OPTIMIZATION OF TRAJECTORY FOR THE DUAL- ARM ROBOT USING GENETIC ALGORITHM IN CONSIDERATION OF CONTROLLER

THIẾT KẾ TỐI ƯU QUỸ ĐẠO CHO HỆ TAY MÁY ĐÔI SỬ DỤNG THUẬT TOÁN DI TRUYỀN XEM XÉT TỚI ẢNH HƯỞNG CỦA BỘ ĐIỀU KHIỂN

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Abstract:

The optimal trajectory planning of the object in the dual-arm system cooperative movement of the objects will been developed in this paper. The object's motion trajectory includes: along X and Y axes, and object rotation. The third-order and fifth-order polynomial trajectories are chosen to test the optimal trajectory planning base on minimum execution time for the object. This paper presents planning the optimal trajectory using genetic algorithm. When the optimal trajectory is designed with considered constraints such as torque limit, range of motion of joints as well as velocity of joints. Unlike previous researches, the reference trajectory is assumed to be the same as the real one. Therefore, the torque at the joints are calculated by using the inverse kinematic and dynamic of the dual-arm robot system. The paper proposes to add a controller when planning optimal trajectory, the torque at the robot joints is calculated from the output of the controller. This design ensures similarity between the design trajectory and the actual implementation. Finally, simulation on Matlab-Simulink with different types of orbits have proved the feasibility of the proposed solution.

Keywords:

Genetic algorithms, dual-arm robotic, trajectory planning, optimal trajectory, time optimization.

Tóm tắt:

Bài báo phát triển thiết kế quỹ đạo chuyển động tối ưu của đối tượng trong hệ thống tay máy đôi phối hợp chuyển động. Quỹ đạo chuyển động của đối tượng gồm: chuyển động theo trục X, trục Y và chuyển động xoay của đối tượng. Quỹ đạo chuyển động của đối tượng là đa thức bậc ba, bậc năm được chọn lựa để xây dựng quỹ đạo tối ưu dựa trên thời gian thực hiện tối thiểu. Bài báo trình bày cách thức thiết kế quỹ đạo tối ưu sử dụng thuật toán di truyền (GA), khi đó quỹ đạo tối ưu được thiết kế với các điều kiện ràng buộc được xem xét như: giới hạn mômen, phạm vi chuyển động của khớp cũng như tốc độ chuyển động của các khớp. Khác với các nghiên cứu trước, quỹ đạo tham chiếu được cho là giống quỹ đạo thực, do đó, mô men tác động tại các khớp được tính toán bằng sử dụng động học ngược và động lực học của hệ thống tay máy đôi. Bài báo đề xuất đưa thêm một bộ điều khiển vào khi thiết lập quỹ đạo tối ưu, lúc này mômen tác động lên các khớp được lấy từ đầu ra của bộ điều khiển. Với cách thiết kế này đảm bảo sự tương đồng giữa quỹ đạo thiết kế và quỹ đạo thực. Cuối cùng, mô phỏng trên Matlab/Simulink với các dạng quỹ đạo khác nhau đã chứng minh được tính khả thi của giải pháp đề xuất.

Từ khóa:
Thuật toán di truyền, tay máy đôi, thiết lập quỹ đạo, quỹ đạo tối ưu, thời gian tối ưu.

