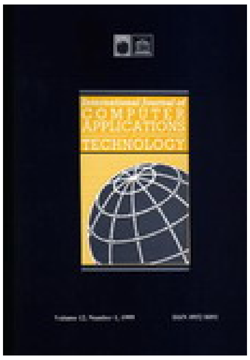

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Model and simulation of tracking motion for accurate welding using a universal Cobot

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Abstract: Welding is a process that requires the skill and time of a professionally-trained welder. However, this welding performance is not highly productive. Therefore, in this paper, the control approach of a 6-DOF collaborative robot (Cobot) arm is investigated in the application of a MIG (metal inert gas). By studying the trajectory generation algorithm, the Cobot can be used to track the welding curve. A theoretical model of the 6-DOF Cobot arm is successfully established in 3D space. Then, the results to validate the method according to the welding trajectory are presented in numerical simulations. It can be clearly seen that our approach shows great position-controlled ability. From these achievements, the applications of this Cobot are expected to be implemented in many industrial fields.

Keywords: robot arm; Cobot; automatic welding; position control; motion tracking.

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1 Introduction

Currently, it seems as though robots are appearing more frequently and are increasing in popularity. Robots can be utilised in entertainment (Morris et al., 2019) and multitask care (Van Aerschot and Parviainen, 2020), as pets (White and Katsuno, 2021) and even for dancing (Xu et al., 2020). Robots have become not only service suppliers but also friends, so they play an important role in our daily lives. In particular, to decrease the use of manual labour, numerous solutions have been previously described, such as using a motor for rotating purposes (Lv et al., 2017), using a sensor for measuring dimensions (Kolb et al., 2008) and using gears to decrease the operating force (Mathivana and Babu, 2019). In reality, these results are impractical for many reasons, such as not being interactive, flexible or intelligent. In recent years, the term collaborative robot (Cobot) has been defined to match the above requirements. Cobots not only perform the same tasks as traditional robots but are also required to collaborate with workers in the factory, especially in the welding process. In the domain of human-robot interaction, the Cobot must provide flexible motion, be light weight and easily maintained and have a design that matches the requirements of individual customers (El Zaatari et al., 2019). In addition, practical applications of Cobots include their appearance and communication with humans in the same workspace to realise collaborative missions. Following these conditions, UR5, a Cobot made by Universal Robotics (Oh, 2021), is an excellent collaborative robot owing to its reasonable cost, payload capabilities, and safety features. Because the Cobot is created for close-proximity interactions with humans, it must adhere to strict safety regulations. To enable collaboration, it is necessary to integrate the Cobot with cognitive abilities (Subramaniam et al., 2018; Fast-Berglund et al., 2016). Conventionally, robots are programmed to track fixed paths and execute a sequence of actions to successfully perform assembly tasks. Nevertheless, when in close proximity to humans, special safety precautions should be taken (Pollak et al., 2020; Timms, 2016). This can be achieved by using embedded safety standards, such as limiting velocity and collision detection, or using a laser sensor to measure the minimum safe distance. More sophisticated works can achieve a high level of safety by detecting objects or humans (Bi et al., 2021) as well as planning real-time optimised collision-free paths (Peron et al., 2020).

2 Background research

Currently, many Cobot solutions exist in industrial applications. It can be understood that there are a variety of manufacturers, and several structures do not have six DOFs (degrees of freedom) and serial configuration. Some cobots are programmed offline, while others are programmed online. However, the most important programming feature is end user ease of use, which can be achieved via a simple graphical interface. Extra hardware is attached, e.g., a dual-arm configuration for extended tasks. Additionally, customised control algorithms, human-robot interfaces and embedded sensors to prevent collision are implemented within these solutions. All of them allow for rapid reprogramming and a flexible task handler. The related Cobot solutions are summarised in Table 1.

Typically, an operator carries out the offline program for the robot arm. This program is not flexible, not human aware, and cannot be altered during runtime. As a result, this program cannot be used to unite robots and humans in one loop while the operator is actually present. These challenges can be solved in human interactions with the Cobot. Users can be explicitly or implicitly involved in changing or affecting the Cobot’s program. To strengthen the background research, an overview of related investigations in recent years is provided in Table 3.

