf{x}}, \quad (7)$$

where  $\mathbf{J}^+(\mathbf{q})$  is the pseudo-inverse matrix of  $\mathbf{J}(\mathbf{q})$  matrix and is defined as [2]

$$\mathbf{J}^+(\mathbf{q}) = \mathbf{J}^T(\mathbf{q})[\mathbf{J}(\mathbf{q})\mathbf{J}^T(\mathbf{q})]^{-1}. \quad (8)$$

The joints acceleration is calculated from (7) as follows

$$\ddot{\mathbf{q}} = \mathbf{J}^+(\mathbf{q})(\ddot{\mathbf{x}} - \dot{\mathbf{J}}\dot{\mathbf{q}}). \quad (9)$$

Similarly, the joints jerk also is determined from (9) as the following equation

$$\dddot{\mathbf{q}} = \mathbf{J}^+(\mathbf{q})(\dddot{\mathbf{x}} - 2\dot{\mathbf{J}}\ddot{\mathbf{q}} - \ddot{\mathbf{J}}\dot{\mathbf{q}}). \quad (10)$$

For the given  $\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}, \dddot{\mathbf{x}}$  vectors and using the algorithm for adjusting the increments of generalized vector, the approximately joint variables value can be determined exactly [10–12]. Given a geometric trajectory such as a tool-path in parametric domain  $\mathbf{x}(u) = [x(u) \ y(u) \ z(u)]^T$ ,  $u = [0, 1]$ . Note that  $F(t) = \dot{s}(t)$  is the feeding rate along the tool-path [12], where  $s$  is the arc length of curve  $\mathbf{x}(s) = [x(s) \ y(s) \ z(s)]^T$ . The inverse kinematics equation in parametric domain is rewritten as

$$\mathbf{q}(u) = f^{-1}(\mathbf{x}(u)). \quad (11)$$

Note that the derivatives with respect to time  $t$  and the parameter  $u, s$  are denoted by dots and primes, respectively. Assume that the vector  $\mathbf{q}(u)$  is calculated by the method mentioned above. The velocity, acceleration and jerk of joints need to be determined in parametric domain. From (7), we have

$$\dot{\mathbf{q}} = \mathbf{J}^+ \frac{d\mathbf{x}}{ds} \frac{ds}{dt} = \mathbf{J}^+ \mathbf{x}'_s \dot{s}, \quad (12)$$

where  $ds \cong \left| \frac{d\mathbf{x}}{du} \right| du$  or  $\frac{ds}{du} = \left| \frac{d\mathbf{x}}{du} \right|$ . The derivative of  $x$  by  $s$  can be calculated as

$$\mathbf{x}'_s = \frac{d\mathbf{x}}{ds} = \frac{d\mathbf{x}/du}{ds/du} = \frac{d\mathbf{x}/du}{|d\mathbf{x}/du|} = \frac{\mathbf{x}'_u}{|\mathbf{x}'_u|}. \quad (13)$$

The generalized velocity vector can be given as

$$\dot{\mathbf{q}} = \mathbf{J}^+ \frac{\mathbf{x}'_u}{|\mathbf{x}'_u|} F. \quad (14)$$

The acceleration and jerk of joints are determined in parametric domain as

$$\ddot{\mathbf{q}} = \mathbf{J}^+ \left( \left( \frac{\mathbf{x}'_u}{|\mathbf{x}'_u|^2} + \frac{\mathbf{x}'_u((\mathbf{x}'_u)^T \mathbf{x}''_u)}{|\mathbf{x}'_u|^4} \right) F^2 + \frac{\mathbf{x}'_u}{|\mathbf{x}'_u|} \dot{F} - \dot{\mathbf{J}}\dot{\mathbf{q}} \right) \quad (15)$$