1. INTRODUCTION

The problem of trajectory design is necessary for the range of robot control. The objective of trajectory designs is to generate reference inputs for the controller system to ensure the execution of the designed motion. Trajectory planning is a fundamental issue for robotic applications. For single robot, various trajectory planning algorithms have been done, see [1] for survey. The trajectory planning problem is usually considered as optimization problem with different criteria, the most significant are minimum execution time, minimum energy, minimum jerk. Various constraints are usually added to the trajectory planning problem to guarantee the possibility of the planned trajectory in practice. The planned trajectory must satisfy the kinematic and dynamic constraints of the manipulators such position, velocity and torque constraints. A trajectory for many manipulators with passive joints to transport a common object has been designed [2]. An acceleration-level trajectory planning method for a dual-arm space robot. The physical constraints of joint robots are taken into account when trajectory planning is performed in [3] to design trajectory for collaborative welding robots with multiple manipulators. In addition, the optimal trajectory planning is to run an optimal motion with respect to some relevant criterion, it is possible to find different optimality criteria as minimum execution time, minimum energy, minimum jerk. [4] design a trajectory planning by using GA techniques for the robot to determine the optimal trajectory based on minimum joint torque requirements. The authors use a polynomial of 4th degree in time for trajectory representation to joint space variables. Energy optimal trajectories planning methods are described in [5]. The physical limits of regarding the joint velocity of the arms, the constraints contain obstacle avoidance, base maneuvering restrictions, the joint acceleration. A trajectory planning algorithm that use the bias force on the spacecraft base as a key constraint is developed [6]. Other minimum time algorithms are established in [7, 8]. An optimization method based on the Genetic Algorithms (GAs) which chooses the parameters of the polynomial, such that the execution time and the drive torques for the robot joints are minimized has been presented [9]. The trajectory planning method based on GA while adopting the direct kinematics and the inverse dynamics has been proposed [10]. The optimum trajectory is the one that minimizes traveling time. Trajectory planning that minimizing the end-effector's pose error, minimizing the base attitude disturbance, or maximizing manipulability are presented in [11]. The joint trajectories are parameterized with Bézier curve with anti-collision constraints with different objectives. A dual-robot system trajectory is optimized with different constraints in two different stages including the pre-assembly stage and the assembly stage has been presented [12]. The algorithm uses a hybrid objective function which is the combination of operation time and the joint jerk, and the balance between speed and smoothness can be obtained.

Thus, the previous studies used opened controller with no feedback. The reference trajectory is assumed to be the same as the real one. So, using relationship and inverse dynamics to calculate the torque applied to the joints of the robot. However, since all robots are controlled by a feedback controller for system stability and anti-noise, the desired and actual trajectories will not be the same. Therefore, the actual torque at the robot joints is not the same as the calculated one using the dynamic equation from the desired trajectory. To overcome the above disadvantages, the paper will add a hybrid position/force controller for the dual-arm manipulator into the system when designing the optimal trajectory for the object. At this time, the paper solves both problems: The optimal trajectory problem and the trajectory tracking problem. Then, the torque acting on the joints is taken from the controller output, and measured values of the position of the joint, angular velocities and torque are taken into the GA for consideration with the limited conditions of the robot.

2. DYNAMICS OF THE SYSTEM AND CONTROLLER OF DUAL-ARM ROBOT

2.1. Dynamics of the system

The dual-arm robot system has two manipulators cooperatively holding a rigid object, each one with three degrees of freedom (DOF) as shown in Fig.1 [13].

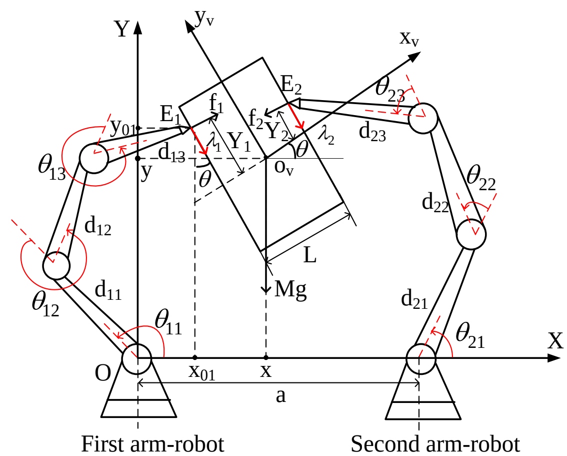

Fig 1. Model of dual-arm robot in holding an object

First coordinate frames are defined as follows.

OXY is the base frame which is the reference coordinate frame for all other frames.

$o_v x_v y_v$ is a coordinate frame, located at the mass center of the object.

E_i $(i = 1 - 2)$ is the contact of the end-effector of the arm-robot ith with surface of the object.

(x_{0i}, y_{0i}) is the position of the end-effector E_i in the reference frame.

Y_i is the distance from E_i to the x_v-axis of the object frame.