Table 1 Summary of related Cobot solutions

Product name	*Manufacturer*	*Specification*
APAS (n.d.)	Bosch	Leather is used as a tactile skin to receive instant feedback when any unusual force is detected
CR-35iA (n.d.)	FANUC	Its heavy lifting and positioning capabilities are beneficial for users in a wide range of industries
Frida-YuMi (n.d.)	ABB	In addition to its compactness, key features of this Cobot include its lightweight and small nature and its agile motion
UR5-e (n.d.)	Universal	Its benefits include fast installation, large force, large payload and high precision

Table 2 List of Denavit–Hartenberg parameters for the UR5 Cobot

Link	*a*	*a*	*d*	θ
1	0	–90	L_0	θ_1
2	*L*1	0	L_a	θ_2
3	*L*2	0	L_b	θ_3
4	0	–90	L_c	θ_4
5	0	90	L_3	θ_5
6	0	0	*L*4	θ_6

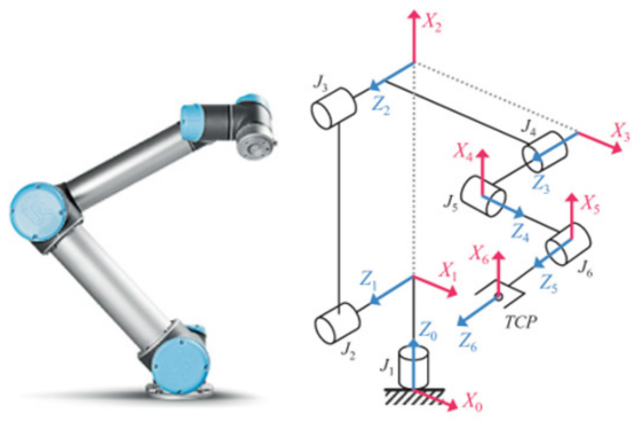
Table 3 Overview of state-of-the-art previous studies in human-robot interaction

Classification	*Author(s)*	*Description*	*Advantage*	*Drawback*
Cobot control via verbal/ nonverbal communication	Pires and Azar (2018)	Recent developments on the human–machine interface with speech interfaces are presented.	Sequences of commands with a well-defined structure and the recognition engines allow command-mode operation.	Only English and Portuguese are supported.
	Kobylarz et al. (2020)	A transfer learning method for gesture classification via an inductive and supervised transductive method with biosignals from operator is suggested.	Social interaction with a humanoid is highly interesting and this system achieves perfect precision for all trials.	Additional gestures or classes could cause the low speed of data processing when the database becomes larger.
Cobot control via mathematical expression	Turnwald and Wollherr (2019)	A design cost function and optimisation algorithm to make the Cobot select the optimal object to grasp are described.	It has a high potential to allow Cobots to navigate in the vicinity of humans and share their workspaces.	Human feels slightly less comfortable when moving toward an agent controlled by the proposed motion planner.
Cobot control by learning skill from worker	El Zaatari et al. (2021)	A novel Learning from Demonstration (LfD) is used to adaptively program a Cobot for a variety of industrial tasks.	Optimal frames are determined from demonstrations by simplifying computational complexity, overcoming occlusions in new settings, and boosting the overall performance.	The rates of eliminating frame error and task parameterised Gaussian mixture regression error are still high.
	Zaatari et al. (2021)	An improved task parameterised learning from demonstration is introduced by using a statistical algorithm and a reinforcement learning algorithm to correspondingly remove redundant frames and irrelevant frames.	The robustness and generality in teaching a Cobot behaviours in a more intuitive and intelligent manner are achieved.	Improvements in further eliminating irrelevant frames should be investigated.

3 Problem statement

In this research, the UR5 Cobot from Universal Robotics is chosen as the hardware target to deploy the proposed control method. This Cobot arm consists of six Degrees-of-Freedom (DOFs) that are integrated with the learning-based path planner for welding applications in a semiclosed and narrow workplace. The practical model and its theoretical diagram are depicted in Figure 1 (Zaatari et al., 2021). This Cobot has a wide range of applications, including packaging, loading and unloading cargo from shelves, quantising in experiments, tightening screws, polishing, mixing, welding, assembling, lifting and placing and quality checking. In the scope of this paper, accurate welding technique is emphasised for the industrial robot arm. Furthermore, since the worker appears in front of the robot, the actual trajectories should be flexible in a 3D space, the control method should be highly precise to reduce the tracking error and the performance for industrial applications should be superior.

Figure 1 Practical model of the UR5 Cobot (a) and its theoretical diagram (b)



(a) (b)

a_i : the distance along X_i from the intersection of the X_i and Z_i axes to O_i (if Z_i intersects Z_{i-1}, locate O_i at this intersection; if Z_i and Z_{i-1} are parallel, locate O_i in any convenient position along Z_i).

d_i : the distance along Z_{i-1} from O_{i-1} to the intersection of the X_i - and Z_{i-1} -axes.