and

$$\dddot{\mathbf{q}} = \mathbf{J}^+ \left( \frac{\mathbf{x}''_u}{|\mathbf{x}'_u|^3} F^3 + \frac{\mathbf{x}''_u((\mathbf{x}'_u)^T \mathbf{x}''_u) + \mathbf{x}'_u((\mathbf{x}''_u)^T \mathbf{x}'_u) + (\mathbf{x}'_u)^T \mathbf{x}'''_u}{|\mathbf{x}'_u|^5} F^3 \right. \\ \left. + \frac{\mathbf{x}''_u}{|\mathbf{x}'_u|^2} + \frac{\mathbf{x}'_u((\mathbf{x}'_u)^T \mathbf{x}''_u)}{|\mathbf{x}'_u|^4} \dot{F} F - 2\dot{\mathbf{J}}\ddot{\mathbf{q}} - \ddot{\mathbf{J}}\dot{\mathbf{q}} \right). \quad (16)$$

From (14), (15) and (16), values of  $\dot{\mathbf{q}}, \ddot{\mathbf{q}}$  and  $\dddot{\mathbf{q}}$  depend mainly on the geometric characteristics of the tool path trajectory ( $\mathbf{x}(u), \mathbf{x}'(u), \mathbf{x}''(u), \mathbf{x}'''(u)$ ), feeding rate ( $F, F^2, F^3, \dot{F}$ ) and the kinematics structure of the robot ( $\mathbf{J}, \dot{\mathbf{J}}, \ddot{\mathbf{J}}$ ).

The inverse dynamics problem is built to determine the forces and torques acting on the robot according to the given motion characteristics. It is necessary to build a system of dynamic equations to solve this problem. The dynamics equations show the relationship between forces and torques with the motion characteristics of robots such as joint position  $\mathbf{q}$ , velocity  $\dot{\mathbf{q}}$ , joint acceleration  $\ddot{\mathbf{q}}$ . The dynamics equations of the robot are described as follows [20]

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau}. \tag{17}$$

### 3. ALGORITHM FOR IMPROVING FEEDING RATES

In this section, the feeding rate of the welding torch along the weld seam is calculated based on the kinematic constraints of the welding robot. The initial value of the feeding rate is given and will increase gradually after the increments of the loop. The growth is only stopped if the constraint conditions are broken. Thus, each position in the parametric trajectory will have a corresponding feeding rate value. Let's denote  $\mathbf{F}_{ini}$  and  $\mathbf{F}_{max}$  be the initial and maximum feeding rate value, general joint vectors  $\dot{\mathbf{q}}_{max}$ ,  $\ddot{\mathbf{q}}_{max}$  and  $\dddot{\mathbf{q}}_{max}$  be the maximum velocity, acceleration and jerk vector of joints. The optimal function can be reached by the following equation

$$\mathbf{F}_{optimal} = \max_{u \in [0,1]} \mathbf{F}(u). \tag{18}$$

The constraint conditions for the optimal problem can be defined as

$$|\dot{\mathbf{q}}| \leq \dot{\mathbf{q}}_{max}, \quad |\ddot{\mathbf{q}}| \leq \ddot{\mathbf{q}}_{max}, \quad |\dddot{\mathbf{q}}| \leq \dddot{\mathbf{q}}_{max}, \quad \mathbf{F} \leq \mathbf{F}_{max}. \tag{19}$$

The proposed algorithm with the constraint conditions is described as Figure 2.

