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# Optimal control of a PMSM driven dual-arm SCARA robot by using the Bees Algorithm

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Abstract

In this study, the optimal control of a dual-arm SCARA robot driven by a Permanent Magnet Synchronous Motor (PMSM) is performed to track the desired trajectory by using the Bees Algorithm, one of the meta-heuristic optimization algorithms. The objective function to be minimized is taken as the shortest perpendicular distance between a desired trajectory and the trajectory to be tracked by the end effector of the robot. The optimal control of the dual-arm SCARA robot is made in such a way that the robot tracks the desired trajectory with minimum error within the workspace. It is thought that the dual-arm SCARA robot tracks the desired trajectory with time constraint, provided that it is within the workspace. The efficiency and sensitivity of the Bees Algorithm used on a sample application are demonstrated. The numerical application results are given graphically.

## 1. Introduction

PMSMs have become one of the most widely used motor types in modern industrial and commercial products due to their power density, high efficiency, and precise control capabilities. These motors are extensively utilized in a variety of fields, including electric vehicles, robotics, renewable energy systems, and industrial automation. The increasing demand for energy-efficient and high-performance motor drives has spurred substantial research efforts aimed at optimizing the design, control, and application of PMSMs. In particular, PMSMs are increasingly being utilized in robotic systems, such as SCARA robots, where precision, speed, and reliability are critical [1-4].

SCARA robots, known for their high- precision and high-speed performance, are extensively used in assembly, packaging, and material handling applications. The dual-arm structure of SCARA robots allows them to perform complex tasks with exceptional accuracy, making them indispensable in modern manufacturing environments. However, the performance of SCARA robots heavily depends on the quality of their drive systems, where PMSMs play a pivotal role. The integration of PMSMs into SCARA robots offers numerous advantages, including improved dynamic response, reduced energy consumption, and enhanced positioning accuracy [5-7].

The importance of PMSMs in SCARA robots lies in their ability to deliver superior performance compared to traditional motor types, such as induction motors and brushed DC motors. The permanent magnets embedded in the rotor eliminate the need for rotor windings, reducing losses and improving overall efficiency. Additionally, PMSMs offer excellent torque-to-inertia ratios, making them ideal for applications requiring rapid acceleration and deceleration, which are essential for the fast and precise movements of SCARA robots. However, the complex dynamics and nonlinear behavior of PMSMs pose significant challenges in their control and operation, necessitating advanced control strategies and optimization techniques [8].

Over the past few decades, numerous scientific studies have focused on addressing these challenges and unlocking the full potential of PMSMs in robotic applications. Research efforts have been directed toward developing sophisticated control algorithms, such as Direct Torque Control (DTC), Field-Oriented Control (FOC), and Model Predictive Control (MPC), to achieve precise speed and position control. These control strategies are particularly important for SCARA robots, where accurate trajectory tracking and minimal overshoot are critical for task performance. Furthermore, advancements in sensorless control techniques have enabled the operation of PMSMs without the need for physical sensors, reducing costs and improving reliability in robotic systems [9].

In recent years, the use of metaheuristic optimization algorithms, such as The Bees Algorithm, has gained significant attention in the optimal control of PMSMs. The Bees Algorithm is inspired by the foraging behavior of honeybees, and a powerful optimization tool that can efficiently solve complex, nonlinear, and multi-modal optimization problems. In the context of PMSM control, The Bees Algorithm can be used to optimize controller parameters, such as proportional-integral (PI) gains, to achieve superior performance in terms of response time, stability, and energy efficiency. The application of The Bees Algorithm in PMSM control is particularly relevant for SCARA robots, where the dynamic and precise nature of tasks demands highly optimized control systems.

Another critical area of research is the optimization of PMSM design parameters, including magnet placement, winding configurations, and thermal management. These studies aim to enhance motor performance, minimize losses, and extend operational lifetimes, which are crucial for the demanding operational environments of SCARA robots. Additionally, the integration of PMSM with new technologies such as artificial intelligence and machine learning has created new possibilities for intelligent motor control and predictive maintenance in robotic systems.