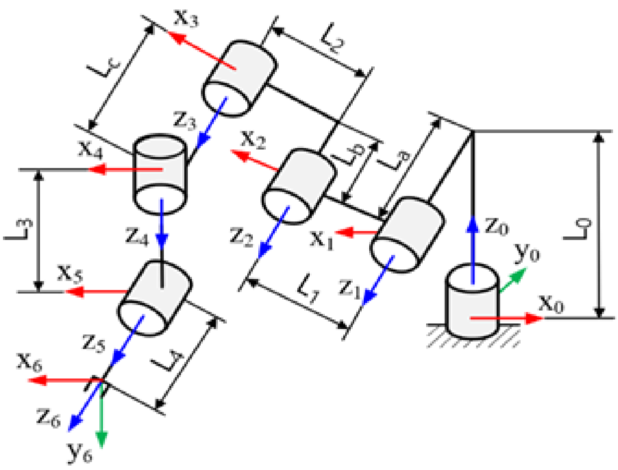
α_i : the angle between Z_{i-1} and Z_i measured about X_i .

θ_i : the angle between X_{i-1} and X_i measured about Z_{i-1} . θ_i is variable if joint i is a revolute joint.

4 Mathematical modelling of forward kinematics and inverse kinematics

The configuration of this Cobot is divided into 6 joints/links, and each joint/link has its own rod. The first joint is fixed to the base, and the others are linked together. The system parameters of the theoretical model are described in Figure 2.

Figure 2 Illustration of the system parameters for the 6-DOF Cobot



4.1 Forward kinematics

The purpose of this Cobot is to manipulate the final joint, which has been previously mentioned as the head of a weld gun. This means that the location and orientation of this joint must be defined. Frame $\{i\}$ is described relative to frame $\{i-1\}$ by the transformation matrix ${}^{i-1}_{i}T$.

Using Denavit–Hartenberg parameters and representing s as sine and c as cosine, the transformation matrix from the first joint to the sixth joint can be found below:

$$
\begin{aligned}
&{}^{0}_{6}T(\theta_1,\theta_2,\theta_3,\theta_4,\theta_5,\theta_6)\\
&= {}^{0}_{1}T(\theta_1)\,{}^{1}_{2}T(\theta_2)\,{}^{2}_{3}T(\theta_3)\,{}^{3}_{4}T(\theta_4)\,{}^{4}_{5}T(\theta_5)\,{}^{5}_{6}T(\theta_6)\\
&= \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{aligned} \tag{1}
$$

The Denavit–Hartenberg notation is introduced as a systematic description of the kinematic relationship ${}^{i-1}_{i}T$ using only four parameters in the D-H table: a (link length), α (link twist), d (link offset) and θ (joint angle). From this method, the transformation matrix from the $\{i-1\}$ joint to the $\{i\}$ joint can be described as:

$$
{}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}
$$

By applying four parameters from the D-H table to the transformation matrix, the component matrix ${}^{0}_{1}T(\theta_1)$ can be obtained as follows:

$$ {}^{0}_{1}T(\theta_1) = \begin{bmatrix} c\theta_1 & 0 & -s\theta_1 & 0 \\ s\theta_1 & 0 & c\theta_1 & 0 \\ 0 & -1 & 0 & L_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

This process can be applied for the other component matrix from ${}^{1}_{2}T(\theta_2)$ to ${}^{5}_{6}T(\theta_6)$.

4.2 Inverse kinematics

In the above section, the component matrices are known, and the problem of computing all angular values of six joints has also been considered. However, the challenge is that there are 3 crosses over axes. Thus, it is not suitable to apply the decoupling method to finalise these variables. The solution to this problem is to first find $\theta_4, \theta_5, \theta_6$. By multiplying the left side of equation (1), the result can be obtained

$$ {}^{1}_{2}T(\theta_2)\,{}^{2}_{3}T(\theta_3)\,{}^{3}_{4}T(\theta_4)\,{}^{4}_{5}T(\theta_5)\,{}^{5}_{6}T(\theta_6) = {}^{0}_{1}T^{-1}(\theta_1)\,{}^{0}_{6}T_{known} \tag{4} $$

where ${}^{0}_{6}T_{Known}$ indicates the position and orientation of the tool frame expressed in the base coordinates. The position from a coordinate system is established and fixed to the base. A point to which the tool frame needs to move can be located with a 3x1 matrix. The overall location expression for the robot hand is not specified until its orientation is also given. For the orientation of the tool frame, a method to describe the base coordinates is presented as follows. Start with the tool frame coincident with a known base coordinate. First, rotate the tool frame about X_A by an angle γ, and then about Y_A by an angle β and finally, about Z_A by an angle α (X_A, Y_A, Z_A represent the *X*-, *Y*- and *Z*-axes of the base coordinates).