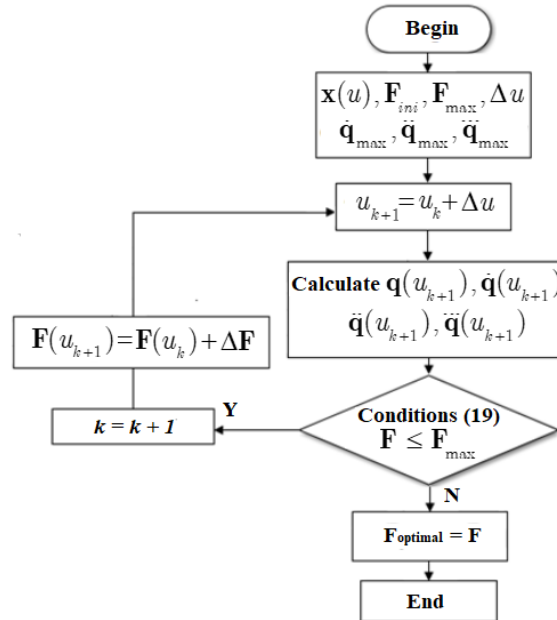


Figure 2. The algorithm for improving feeding rates

#### 4. SIMULATION RESULTS

This section presents the simulation results for welding robot TA 1400 with a complex weld seam. Some parameters of the system can be showed as follows:  $d_1 = 0.42(\text{m})$ ,  $a_1 = 0.15(\text{m})$ ,  $a_2 = 0.56(\text{m})$ ,  $a_3 = 0.13(\text{m})$ ,  $d_4 = 0.6(\text{m})$ ,  $d_6 = 0.325(\text{m})$ ,  $f_{\max} = 1.2(\text{m/s})$ ,  $m_1 = 50(\text{kg})$ ,  $m_2 = 39(\text{kg})$ ,  $m_3 = 46(\text{kg})$ ,  $m_4 = 20(\text{kg})$ ,  $m_5 = 3.2(\text{kg})$ ,  $m_6 = 2.7(\text{kg})$ ,  $g = 9.81(\text{m/s}^2)$ . Then,

$$\dot{\mathbf{q}}_{\max} = [ 2.97 \quad 3.32 \quad 3.32 \quad 6.64 \quad 6.54 \quad 10.5 ]^T, \quad (20)$$

$$\ddot{\mathbf{q}}_{\max} = [ 7.4 \quad 8.3 \quad 8.3 \quad 16.2 \quad 16.4 \quad 26.3 ]^T, \quad (21)$$

$$\dddot{\mathbf{q}}_{\max} = [ 37 \quad 41.5 \quad 41.5 \quad 81 \quad 82 \quad 131.5 ]^T. \quad (22)$$

The weld seam is defined as follows

$$\begin{aligned} x(u) &= 0.4 + 0.3(1 + \sin(2u) \cos(u)), \\ y(u) &= 0.4 + 0.3(1 + \sin(2u) \sin(u)), \\ z(u) &= 0.8. \end{aligned} \quad (23)$$

It is noticed that these parameters are selected based on the parameters of the real welding robot concerning voltage, welding current, and wire output speed. Actually, the weld seam is conducted with a feeding rate value much smaller than the maximum value. Therefore, the maximum speed limit for the algorithm can be redefined as follows  $f_{ini} = 0.01(\text{m/s})$ ,  $\Delta f = 0.005(\text{m/s})$ ,  $f_{\max} = 0.3(\text{m/s})$ ,  $\Delta u = 0.01$ ,  $\mathbf{q}_0 = [ 0.78 \quad 1.34 \quad 0.23 \quad 0.15 \quad 1.22 \quad 0 ]^T$ .

Based on the algorithm in Figure 2 with the given parameters of the welding robot, the steps for calculating the optimal feeding rates are shown in Figure 3.