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The growing emphasis on automation and Industry 4.0 has further underscored the importance of PMSMs in SCARA robots and other robotic systems. As manufacturing processes become increasingly automated, the demand for high-performance, energy-efficient, and reliable robotic systems continues to grow. PMSMs, with their superior performance characteristics, are expected to play a pivotal role in meeting these demands. This has spurred interdisciplinary research efforts, combining expertise from electrical engineering, mechanical engineering, and control theory, to push the boundaries of PMSM technology in robotics.

This study aims to contribute to the ongoing research on PMSMs by addressing key challenges in their control and optimization for dual-arm SCARA robot applications. By leveraging advanced control strategies, such as The Bees Algorithm, and computational tools, we seek to enhance the performance, efficiency, and reliability of PMSMs in dual-arm SCARA robots [10-12]. The results of this study are expected to provide valuable information to engineers and researchers working on next-generation robotic systems, leading to more accurate, efficient and sustainable automation solutions. The integration of metaheuristic optimization techniques, such as The Bees Algorithm, into PMSM control systems represents a promising direction for achieving optimal performance in complex and dynamic robotic applications.

## 2. Kinematic model of the dual-arm SCARA robot

In Figure 1, The dual-arm SCARA robot driven by PMSM, examined in this study, is illustrated. The robot manipulator possesses two degrees of freedom. It is capable of performing translational motion along the x and y axes to position a part held by the end-effector at point D of the robot, as well as rotational motion around the z axis to orient the part. The translational motion in the xy plane is accomplished through a five-bar parallel mechanism. Since the robot manipulator has two degrees of freedom, the necessary mobility is provided by motors connected to the $O_1$ and $O_2$ joints. The forward and inverse kinematic models of the dual-arm SCARA robot are derived. In the forward kinematics problem, it is assumed that the joint variables are known, and the goal is to calculate the position and orientation (pose) of the end effector. For parallel robots, forward kinematics is typically more complex compared to inverse kinematics. However, due to the simplicity of its design, the forward kinematic solutions for the dual-arm SCARA robot can be easily expressed in analytical form.

As depicted in Figure 1, $O_i$ represents the fixed base points of the joints, $L_i$ denotes the lengths of the limbs, and $q_i$ signifies the rotation angles of the joints. The pose of the end effector is given by D = [$x_D$, $y_D$, α], while the joint variables are [$q_1$, $q_2$]. In the forward kinematics problem, the joint variable $q_i$ is provided, and the pose of the end effector D = [$x_D$, $y_D$, α] is to be determined. Using Figure 1 for forward kinematics, the following equations are derived:

$$x_D = x_A + L_4 cos(\theta_1) + L_5 cos(\theta_2) \quad (1)$$
$$y_D = y_A + L_4 sin(\theta_1) + L_5 sin(\theta_2) \quad (2)$$
$$\theta_1 = \delta_1 + \psi \quad (3)$$
$$\psi = atan2(y_B - y_A, x_B - x_A) \quad (4)$$