Vector $\boldsymbol{q}_i = \left[\theta_{i1}, \theta_{i2}, \theta_{i3}\right]^T$ represents the joint angle vector of the i^{th} robot.

Vector $\boldsymbol{z} = \left[x, y, \theta\right]^T$ is the position and rotational angle of the object in the reference frame *OXY*.

When the end-effectors of the dual-arm robot contact on the object, interactional forces f_1, f_2 arising has the normal direction to the surface of the object and forces λ_1, λ_2 have the parallel direction to the surface of the object.

Parameters d_{ij}, m_{ij} and I_{ij} are length, mass, and inertia moment of link j of the arm-robot i, (for j=1-3).

Besides according to [13] the relationship between object velocity and joints velocity of the i^{th} robot is described as follows:

$$\dot{\boldsymbol{q}} = \boldsymbol{A}\dot{\boldsymbol{z}};\ \ddot{\boldsymbol{q}} = \boldsymbol{A}\ddot{\boldsymbol{z}} + \boldsymbol{B}\dot{\boldsymbol{z}}, \quad (1)$$

where

$$\boldsymbol{q} = [\boldsymbol{q}_1^T, \boldsymbol{q}_2^T]^T \in R^{6\times1};$$

$$\boldsymbol{A} = [(\boldsymbol{A}_1^{-1})^T, (\boldsymbol{A}_2^{-1})^T]^T \in R^{6\times3}$$

$$\boldsymbol{B} = [(-\boldsymbol{A}_1^{-1}\dot{\boldsymbol{A}}_1\boldsymbol{A}_1^{-1})^T, (-\boldsymbol{A}_2^{-1}\dot{\boldsymbol{A}}_2\boldsymbol{A}_2^{-1})^T]^T \in R^{6\times3}$$

The dynamic of the dual-arm can be formulated as in [14]

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{J}_B^T\boldsymbol{F} = \boldsymbol{\tau}, \quad (2)$$

where

$\boldsymbol{\tau} = [\boldsymbol{\tau}_1, \boldsymbol{\tau}_2]^T$ is the vector of applied joint torques;

$\boldsymbol{F} = \left[f_1, \lambda_1, f_2, \lambda_2\right]^T$ denotes force vector at the points of contact;

$\boldsymbol{H}(\boldsymbol{q}) = \text{blockdiag}\left[\boldsymbol{H}_1(\boldsymbol{q}_1), \boldsymbol{H}_2(\boldsymbol{q}_2)\right]$,

$\boldsymbol{H}_i(\boldsymbol{q}_i)$ denotes the symmetric positive definite inertial matrix of the i^{th} manipulator;

$\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \text{blockdiag}\left[\boldsymbol{C}_1(\boldsymbol{q}_1, \dot{\boldsymbol{q}}_1), \boldsymbol{C}_2(\boldsymbol{q}_2, \dot{\boldsymbol{q}}_2)\right]$ is the matrix of Coriolis and centrifugal;

$\boldsymbol{G}(\boldsymbol{q}) = \left[\boldsymbol{G}_1(\boldsymbol{q}_1), \boldsymbol{G}_2(\boldsymbol{q}_2)\right]^T$ represents the gravity term;

$\boldsymbol{J}_B = \begin{bmatrix} \boldsymbol{J}_1(\boldsymbol{q}_1) & \boldsymbol{0}_{2\times3} \\ \boldsymbol{0}_{2\times3} & \boldsymbol{J}_2(\boldsymbol{q}_2) \end{bmatrix}$ is a 4×6 matrix expressing the analytical Jacobian matrix of the manipulator.

And the dynamics of the grasped object can be represented by the following motion equation [13] is

$$\boldsymbol{H}_z\ddot{\boldsymbol{z}} + \boldsymbol{C}_z(\boldsymbol{z}, \dot{\boldsymbol{z}})\dot{\boldsymbol{z}} + \boldsymbol{g}_z = \boldsymbol{F}_z, \quad (3)$$

where $\boldsymbol{H}_z$ represents the inertia matrix; $\boldsymbol{C}_z(\boldsymbol{z}, \dot{\boldsymbol{z}})$ is the Centrifugal and Coriolis matrix and $\boldsymbol{g}_z$ denotes the gravitational vector of the object; $\boldsymbol{F}_z$ denotes the total force/moment impacting at the center of the object represented in the base frame {OXY}.