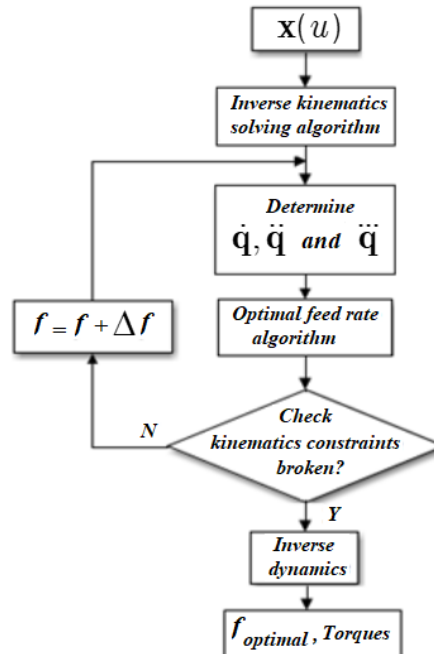


Figure 3. Steps for calculating the optimal feeding rates

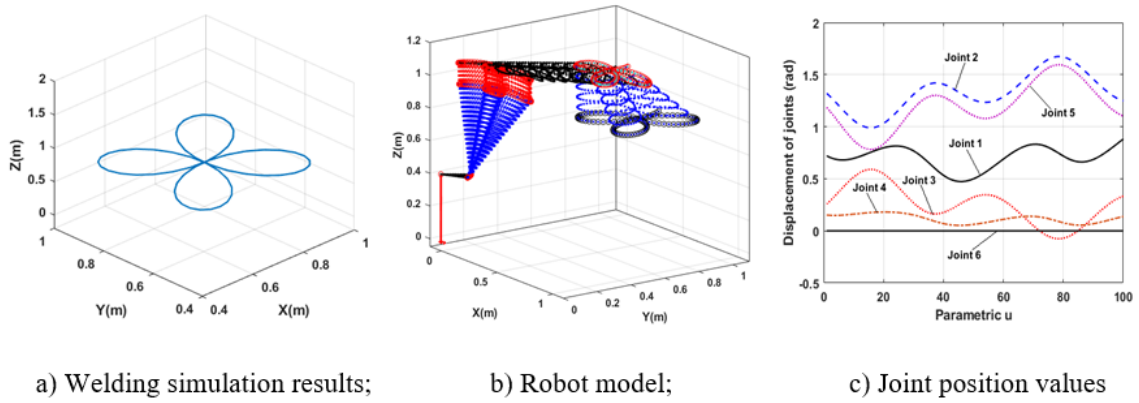


Figure 4. The trajectory of EE, robot model and the joints position values

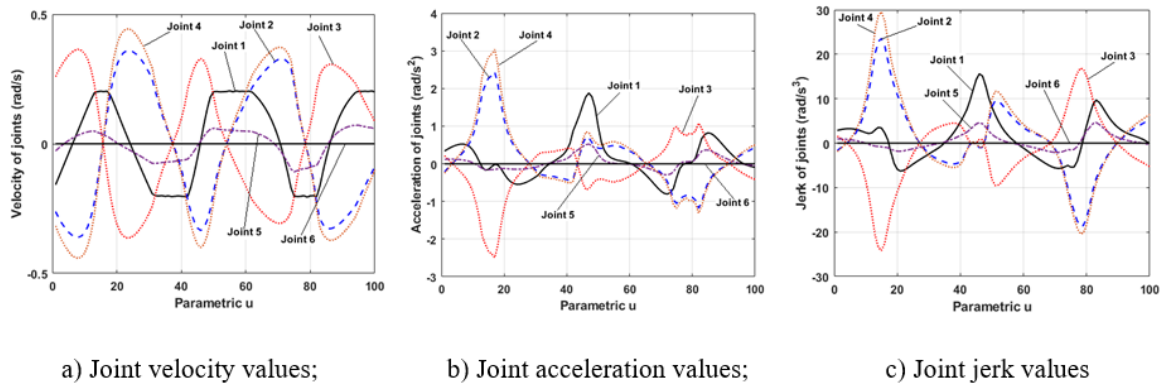


Figure 5. The values of joints velocity, acceleration and jerk

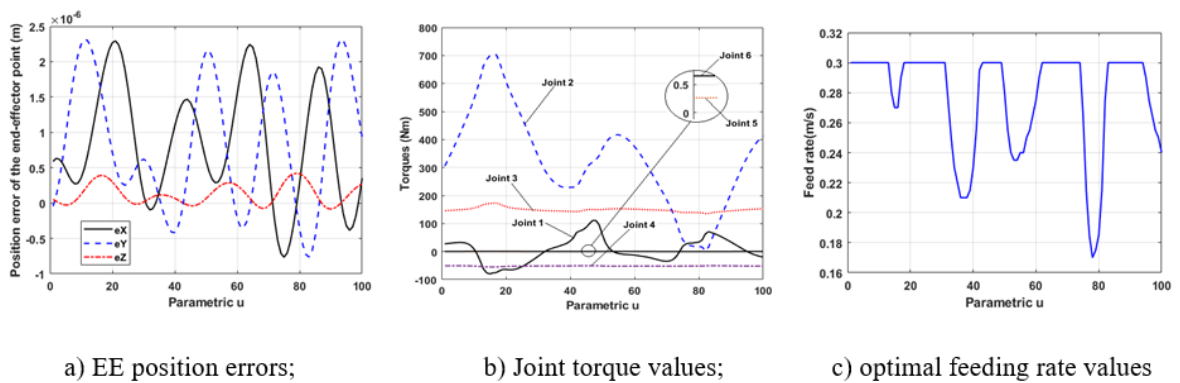


Figure 6. The values of EE errors, joints torque and optimal feeding rates

The simulation results in Figure 4 include: Figure 4a shows the trajectories of EE as the welding simulation results; Figure 4b displays the weld seam trajectories in the 3D workspace; Figure 4c depicts the joint position values respected to the trajectories.

Figure 5 (a, b, c) present the results of the inverse kinematics problem in the parametric domain including velocity, acceleration and jerk joints, respectively.

The errors of EE between the desired and actual weld seam are shown in Figure 6a. The optimal values of feeding rate through the optimization algorithm present in Figure 6c. According to the given weld seam profile, feeding rate values change accordingly. Figure 6b shows the torque values of the joints through solving the inverse dynamics problem.

Based on the given weld seam profile and the dynamics parameters of the robot, it was found that joint 2 has the maximum torque value.

## 5. CONCLUSION

The paper presents the algorithm for improving the feeding rate of welding robots. The position values on the given weld seam have been determined based on the kinematics, dynamics modeling in the parameter domain. The performance of