Comparing the 1st to 4th columns for the 3rd row, we obtain the follow system of equations:

$$ \begin{cases} n_y c\theta_1 - n_x s\theta_1 = -c\theta_6 s\theta_5 \\ o_y c\theta_1 - o_x s\theta_1 = s\theta_5 s\theta_6 \\ a_y c\theta_1 - a_x s\theta_1 = c\theta_5 \\ p_y c\theta_1 - p_x s\theta_1 = L_{abc} + L_4 c\theta_5 \end{cases} \tag{5} $$

where

$$ (-p_x + a_x L_4)s\theta_1 + (p_y - a_y L_4)c\theta_1 = L_{abc} \tag{6} $$

$$ L_{abc} = L_a + L_b + L_c \tag{7} $$

where L_{abc} represents the distance between frame {0} and frame {4}, which is associated with joint 5 in the plane. Figure 2 shows the formation of Z_0 and Z_3 along the Z_3 direction. Since L_b is the opposite of L_a and L_c, its value is negative.

The above equation is similar to the linear equation of sine and cosine where θ_1 is unknown. One condition to solve this equation is:

$$ (-p_x + a_x L_4)^2 + (p_y - a_y L_4)^2 \geq L_{abc}^2 \tag{8} $$

When this requirement is satisfied, there are two solutions for θ_1. To obtain θ_5, substitute θ_1 into equation (5); we obtain the following equation:

$$ \begin{aligned} \theta_5 &= atan2(s\theta_5, c\theta_5) = atan2\left(\pm\sqrt{1 - c\theta_5^2}, c\theta_5\right) \\ &= atan2\left(\pm\sqrt{1 - (a_y c\theta_1 - a_x s\theta_1)^2}, a_y c\theta_1 - a_x s\theta_1\right) \end{aligned} \tag{9} $$

To obtain θ_6, we have:

$$ \begin{aligned} \theta_6 &= atan2(s\theta_6, c\theta_6) \\ &= atan2\left(\frac{o_y c\theta_1 - o_x s\theta_1}{s\theta_5}, \frac{n_y c\theta_1 - n_x s\theta_1}{s\theta_5}\right) \end{aligned} \tag{10} $$

For each case of θ_1, there are two solutions for θ_5 and θ_6. The method to choose the solution will not be described in this paper. By applying θ_1, θ_5 and θ_6, we obtain ${}^{0}_{1}T(\theta_1)$, ${}^{4}_{5}T(\theta_5)$, ${}^{5}_{6}T(\theta_6)$ and ${}^{0}_{6}T_{known}$.

From equation (4), multiplying the right side of the equation for ${}^{5}_{6}T^{-1}(\theta_6)\,{}^{4}_{5}T^{-1}(\theta_5)$, we have

$$ \begin{aligned} &{}^{0}_{1}T(\theta_1)\,{}^{1}_{2}T(\theta_2)\,{}^{2}_{3}T(\theta_3)\,{}^{3}_{4}T(\theta_4) \\ &= {}^{0}_{6}T_{known}\,{}^{5}_{6}T^{-1}(\theta_6)\,{}^{4}_{5}T^{-1}(\theta_5) = {}^{0}_{4}T \end{aligned} \tag{11} $$

The matrix ${}^{0}_{4}T$ indicates the position of point C as shown in Figure 3. This value is affected by the joint angles of $\theta_1, \theta_2, \theta_3$. To calculate $\theta_1, \theta_2, \theta_3$, a 3-DOF robot is considered. Additionally, there are two solutions for θ_2, θ_3 with respect to θ_1, which is found in the previous step. Substitute all joint positions $\theta_1, \theta_2, \theta_3, \theta_5, \theta_6$ into equation (4) to find θ_4. In total, the solution of the computing angles for $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6$ is found. The procedure for calculating the inverse kinematic is shown in Figure 4.

Figure 3 Explanation of point *C* to compute θ_2, θ_3

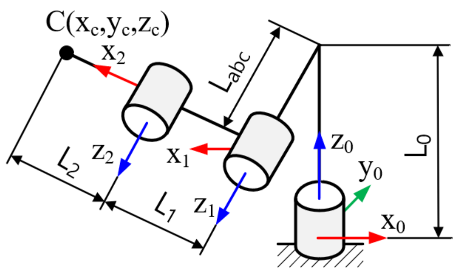
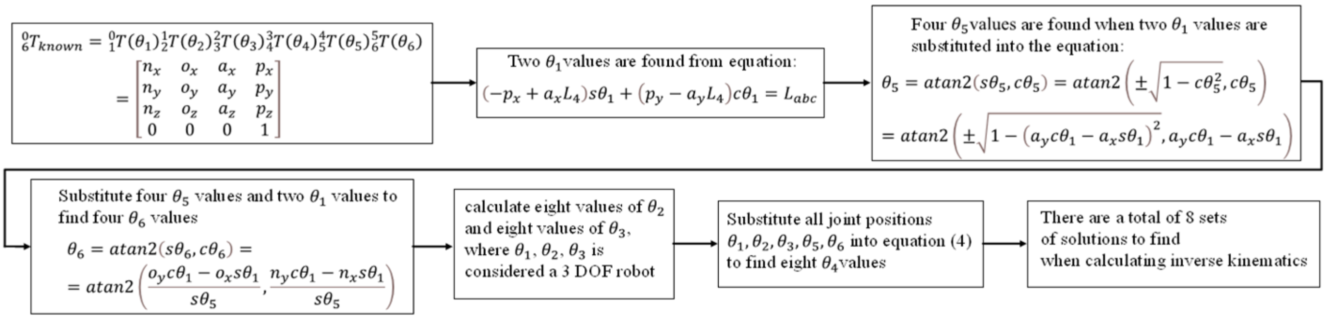