The force/torque vector F_z at the center of the object can be described in terms of the force/torque vectors F of the dual-arm robot affected on the object at the end-effectors as follows [13]:

$$\boldsymbol{F}_z = \boldsymbol{E}\,\boldsymbol{F},$$

where $\boldsymbol{E}$ is the grasp matrix from the coordinate frame of the end-effectors to the object frame $\{o_v x_v y_v\}$ represented in the original coordinate frame $\{OXY\}$.

so $\boldsymbol{F} = \boldsymbol{E}^{+}\boldsymbol{F}_z$ (4)

2.2. The controller for the dual-arm robot

First, the reference velocity of the object is defined as:

$$\dot{\boldsymbol{z}}_r = (\dot{\boldsymbol{z}}_d + \gamma \boldsymbol{e}_p) \tag{5}$$

with γ is a positive definite gain matrix, $\boldsymbol{e}_p = \boldsymbol{z}_d - \boldsymbol{z}$ is the tracking errors. So, the desired force on the object is determined through the object's reference model:

$$\boldsymbol{F}_z{}^d = \boldsymbol{H}_z \ddot{\boldsymbol{z}}_r + \boldsymbol{C}_z(\boldsymbol{z}, \dot{\boldsymbol{z}}_r)\dot{\boldsymbol{z}}_r + \boldsymbol{g}_z \tag{6}$$

The errors between the reference and the actual velocities of the object are calculated as follows:

$$\boldsymbol{s}_0 = \dot{\boldsymbol{z}} - \dot{\boldsymbol{z}}_r = -\dot{\boldsymbol{e}}_p - \gamma \boldsymbol{e}_p \tag{7}$$

From (4), the desired forces at contact points determines as follows:

$$\boldsymbol{F}^d = \boldsymbol{E}^{+}\boldsymbol{F}_z{}^d \tag{8}$$

take Eq.(3) minus Eq. (6) as:

$$\boldsymbol{H}_z \dot{\boldsymbol{s}}_0 + \boldsymbol{C}_z \boldsymbol{s}_0 = \boldsymbol{F}_z - \boldsymbol{F}_z{}^d \tag{9}$$

Now, the robotic manipulator reference velocity is defined as $\dot{\boldsymbol{q}}_r$. The error between the reference and the actual velocities of the joints of the dual-arm robot are determined as:

$$\boldsymbol{s} = \dot{\boldsymbol{q}} - \dot{\boldsymbol{q}}_r = \boldsymbol{A}\boldsymbol{s}_0 \tag{10}$$

The dynamic of the dual-arm robot in Eq.(2) can be rewritten

$$\boldsymbol{H}(\boldsymbol{q})\dot{\boldsymbol{s}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{s} + f(\boldsymbol{q}) = \boldsymbol{\tau} - \boldsymbol{J}_B^T(\boldsymbol{q})\boldsymbol{F} \tag{11}$$

where $f(\boldsymbol{q}) = \boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}}_r + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}_r + \boldsymbol{G}(\boldsymbol{q})$

Now, the hybrit position/force control without the measurement of force at contact points is proposed:

$$\boldsymbol{\tau} = f(\boldsymbol{q}) + \boldsymbol{J}_B^T \boldsymbol{F}^d - \boldsymbol{K}_s(\boldsymbol{A}\boldsymbol{s}_0) \tag{12}$$

where $\boldsymbol{K}_s$ is a positive defined parameter matrix.

The system is considered stability according to the Lyapunov stability principle, the candidate of Lyapunov function can be selected as:

$$V = \frac{1}{2}\boldsymbol{s}^T \boldsymbol{H}\,\boldsymbol{s} + \frac{1}{2}\boldsymbol{s}_0^T \boldsymbol{H}_z \boldsymbol{s}_0 \tag{13}$$

The following lemmas as [15].

Lemma 1: $\boldsymbol{A}^T \boldsymbol{J}_B{}^T = \boldsymbol{E}$ and $\boldsymbol{A}^T \boldsymbol{J}_B{}^T \boldsymbol{E}^{+} = \boldsymbol{I}$ where $\boldsymbol{I}$ is the identity matrix.