the proposed algorithm is evaluated in the simulation environment under the model of the Panasonic industrial welding robot TA 1400. In the simulation, the algorithm supports the system for adjusting the increments of the general joint vector with an effective solution concerning the inverse kinematics. The position, velocity, acceleration, and jerk of the joints are calculated within the kinematics limits of the welding robot and ensuring weld seam errors in the workspace. In addition, the simulation results of this study show that the principle of the given algorithm can be applied not only for the Panasonic industrial welding robot TA 1400 but also other kinds of welding robots with  $n$ -DOF ( $n \geq 6$ ).

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## REFERENCES

- [1] M. Azad, J. Babi, and M. Mistry, "Effects of the weighting matrix on dynamic manipulability of robots," *Auton Robot*, vol. 43, pp. 1867–1879, 2019. <https://doi.org/10.1007/s10514-018-09819-y>
- [2] M. W. Spong, S. Hutchinson, M. Vidyasagar, *Robot Modeling and Control*, Second Edition. John Wiley & Sons, 2001.
- [3] A. Valera, V. Mata, M. Valles, F. Valero, N. Rosillo, F. Benimeli, "Solving the inverse dynamic control for low cost real-time industrial robot control applications," *Robotica*, vol 21, no. 3, pp. 261–269, 2003. Doi: 10.1017/S0263574702004769
- [4] Michal Kelemen, Ivan Virgala, Tom Liptk, ubica Mikov, Filip Filakovsk and Vladimr Bulej, "A Novel Approach for an Inverse Kinematics Solution of a Redundant Manipulator," *Applied Sciences*, vol. 8, no. 11, 2018, p. 2229. Doi:10.3390/app811222