Figure 4 Inverse kinematics calculation procedure



5 Practical implementation

The problem is that when the weld gun moves, the system must know its initial position and the next point location exactly. The collection of these points is called the weld contour. At this point, we should distinguish the difference between the continuous welding contour and discrete welding contour.

In real-world operations, the welding contour is a continuous boundary between two (or more) surfaces, which means that there should be no gap between each welding section so that the contour is more concise.

Since the controller of the system cannot handle a continuous line, the system appears encounters a problem. There is no specific point at which the weld gun should stop when one section is finished. Thus, when the welding contour is divided into many sections, the aim of the weld gun in operation is to move along these points. With this type of control, anti-singularities should be achieved and the solution can be described step by step:

- *Step 1*: The welding contour, which is known beforehand, is imported to the HMI.
- *Step 2*: The system runs the virtual simulation to obtain the singularity variables of theta to avoid them.
- *Step 3*: The weld gun is operated.

There is a mini step between steps 2 and 3. In this step, the velocity of changing location in the *x*-, *y*- and *z*-coordinates is varied. We have previously mentioned that the velocity does not change in all welding con sections. Therefore, this term is defined as:

$$f\left(v_x, v_y, v_z\right) = \text{const} \tag{12}$$

This means that the velocity, such as v_x, v_y, v_z, will change but the overall velocity will not change, and the program is designed to handle this problem. In Step 1, all welding points are approximated to become an equation of the continuous welding contour by using the Lagrange approximation so that the system can use the derivative to find a suitable velocity for the whole welding contour. Assuming that W is the velocity matrix and $q_j(i)$ is defined as the velocity at the i state in the j joint, we have:

$$\begin{aligned} W &= \left[v_x, v_y, v_z, \omega_x, \omega_y, \omega_z\right] \\ &= \left[v_x, v_y, v_z, v_x / R_x, v_y / R_y, v_z / R_z\right] \end{aligned} \tag{13}$$

$$q_j(i) = q_j(i-1) + \dot{q}_j \Delta t \tag{14}$$

Hence, the Jacobian matrix is inevitable. In addition, we assume that the welding contour is known before. This problem can be explained by the fact that when mass production occurs, the contour should be obtained first. The next step is to jig objects concisely by hole tables.

This section is a future research direction for when there is velocity control as mentioned before. We can set the transform matrix ${}^i_jT$ in the following form:

$${}^i_jT = \begin{bmatrix} {}^i_jR & {}^i_jd \\ 0 & 1 \end{bmatrix} \tag{15}$$

The Jacobian matrix can be calculated column by column. The *i*-th column of *J* is called the Jacobian generating vector and is denoted by ***ci***:

$$J = \left[c_1, c_2, c_3, c_4, c_5, c_6\right] \tag{16}$$

$$c_i = \begin{bmatrix} {}^0\hat{k}_{i-1} \times {}^0\,{}^{i-1}_6d \\ {}^0\hat{k}_{i-1} \end{bmatrix} \tag{17}$$

Vector ${}^0\,{}^{i-1}_6d$ is the position of the origin, and vector ${}^0\hat{k}_{i-1}$ is the joint axis unit vector of the frame attached to link $i-1$. Both vectors are expressed in the base frame.

Vector ${}^0\hat{k}_{i-1}$ can be calculated by the following formula:

$${}^0\hat{k}_{i-1} = {}^0_{i-1}R\,{}^{i-1}\hat{k}_{i-1} \tag{18}$$

With each $(i-1)$ frame, we have:

$${}^{i-1}\hat{k}_{i-1} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{19}$$

The first half of c_i is ${}^0\hat{k}_{i-1} \times {}^0\,{}^{i-1}_6d$, which can be found conveniently by transforming the resultant of $\hat{k}_{i-1} \times {}^{i-1}_6d$ into the base frame.

$${}^0\hat{k}_{i-1} \times {}^0\,{}^{i-1}_6d = {}^0_{i-1}R\left(\hat{k}_{i-1} \times {}^{i-1}_6d\right) \tag{20}$$

By this method, we can find the Jacobian matrix for each position based on the forward kinematic function. Therefore, in regard to the Jacobian matrix, the singularities appear when $det(J)=0$, which means that $\theta_5 = 0^o, \theta_5 = 180^o$, $\theta_3 = 0^o$, $\theta_3 = 180^o$. Shoulder singularities are complicated; they can be calculated when solving inverse kinematics.