The time derivative (13) of the Lyapunov function becomes:

$$\dot{V} = \boldsymbol{s}^T \boldsymbol{H}\,\dot{\boldsymbol{s}} + \frac{1}{2}\boldsymbol{s}^T \dot{\boldsymbol{H}}\,\boldsymbol{s} + \boldsymbol{s}_0^T \boldsymbol{H}_z\,\dot{\boldsymbol{s}}_0 + \frac{1}{2}\boldsymbol{s}_0^T \dot{\boldsymbol{H}}_z \boldsymbol{s}_0$$

Using Eqs.(9), (11) and property of skew-symmetric matrix $\dot{\boldsymbol{H}} - 2\boldsymbol{C}$ and $\dot{\boldsymbol{H}}_z - 2\boldsymbol{C}_z$ so $\boldsymbol{s}^T\left(\dot{\boldsymbol{H}} - 2\boldsymbol{C}\right)\boldsymbol{s} = 0$ and $\boldsymbol{s}_0{}^T(\dot{\boldsymbol{H}}_z - 2\boldsymbol{C}_z)\boldsymbol{s}_0 = 0$, the derivative of the Lyapunov is determined as follows:

$\dot{V} = -(\boldsymbol{A}\,\boldsymbol{s}_0)^T \boldsymbol{K}_s(\boldsymbol{A}\,\boldsymbol{s}) \leq 0$.

It is possible to prove that the dynamic system is stable under the control input (12). According to the Lyapunov stability principle, the system is stable.

3. DESIGN TRAJECTORY

The motion trajectory of the object is designed in many types of different trajectories. In this paper, the motion trajectory of the object is designed according to the third-order and fifth-order polynomial [16]

3.1. The third - order polynomial trajectories

The third-order polynomial trajectory is designed for the position and direction of the object as Eq. (14).

$$\boldsymbol{z}_d(t) = \boldsymbol{a}_0 + \boldsymbol{a}_1(\mathrm{t} - \mathrm{t}_0) + \boldsymbol{a}_2(t - t_0)^2 + \boldsymbol{a}_3(t - t_0)^3, \quad (14)$$

where $t_0 \le t \le t_f$, t_0 and t_f is initial time and the movement final time, $\boldsymbol{a}_k$ ($k = 0 - 3$) are the parameters vectors of the trajectory. The parameters vector $\boldsymbol{a}_k$ in Eq.(14) is determined as follows [16]

$$\boldsymbol{a}_0 = \boldsymbol{z}_0, \quad (15)$$
$$\boldsymbol{a}_1 = \dot{\boldsymbol{z}}_0,$$

$$\boldsymbol{a}_2 = \frac{3}{(t_f - t_0)^2}\left(\boldsymbol{z}_f - \boldsymbol{z}_0\right) - \frac{2}{t_f - t_0}\dot{\boldsymbol{z}}_0 - \frac{1}{t_f - t_0}\dot{\boldsymbol{z}}_f$$

$$\boldsymbol{a}_3 = -\frac{2}{(t_f - t_0)^3}\left(\boldsymbol{z}_f - \boldsymbol{z}_0\right) + \frac{1}{(t_f - t_0)^2}\left(\dot{\boldsymbol{z}}_f + \dot{\boldsymbol{z}}_0\right)$$

$\boldsymbol{z}_0, \dot{\boldsymbol{z}}_0$ is the initial positions and velocities;

$\boldsymbol{z}_f, \dot{\boldsymbol{z}}_f$ is the final positions and velocities.