- [5] J. Zhao, N. I. Badler, "Inverse kinematics positioning using nonlinear programming for highly articulated figures," *Transactions on Graphics*, vol 13, pp. 313–336, 1994. Doi: 10.1145/195826.195827
- [6] J. Wang, Y. Li, X. Zhao, "Inverse kinematics and control of a 7-dof redundant manipulator based on the closed loop algorithm," *International Journal of Advanced Robotics Systems*, vol 7, 2010, pp. 1–10. Doi: 10.5772/10495
- [7] H. Pan, B. Fu, L. Chen, J. Feng, "The Inverse Kinematics Solutions of robot manipulators with offset wrist using the offset modification method," *Advances in Automation and Robotics*, vol 1, pp. 655–663, 2011.
- [8] ] Y. Feng, W. Yaonan, Y. Yimin, "Inverse kinematics solution for robot manipulator based on Neural Network under joint subspace," *International Journal of Computer and Communications*, vol 7, pp. 459–472, 2012. Doi: 10.15837/ijccc.2012.3.1387
- [9] S. Lian, Y. Han, Y. Wang, Y. Bao, H. Xiao, X. Li, N. Sun, "Accelerating Inverse Kinematics for High-DOF Robots," *Proceedings of the 54th Annual Design Automation Conference*, Austin, USA, 2017. Doi: 10.1145/3061639.3062223
- [10] N. V. Khang, N. P. Dien, N. V. Vinh, T. H. Nam, "Inverse kinematic and dynamic analysis of redundant measuring manipulator BKHNMCX-04," *Vietnam Journal of Mechanics*, VAST, vol 32, pp. 15–26, 2010. Doi: 10.15625/0866-7136/32/1/313
- [11] N. Q. Hoang, T. P. Thao, "On solving inverse kinematics of redundant robotic manipulators by using coordinate and velocity projection methods," *Journal of Computer Science and Cybernetics*, vol 28, no. 1, pp. 31–40, 2012. Doi: <https://doi.org/10.15625/1813-9663/28/1/1063>
- [12] N. V. Khang, L. A. Tuan, "A comparison of some methods of computing the inverse kinematics of redundant parallel robots," *Journal of Computer Science and Cybernetics*, vol 29, no. 1, pp. 3–15, 2013. Doi: <https://doi.org/10.15625/1813-9663/29/1/2743>
- [13] Y. Ayduun, S. Kucuk, "Quaternion based inverse kinematics for industrial robot manipulators with Euler wrist," *2006 IEEE International Conference on Mechatronics*, Budapest, 2006, pp. 581–586. Doi: 10.1109/ICMECH.2006.252591
- [14] M. Kelemen, I. Virgala, T. Liptak, L. Mikova, F. Filakovsky, V. Bulej, "A Novel Approach for an Inverse Kinematics Solution of a Redundant Manipulator," *Applied Sciences*, vol 8, pp. 2–20, 2018. Doi: 10.3390/app8112229
- [15] H. C. Fang, S. K. Ong, A. Y. C. Nee, "Robot path planning optimization for welding complex joints," *International Journal of Advanced Manufacturing Technology*, vol 90, pp. 3829–3839, 2017. Doi: 10.1007/s00170-016-9684-z
- [16] T. Lau, O. Stefan, K. Sherif, W. Steiner, "Inverse dynamics of an industrial robot using motion constrains," *20th International Conference on Research and Education in Mechatronics (REM)*, Wels, Austria, 2019. Doi: 10.1109/REM.2019.87441
- [17] M. J. Mahmoodabadi, A. Ziaei, "Inverse dynamics based optimal fuzzy controller for a robot manipulator via particle swarm optimization," *Journal of Robotics*, vol 19, pp. 1–10, 2019. Doi: <https://doi.org/10.1155/2019/5052185>

- [18] A. Olabi, R. Bearee, O. Gibaru, M. Damak, “Feed rate planning for machining with industrial six-axis robots,” *Control Engineering Practice*, vol 18, no. 5, pp. 471–482, 2010. <https://doi.org/10.1016/j.conengprac.2010.01.004>
- [19] S. Seungkil, T. Kim, S. E. Sarma, A. H. Slocum, “A hybrid 5-axis CNC milling machine,” *Journal of Precision Engineering*, vol. 33, no. 4, pp. 430–446, 2009. Doi: 10.1016/j.precisioneng.2008.12.001
- [20] L. N. Truc, N. V. Quyen, N. P. Quang, “Dynamic model with a new formulation of Coriolis/Centrifugal matrix for robot manipulators,” *Journal of Computer Science and Cybernetics*, vol 369, no. 1, pp. 89–104, 2020. Doi: 10.15625/1813-9663/36/1/14557

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