6 Study results

To validate our approach, several results of numerical simulations are described. In these tests, the Cobot makes an effort to follow the desired contour, and the actual welding trajectory using the proposed method is shown in Figure 5. Since the weld gun contacts the surface, it is necessary to estimate the velocities of the end-effector as well as the tracking error of the end-effector in Figures 6, 7 and 8. The overall simulation of the Cobot tracking performance is shown in Figure 9.

Figure 5 Result of tracking performance between desired contour and actual welding contour

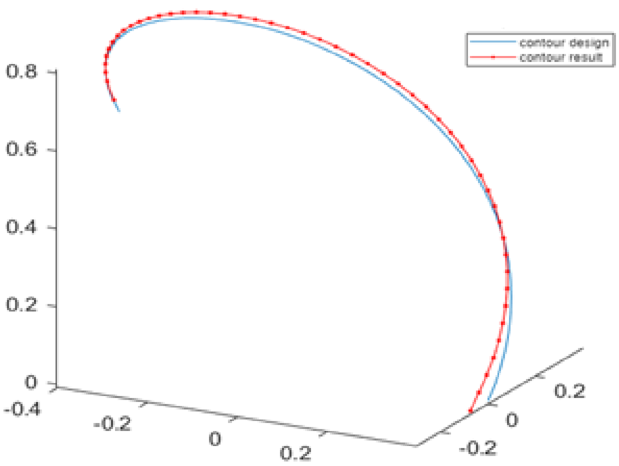


Figure 6 Result of velocities in the end-effector

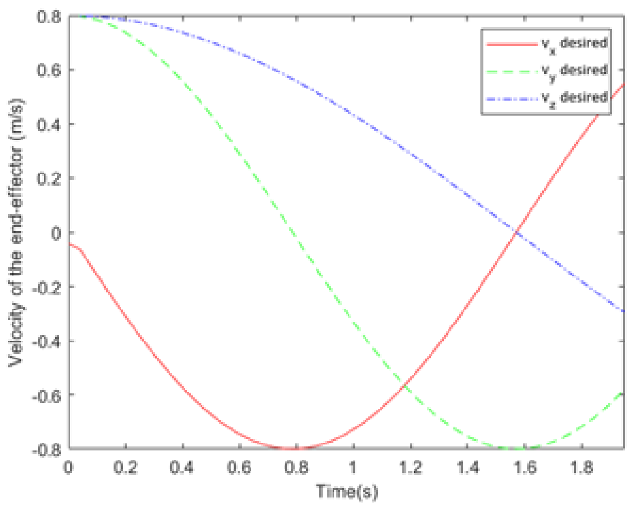
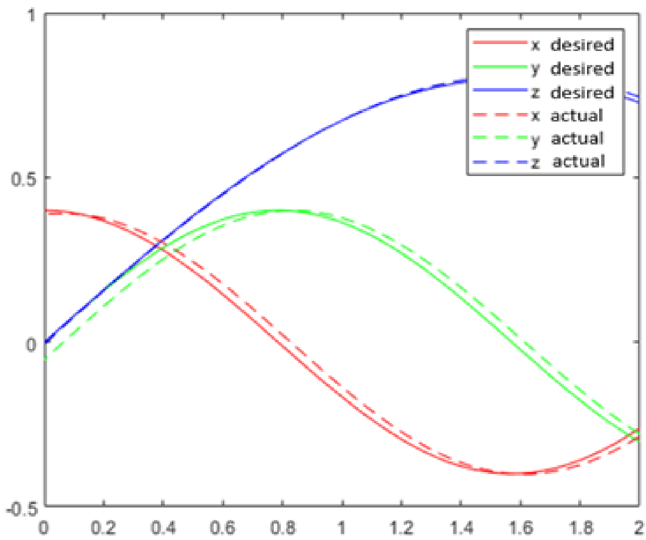
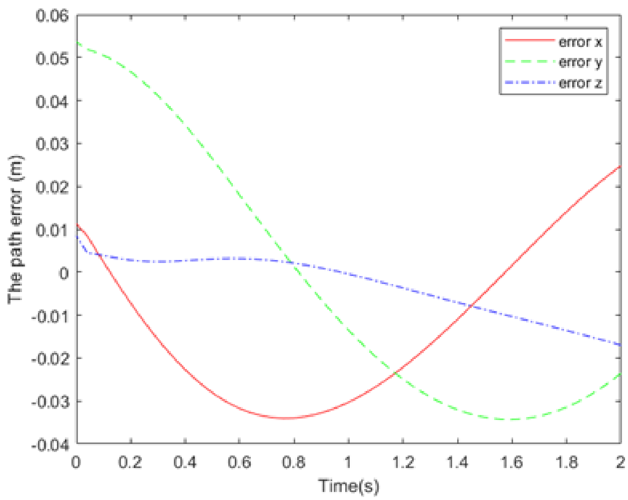