3.2. The fifth - order polynomial trajectories

The fifth-order polynomial trajectory is designed for the position and direction of an object, ensuring that acceleration of the object can be zero. It is given by the equation:

$$\boldsymbol{z}_d(t) = \boldsymbol{a}_0 + \boldsymbol{a}_1(\mathrm{t} - \mathrm{t}_0) + \boldsymbol{a}_2(t - t_0)^2 + \boldsymbol{a}_3(t - t_0)^3 + \boldsymbol{a}_4(t - t_0)^4 + \boldsymbol{a}_5(t - t_0)^5, \quad (16)$$

where $\ddot{\boldsymbol{z}}_0$ the initial acceleration; $\ddot{\boldsymbol{z}}_f$ the final acceleration. The parameters $\boldsymbol{a}_k$ in the Eq. (16) is determined as follows

$$\boldsymbol{a}_0 = \boldsymbol{z}_0,$$
$$\boldsymbol{a}_1 = \dot{\boldsymbol{z}}_0,$$
$$\boldsymbol{a}_2 = \frac{\ddot{\boldsymbol{z}}_0}{2}, \quad (17)$$

$$\boldsymbol{a}_3 = \frac{20(\boldsymbol{z}_f - \boldsymbol{z}_0) - (8\dot{\boldsymbol{z}}_f + 12\dot{\boldsymbol{z}}_0)(t_f - t_0) - (3\ddot{\boldsymbol{z}}_0 - \ddot{\boldsymbol{z}}_f)(t_f - t_0)^2}{2(t_f - t_0)^3},$$

$$\boldsymbol{a}_4 = \frac{30(\boldsymbol{z}_0 - \boldsymbol{z}_f) + (14\dot{\boldsymbol{z}}_f + 16\dot{\boldsymbol{z}}_0)(\mathrm{t}_f - t_0) + (3\ddot{\boldsymbol{z}}_0 - 2\ddot{\boldsymbol{z}}_f)(\mathrm{t}_f - t_0)^2}{2(t_f - t_0)^4},$$

$$\boldsymbol{a}_5 = \frac{12(\boldsymbol{z}_f - \boldsymbol{z}_0) - 6(\dot{\boldsymbol{z}}_f + \dot{\boldsymbol{z}}_0)(\mathrm{t}_f - t_0) - (\ddot{\boldsymbol{z}}_0 - \ddot{\boldsymbol{z}}_f)(\mathrm{t}_f - t_0)^2}{2(\mathrm{t}_f - t_0)^5}$$

The motion trajectory of the object as Eq.(14) or Eq.(16) shows the parameters of the trajectory need to be determined $\boldsymbol{a}_{zk}$, where z is the index indicates the motion trajectory in the x, y axis and rotational angle θ of the object, k is the index indicates the coefficients of the motion transitory. Parameters for transitory design need be determined to ensure the objective of the posed problem

4. DESIGN TRANJECTORY PLANNING

The optimal trajectory planning for the object focuses on generating off-line movements to perform tasks known and in a defined environment. The optimal trajectory planning problem can be followed different optimality criteria of robot as: minimum execution time; minimum energy; minimum jerk.

The trajectory planning based on energy criteria. On the one hand, it creates a smooth trajectory that is easy to follow. On the other hand, this method allows energy saving, which doesn't just make economic sense, since this characteristic can be required by specific applications in which the energy source is limited by technical factors, such as the robot is applied for underwater exploration, for military tasks, applications in outer space.

Next, the method takes into account the limit on the jerk. The minimization of the jerk produces positive results, such as: reducing the trajectory tracking error, reducing the excitation of resonance frequencies, limiting the stresses to the manipulator structure and to the actuators.

The most important and prominent in the industrial interest is the trajectories planned using the minimum execution time criterion. Because it reduces the production cycles, which is the economic implication due to increasing productivity in the industry. Therefore, the criterion of minimum motion time is chosen as the objective function of the problem.

$$f = T_f \tag{18}$$

where T_f is the time for the object moving from the start point to the end point.

The algorithm is used to calculate the trajectory planning base on minimum execution time for the object needs to consider the constraints of the robot. Due to each robot, the angle joints have a range limitation of motion position, speed of movement. In addition, the torque control at the joints of the robot must not greater than the possible maximum torque provided by the motor. These limits are constraint conditions of joint angle, speed and torque of the joint when designing trajectory planning and they expressed as the following

$$\begin{aligned} &\boldsymbol{q}_{\min} \le \boldsymbol{q} \le \boldsymbol{q}_{\max}; \\ &\dot{\boldsymbol{q}}_{\min} \le \dot{\boldsymbol{q}} \le \dot{\boldsymbol{q}}_{\max}; \\ &\boldsymbol{\tau}_{i\min} \le \boldsymbol{\tau}_i \le \boldsymbol{\tau}_{i\max}. \end{aligned} \tag{19}$$

Using the GA algorithm as [17] to determine the optimal time T_f with the fitness function (18) and constraints (19). When T_f is determined, the parameters $\boldsymbol{a}_{zk}$

of the optimal trajectory will be determined, since the parameters $\boldsymbol{a}_{zk}$ are the function of T_f $(T_f = t_f - t_0)$.