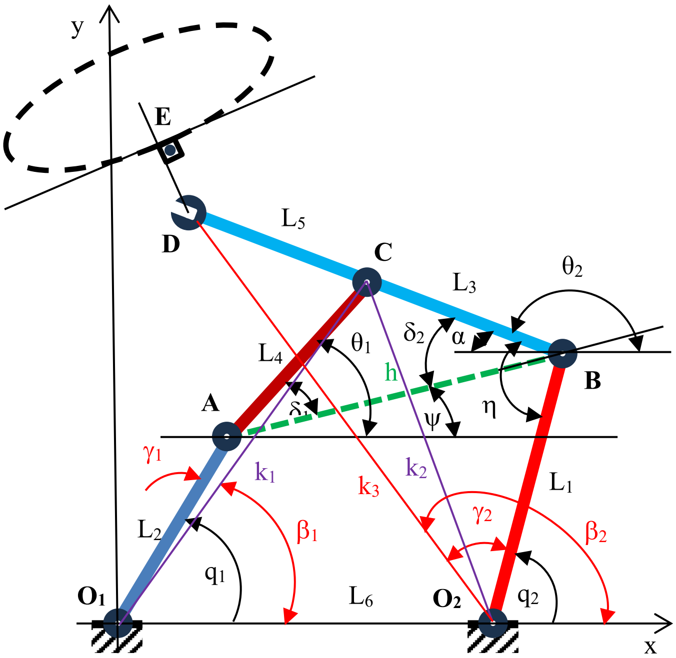


**Figure 1.** Dual-arm SCARA robot

The position of joints A and B can be expressed as a function of the joint variables $q_i$:

$$x_A = L_2 cos(q_1) \quad (5)$$
$$y_A = L_2 sin(q_1) \quad (6)$$
$$x_B = L_1 cos(q_2) + L_6 \quad (7)$$
$$y_B = L_1 sin(q_2) \quad (8)$$

The variables $\delta_i$ in the above equations are as follows:

$$\delta_1 = \pm\, acos\left((L_3^2 - L_4^2 - h^2)/2L_4 h\right) \quad (9)$$
$$\delta_2 = acos\left(\frac{(L_4^2 - L_3^2 - h^2)}{2L_3 h}\right) \quad (10)$$
$$h = \sqrt{(y_B - y_A)^2 + (x_B - x_A)^2} \quad (11)$$

The sign "±" in the equations depends on the mounting configuration of the robot, which can result in two possible solutions. Ultimately, the absolute rotation α of the end effector can be determined as follows:

$$\alpha = \pi - \theta_2 \quad (12)$$
$$\theta_2 = \pi - (\delta_2 - \psi) \quad (13)$$

For the inverse kinematic analysis, assuming that the pose of the end effector (D = [$x_D$, $y_D$, α]) is known, the problem is defined as finding the joint variables ([$q_1$, $q_2$) of the robot. Due to the relatively straightforward geometry of the robotic arm, the inverse kinematics problem can be solved with ease. Based on Figure 1, the following formulas for inverse kinematics are derived:

$$q_2 = \beta_2 - \gamma_2 \quad (14)$$
$$q_1 = \beta_1 + \gamma_1 \quad (15)$$

The two intermediate variables $\beta_1$, $\beta_2$, $\gamma_1$ and $\gamma_2$ are defined as follows:

$$\beta_2 = \pi - atan2(y_D, L_6 - x_D) \quad (16)$$
$$\beta_1 = atan2(y_C, x_C) \quad (17)$$
$$x_C = x_D + L_5 cos(\alpha) \quad (18)$$
$$y_C = y_D - L_5 sin(\alpha) \quad (19)$$
$$\gamma_2 = \pm\, acos\left(\frac{(L_1^2 + k_3^2 - (L_3 + L_5)^2)}{2L_1 k_3}\right) \quad (20)$$
$$\gamma_1 = \pm\, acos\left((L_2^2 + k_1^2 - L_4^2)/2L_2 k_1\right) \quad (21)$$
$$k_1 = \sqrt{x_C^2 + y_C^2} \quad (22)$$
$$k_3 = \sqrt{(L_6 - x_D)^2 + y_D^2} \quad (23)$$

Depending on the sign chosen for $\gamma_1$ and $\gamma_2$, it can be obtained four different inverse kinematic solutions for a two-arm SCARA robot. Also, the joint coordinates for the α orientation of the end-effector can be written as:

$$\eta = \pm\, acos\left(((L_3 + L_5)^2 + L_1^2 - k_3^2)/2L_1(L_3 + L_5)\right) \quad (24)$$
$$\alpha = \eta - q_2 \quad (25)$$

The coordinates of the D point of the end effector on the xy coordinate system are defined as ($x_D$, $y_D$) and the coordinates of the E point on the desired trajectory of the end-effector are defined as ($x_E$, $y_E$). The shortest distance z between points D and E can be defined as follows:

$$z = \sqrt{(x_E - x_D)^2 + (y_E - y_E)^2} \quad (26)$$

## 3. Mathematical Model for Position Control of the PMSM

The block diagram of PMSM control system is shown in Figure 2. Four PI controllers are used in the speed loop of field oriented control (FOC) algorithm. The parameter tuning problem in PI controller leads to poor adaptability of control system. Hysteresis of integral term causes insufficient dynamic response of controller. Many controller parameters can make tuning very difficult, but the idea of separating FOC algorithm is important for high precision control.