Figure 7 Results of the tracking path in the end-effector along the *x*-, *y*- and *z*-axes



Whenever the Cobot moves, if there is a sudden change in the direction of the velocity vector, the tracking position in that direction would be the largest and vice-versa (the maximum value of the error is 0.053, as shown in Figure 8). In this validation study, the velocity vector in the *x*-, *y*-directions changes at time $t = 0.8$ s and $t = 1.6$ s, respectively, as shown in Figure 6; hence, the tracking position error shown in Figure 7 becomes the greatest at that time. Additionally, since the velocity vector in the *z*-direction always decreases, the tracking position error is at its lowest.

Figure 8 Results of tracking errors in the end-effector along the *x*-, *y*- and *z*-axes



Compared to Irmawati et al. (2019), the result from V-REPPRO EDU is not only larger than our method, as shown in Table 4, but the 6-DOF Cobot is simulated using a complicated contour. The testing contour of the welding manipulator based on V-REPPRO EDU is not as practical as our contour for welding in real situations. In addition, the information and data from our study demonstrate not only the error of the tracking performance but also the change in velocity and error along the *x*-, *y*- and *z*-axes.

Figure 9 Overall simulation of the tracking performance of the Cobot

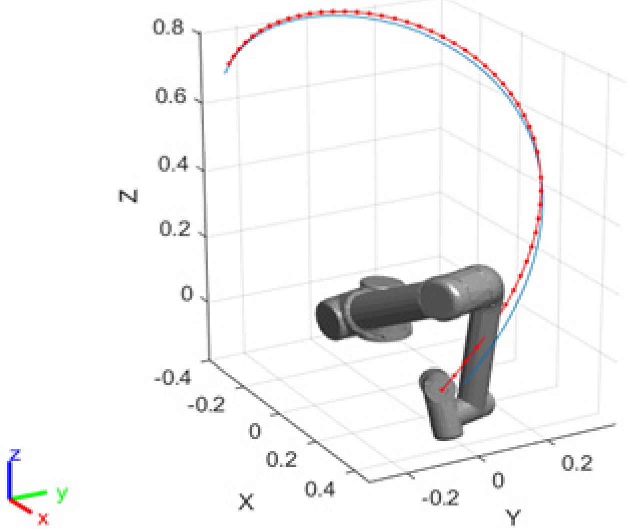


Table 4 Competitive performance for the tracking error between our approach and V-REPPRO EDU (Irmawati et al., 2019)

Method	*Max*	*Average*
Our solution	0.053	0.037
V-REPPRO EDU (Irmawati et al., 2019)	0.094	0.0406

7 Conclusion

In this paper, a novel motion controller based on the analysis of kinematics has been proposed for the solution to six DOF Cobot welding applications. Owing to the hardware specification of the UR5 Cobot, the computing process has been explained in detail. Some discussions have been carried out for practical implementation. To verify our approach, a series of numerical simulations were performed to obtain the best results. From these achievements, it can be seen clearly that the applications of Cobot are effective, feasible and useful for many industrial fields.

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References

Bi, Z.M., Luo, C., Miao, Z., Zhang, B., Zhang, W.J. and Wang, L. (2021) 'Safety assurance mechanisms of collaborative robotic systems in manufacturing', *Robotics and Computer-Integrated Manufacturing*, Vol. 67. Doi: 10.1016/j.rcim.2020.102022.

APAS (n.d.) *Bosch APAS assistant*. Available online at: https://www.boschrexroth.com/en/xc/products/product-groups/production-assistants-apas/

El Zaatari, S., Marei, M., Li, W. and Usman, Z. (2019) 'Cobot programming for collaborative industrial tasks: an overview', *Robotics and Autonomous Systems*, Vol. 116, pp.162–180.

El Zaatari, S., Wang, Y., Li, W. and Peng, Y. (2021) 'iTP-LfD: Improved task parametrised learning from demonstration for adaptive path generation of cobot', *Robotics and Computer-Integrated Manufacturing*, Vol. 69. Doi: 10.1016/j.rcim.2020.102109.