The GA algorithm is built as shown in Fig. 2.

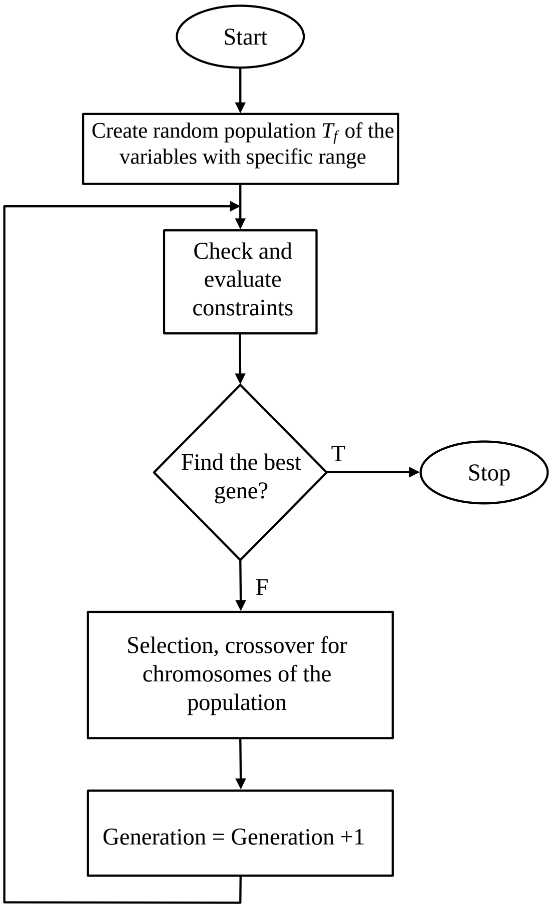

Fig 2. Flow chart of GA

At the start of the program, the initial T_f population is created and evaluated, each individual T_f in the initial population, the parameters of the initial trajectory is determined (the parameters of the trajectory are determined by (15), (17)), so the initial trajectory is built and brought to the controller. The torque applied on the joints is taken from the output controller, which is evaluated by (19) and the actual velocity and position of the joints are also evaluated by constraints (19). The initial population evaluation process, if a good gene is found, that means the optimal T_f is found, then the search process stops. If not, based on chromosomal optimization, the T_f is selected for the next process, and the selection process ensures the most suitable T_f. Then genetic processes will be carried out to create offspring for the next population, the next population continues to be evaluated. The searching process for the optimal value of T_f continues until the optimal finding value or runs to the required number of generations.

5. SIMULATION WORKS

In this section, the optimal trajectory planning is performed using GA, the constraints of torque of the joints are obtained from the controller. A simulation of the closed dynamics of the whole system has been carried out in Matlab/Simulink. The effectiveness of the proposed GA algorithm will be surveyed.

The parameters of the dual-arm robot - object are

given in [13]

The diagram depicts the system using GA to optimize the motion time of the object as shown in Fig. 3.