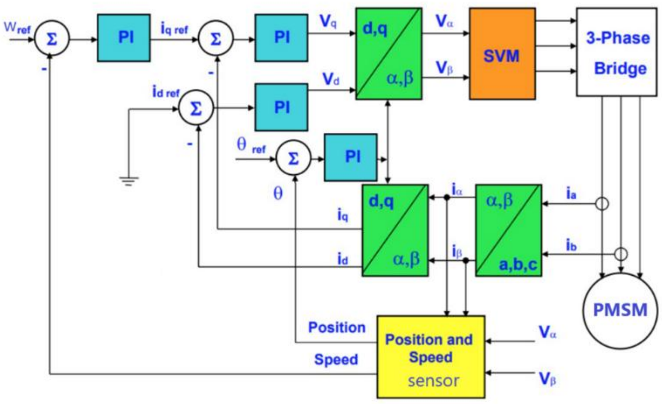


**Figure 2.** Block diagram of the PMSM control system

The PMSM requires a hierarchical control structure that includes torque, speed, and position control loops. The mathematical model of the PMSM is derived in the dq-axis reference frame, and the control design is based on FOC. Below, the mathematical model and control equations are presented in detail.

The stator voltage equations in the dq-axis reference frame are given as:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (27)$$
$$v_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_e L_d i_d + \omega_e \lambda_{pm} \quad (28)$$

where $v_d, v_q$: d-axis and q-axis stator voltages, $i_d, i_q$: d-axis and q-axis stator currents, $R_s$: Stator resistance, $L_d, L_q$: d-axis and q-axis inductances, $\omega_e$: Electrical angular velocity (rotor speed), $\lambda_{pm}$: Permanent magnet flux linkage. The magnetic flux equations in the dq-axis reference frame are expressed as:

$$\lambda_d = L_d i_d + \lambda_{pm} \quad (29)$$
$$\lambda_q = L_q i_q \quad (30)$$

where $\lambda_d, \lambda_{dq}$: d-axis and q-axis magnetic fluxes. The electromagnetic torque produced by the PMSM is given by:

$$T_e = \frac{3}{2} P\left(\lambda_{pm} i_q + (L_d - L_q) i_d i_q\right) \quad (31)$$

where $T_e$: Electromagnetic torque, $P$: Number of pole pairs. The mechanical dynamics of the motor are described by:

$$T_e - T_L = J\frac{d\omega_m}{dt} + B\omega_m \quad (32)$$

where $T_L$: Load torque, $J$: Rotor moment of inertia, $B$: Friction coefficient, $\omega_m$: Mechanical angular velocity (rotor speed). The relationship between electrical angular velocity ($\omega_e$) and mechanical angular velocity ($\omega_m$) is:

$$\omega_e = P\omega_m \quad (33)$$

The rotor position ($\theta_r$) and speed ($\omega_m$) are related by:

$$\frac{d\theta_r}{dt} = \omega_m \quad (34)$$

The position control loop generates the speed reference ($\omega^*$) based on the error between the reference position ($\theta^*$)) and the measured rotor position ($\theta_r$). A PI controller is typically used for this purpose:

$$\omega^* = K_{p,\theta}(\theta^* - \theta_r) + K_{i,\theta}\int(\theta^* - \theta_r)dt \quad (35)$$

where $\theta^*$: Reference position (target angle), $\theta_r$: Measured rotor position, $K_{p,\theta}$: Proportional gain of the position controller, $K_{i,\theta}$: Integral gain of the position controller. The speed control loop generates the q-axis reference current ($i_q^*$) based on the error between the speed reference ($\omega^*$) and the measured rotor speed ($\omega_r$). A PI controller is used for this purpose:

$$i_q^* = K_{p,\omega}(\omega^* - \omega_r) + K_{i,\omega}\int(\omega^* - \omega_r)dt \quad (36)$$

where $\omega_r$: Measured rotor speed, $K_{p,\omega}$: Proportional gain of the speed controller, $K_{i,\omega}$: Integral gain of the speed controller. The current control loops regulate the d-axis and q-axis currents using PI controllers. The control equations are:

**d-axis current control:**

$$v_d^* = K_{p,d}(i_q^* - i_d) + K_{i,d}\int(i_q^* - i_d)dt \quad (37)$$

**q-axis current control:**

$$v_q^* = K_{p,q}\left(i_q^* - i_d\right) + K_{i,q}\int\left(i_q^* - i_d\right)dt \qquad (35)$$

where $v_d^*, v_q^*$: d and q-axis reference voltages, $i_d^*, i_q^*$: d-axis and q-axis reference currents, $K_{p,d}, K_{p,q}$: Proportional gains of the current controllers, $K_{i,d}, K_{i,q}$: Integral gains of the current controllers.

The reference voltages ($v_d^*$ and $v_q^*$) are limited to the maximum inverter output voltage and transformed back to the stator reference frame using the inverse Park transformation:

$$v_\alpha = v_d^* \cos(\theta_r) - v_q^* \sin(\theta_r) \qquad (39)$$
$$v_\beta = v_d^* \sin(\theta_r) - v_q^* \cos(\theta_r) \qquad (40)$$

where $v_\alpha, v_\beta$: αβ-axis reference voltages. The αβ-axis reference voltages are converted into switching signals for the inverter using Space Vector Modulation (SVM). The rotor position ($\theta_r$) and speed ($\omega_r$) are estimated using sensors (e.g., encoders) or sensorless methods (e.g., observer-based techniques). The mathematical model and control equations presented above provide a comprehensive framework for the position control of a PMSM. The hierarchical control structure, consisting of position, speed, and current control loops, ensures precise and efficient motor control. This model can be directly implemented in simulations or experimental setups for performance analysis and validation.

## 4. The Bees Algorithm

In this study, the Bees Algorithm which is a meta-heuristic optimization algorithm, is used to solve the optimization problem. It was first developed by Pham et al. In 2006, Bees Algorithm is a swarm intelligence-based screening algorithm that mimics the resource search behavior of honey bees (nectar, water, etc.) [13-21]. The block diagram of the Bees Algorithm is shown in Figure 2. The Bees Algorithm includes a number of parameters that need to be adjusted during optimization. These are the number of optimal screening areas selected from n visited points (m), the number of scout bees (n), the number of bees sent to the best screening area (nep), the number of elite screening areas within the selected m screening area (e), the number of bees sent to the remaining (m-e) screening area (nsp), the size of the screening area (ngh), and the number of iterations accepted as the stopping criterion (itr). The optimization problem starts with sending n random scout bees to the screening area. In the second stage, the suitability of the points scanned by the scout bees is evaluated. In the third stage, m scan area with more suitable values is selected from n scan area. In the fourth and fifth steps, elite scan areas (e) with the best suitability value and scan areas (m-e) within m scan area are selected. Neighborhood scan size (ngh) is defined for these areas. In the selected scan areas, more follower bees (nep) are sent to the best scan area e, which is a more promising solution compared to other selected scan areas, while a more detailed search is performed by sending fewer follower bees (nsp) to other scan areas. The bee with the most suitable value is selected in each scan area. In the sixth, seventh and eighth steps, other bees except the bee with the most suitable value for each scan area are separated from the scan area. Other bees in the swarm (n-m) are sent to the random scan area again to obtain new potential solutions. The process continues until the optimization stopping criterion (itr) is met. After each iteration, a new swarm consists of representatives from each selected scan area and randomly scanning scout bees.