FANUC (n.d.) *FANUC CR-35iA collaborative robot*. Available online at: https://www.fanuc.eu/be/en/robots/robot-filter-page/collaborative-robots/collaborative-cr35ia

Fast-Berglund, Å., Palmkvist, F., Nyqvist, P., Ekered, S. and Åkerman, M. (2016) 'Evaluating cobots for final assembly', *Procedia CIRP*, Vol. 44, pp.175–180.

Frida-YuMi (n.d.) *ABB Frida YuMi-IRB 14000 collaborative robot*. Available online at: https://new.abb.com/products/robotics/collaborative-robots/irb-14000-yumi

Irmawati, D., Arifin, F., Nasuha, A. and Hasanah, N. (2019) 'Kinematics simulation of welding manipulator based on V-REPPRO EDU', *Journal of Physics: Conference Series*, IOP Publishing, Vol. 1413, No. 1. Doi: 10.1088/1742-6596/1413/1/012002.

Kobylarz, J., Bird, J.J., Faria, D.R., Ribeiro, E.P. and Ekárt, A. (2020) 'Thumbs up, thumbs down: Non-verbal human-robot interaction through real-time EMG classification via inductive and supervised transductive transfer learning', *Journal of Ambient Intelligence and Humanized Computing*, Vol. 11, No. 12, pp.6021–6031.

Kolb, A., Barth, E. and Koch, R. (2008) 'Tof sensors: new dimensions for realism and interactivity', *IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops*, Vol. 1, pp.1–6.

Lv, J., Rezhou, T., Wangchujun, T., Ying, L., Yingfeng, Y. and Shun, J. (2017) 'An investigation into reducing the spindle acceleration energy consumption of machine tools', *Journal of Cleaner Production*, Vol. 143, pp.794–803.

Mathivana, S. and Babu, R.Y. (2019) 'Gear shift force reduction in manual transmission', *National Level Conference on Emerging Trends in Engineering Design and Manufacturing*, Vol. 7, No. 6, pp.1–2.

Morris, K.J., Samonin, V., Baltes, J., Anderson, J. and Lau, M.C. (2019) 'A robust interactive entertainment robot for robot magic performances', *Applied Intelligence*, Vol. 49, No. 11, pp.3834–3844.

Oh, S.J. (2021) 'Emergence of a new sector via a business ecosystem: a case study of Universal Robots and the collaborative robotics sector', *Technology Analysis and Strategic Management*, pp.1–14.

Peron, M., Sgarbossa, F. and Strandhagen, J.O. (2020) 'Decision support model for implementing assistive technologies in assembly activities: a case study', *International Journal of Production Research*, pp.1–27.

Pires, J.N. and Azar, A.S. (2018) 'Advances in robotics for additive/hybrid manufacturing: robot control, speech interface and path planning', *Industrial Robot: An International Journal*, Vol. 45, No. 3, pp.311–327.

Pollak, A., Paliga, M., Pulopulos, M.M., Kozusznik, B. and Kozusznik, M.W. (2020) 'Stress in manual and autonomous modes of collaboration with a cobot', *Computers in Human Behavior*, Vol. 112. Doi: 10.1016/j.chb.2020.106469.

Subramaniam, S., Aggarwal, P., Dasgupta, G.B. and Paradkar, A. (2018) 'Cobots-a cognitive multi-bot conversational framework for technical support', *Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems*, pp.597–604.

Timms, M.J. (2016) 'Letting artificial intelligence in education out of the box: educational cobots and smart classrooms', *International Journal of Artificial Intelligence in Education*, Vol. 26, No. 2, pp.701–712.

Turnwald, A. and Wollherr, D. (2019) 'Human-like motion planning based on game theoretic decision making', *International Journal of Social Robotics*, Vol. 11, No. 1, pp.151–170.

UR5-e (n.d.) *Universal UR5-a flexible collaborative robot arm*. Available online at: https://www.universal-robots.com/products/ur5-robot/

Van Aerschot, L. and Parviainen, J. (2020) 'Robots responding to care needs? A multitasking care robot pursued for 25 years, available products offer simple entertainment and instrumental assistance', *Ethics and Information Technology*, Vol. 22, No. 3, pp.247–256.

White, D. and Katsuno, H. (2021) 'Toward an affective sense of life: artificial intelligence, animacy, and amusement at a robot pet memorial service in Japan', *Cultural Anthropology*, Vol. 36, No. 2, pp.222–251.

Xu, L., Tan, X. and Liu, S. (2020) 'Design of dancing robot control system based on STM32', *MATEC Web of Conferences*, EDP Sciences, Vol. 309. Doi: 10.1051/matecconf/202030904003.

Zaatari, S.E., Wang, Y., Hu, Y. and Li, W. (2021) 'An improved approach of task-parameterized learning from demonstrations for cobots in dynamic manufacturing', *Journal of Intelligent Manufacturing*, pp.1–17.