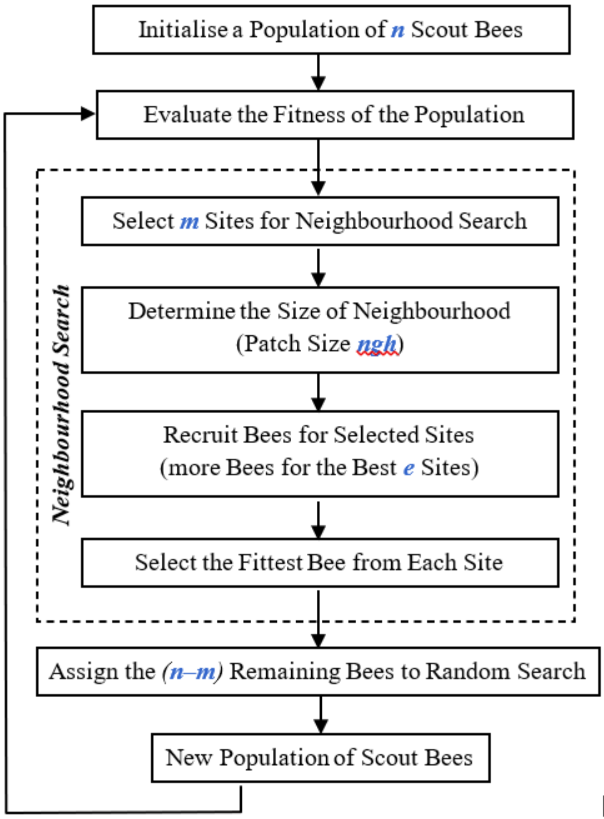


**Figure 3.** Flowchart of the Bees Algorithm

## 5. Optimal control of the robot

The block diagram created for the optimal control of the robot in this study is shown in Figure 4. Two motors of the same type are used for the dual-arm SCARA robot with two degrees of freedom. In order for the robot end-effector to track the desired trajectory, the motor positions corresponding to this trajectory are found using inverse kinematics. In order to get these motor positions from the motors, the controller gains of the motors are optimized using the Bees Algorithm.

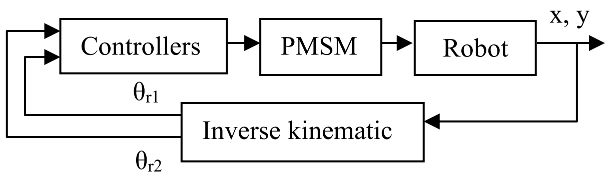


**Figure 4.** Controller block diagram of the robot

## 6. Results and discussion

The dimensions of the planar dual-arm SCARA robot considered in this study are given in Table 1 and the parameters of the PMSM used to drive the dual-arm SCARA robot are given in Table 2. An optimal controller design has been made for the end effector of the dual-arm SCARA robot to track a given trajectory with minimum error. The objective function is taken as the sum of the minimum distances between the desired trajectory and the trajectory to actually track of the end effector, as shown in the equation below.

$$J = \sum \sqrt{(x_E - x_D)^2 + (y_E - y_E)^2} \quad (41)$$

During the trajectory tracking, four PI controllers have been optimized for each of the two motors of the robot manipulator so that the z distance will be minimum despite the specific movement of the $q_1$ and $q_2$ angles. In this study, the optimization problem of controller gains has been solved by using the Bees Algorithm. A total of 16 controller gains, 8 for each motor, have been optimized. The parameters of the Bees Algorithm used in the optimization studies are given in Table 3. The parameters of The Bees Algorithm given in Table 3 are determined by trial and error using past experience. The gains of the controllers obtained after optimization are given in Table 4. The desired and actual trajectory tracked by the end effector of the PMSM driven dual-arm SCARA robot is shown in Figure 5. As can be seen from the figure, the robot tracks the desired trajectory with great precision. The maximum orbital error was 5.72 mm.

**Table 1.** Dimensions of the dual-arm SCARA robot

| Symbol | Value (mm) |
|---|---|
| $L_1$ | 350 |
| $L_2$ | 350 |
| $L_3$ | 450 |
| $L_4$ | 450 |
| $L_5$ | 50 |
| $L_6$ | 500 |

**Table 2.** Parameters of the PMSM

| Symbol | Description | Value |
|---|---|---|
| $R_S$ | Stator resistance | 0.3 Ω |
| $L_d$ | D-axis inductance | 2.5 mH |
| $L_q$ | Q-axis inductance | 2.5 mH |
| $\lambda_{pm}$ | Permanent magnet flux | 0.15 Vs |
| J | Rotor inertia | 0. 002 kg.m$^2$ |
| B | Friction coefficient | 0.0005 N.m.s/rad |
| P | Pole pair | 4 |
| $P_S$ | Rated power | 750 W |

## 7. Conclusions

In this study, optimal control of a PMSM driven dual-arm SCARA robot for trajectory tracking has been realized by using the meta-heuristic optimization algorithm the Bees Algorithm. The objective function is taken as the sum of the squares of distances between the points that form the desired trajectory that the end effector of the dual-arm SCARA robot will track and the points that the end effector of the dual-arm SCARA robot will pass. Optimization of PMSM controllers has been done for this movement of the dual-arm SCARA robot. In this study, it is considered that the end effector of the dual-arm SCARA robot will track the desired trajectory with time constraint and the trajectory is defined as points. As a result of the optimization of the controllers; the coefficient of determination ($R^2$) between the desired trajectory and the realized trajectory has been 0.999. Optimum trajectory tracking of the dual-arm SCARA robot has been successfully realized by using the Bees Algorithm in such a way that the desired trajectory to be followed is followed with minimum error while staying within the working space of the robot manipulator and it has been shown that the Bees Algorithm can be used as an effective optimization tool for trajectory tracking of the dual-arm SCARA robot in the future. The optimization process in the paper can be integrated into all applications where a dual-arm Scara robot is used. For example, it can be widely used in picking and sorting products on a moving belt, product positioning applications, and in the automotive industry for assembly line automation, welding, and painting.

**Table 3.** Parameters of the Bees Algorithm

| n | m | e | nep | nsp | ngh | itr |
|---|---|---|---|---|---|---|
| 50 | 20 | 5 | 10 | 5 | 0.02 | 500 |

**Table 4.** Gains of the optimized controllers

| Symbol | Value |
|---|---|
| $K_{p,\theta}$ | 199.01 |
| $K_{i,\theta}$ | 3132.02 |
| $K_{p,\omega}$ | 1.02 |
| $K_{i,\omega}$ | 0.21 |
| $K_{p,d}$ | 9.95 |
| $K_{i,d}$ | 998.02 |
| $K_{p,q}$ | 9.95 |
| $K_{i,q}$ | 998.02 |

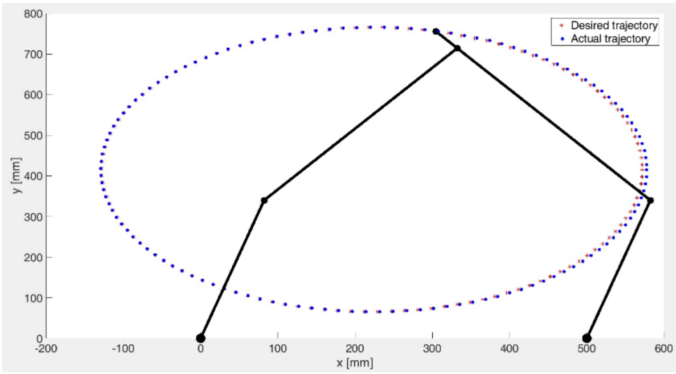


**Figure 5.** Comparison of desired and actual trajectories

**Author contributions**

Ahmet Adsiz: modelling of the dual-arm SCARA robot, controller design, validation, resources, formal analysis, investigation, visualization.

Ahmet Tarhan: modelling of the PMSM, validation, resources, formal analysis, investigation, visualization.

Mete Kalyoncu: conceptualization, methodology, software, validation, resources, optimization, writing-reviewing and editing.

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