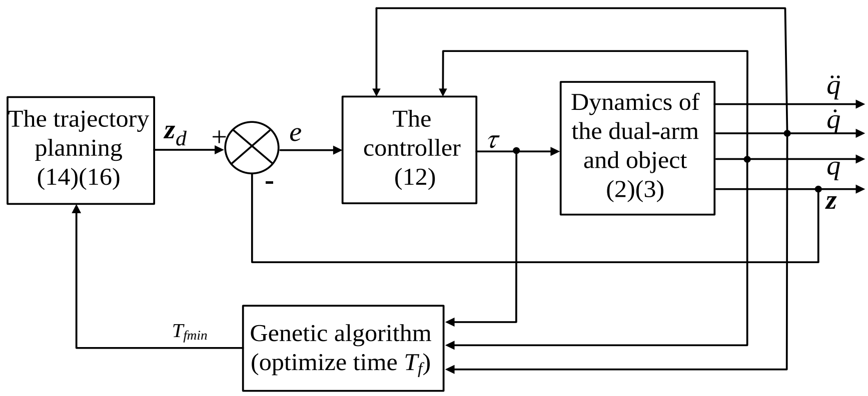

Fig 3. Depicting diagram of the system using GA to optimize motion time

Diagram of the system in Fig. 3 works as follows: With the moving time of the object taken from the T_f population of the GA algorithm, a reference trajectory (14) (16) is built, this trajectory is given to the controller (12). The torque applied on the joints of the robot is taken from the controller output to control the dual-arm robot, which is fed into the GA algorithm to check and consider the limited constraint on the torque of the joints. At the same time, the actual positions and velocities of the joints are also included in the GA algorithm to check the movement limit conditions when optimizing the motion time of the object.

The object's trajectory is constructed as in section 3, with the start and end points of the object motion used in the simulation as follows:

$$x_0 = 0,54\,\text{m};\ y_0 = 1,4\,\text{m};\ \theta_0 = 0\,\text{rad}$$

$$x_f = 1,3\,\text{m};\ y_f = 1,85\,\text{m};\ \theta_f = 0,523\,\text{rad}$$

For the upper and lower bounds of the robot joints conditions as joint angles, speed of movement, torque are reported in Table 2 [9].

Table 1. Upper and lower bounds of the robot joints

Joint	1	2	3	i	1	2	3
item	θ_{i1}	θ_{i2}	θ_{i3}	$\dot{q}_i$	τ_1	τ_2	τ_3
max	3	6	6	10	30	30	30
min	0.3	-1.5	-1.5	-10	-30	-30	-30

Using the GA algorithm, the parameters of GA are as follows:

The number of individuals in each population is 30 (`PopulationSize`);

The genetic process is carried out for a maximum of 20 generations (MaxGenerations);

The population of the next generation will have the best five individuals of the previous generation kept (EliteCount);

The error of the evaluation functions is 10-8 (FunctionTolerance);

Using the crossover function (crossoverFcn): @crossoverscattered

The author simulates two types of trajectories for the object: The third and fifth-orbit polynomial trajectories. For each type of orbit, the optimal motion time of the object will be different, specifically:

The third-order polynomial trajectory of the object with the optimal time T_f = 4,05724s. The optimal trajectory of the position and rotational angle of the object is determined as follows:

$$x = 0{,}54 + 0{,}1385t^2 - 0{,}0228t^3$$

$$y = 1{,}4 + 0{,}082t^2 - 0{,}0135t^3$$

$$\theta = 0{,}0954t^2 - 0{,}0157\,t^3$$

The simulation result GA algorithm with the constraints of torque of the joints, joints angle, angular velocity as shown in Fig. 4 to Fig. 12.

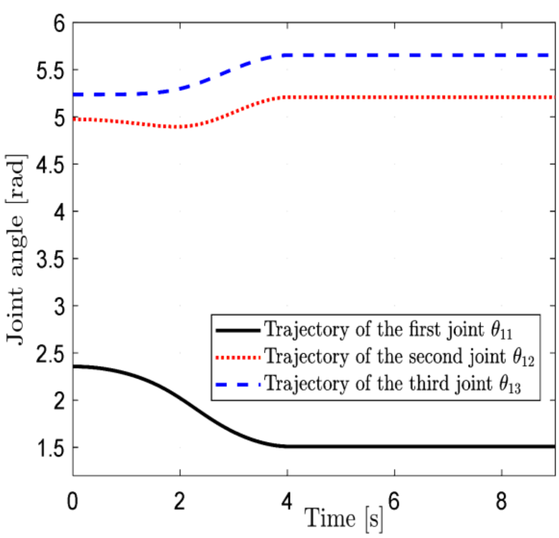

Fig 4. The motion trajectory of jonints angles of the first arm - robot

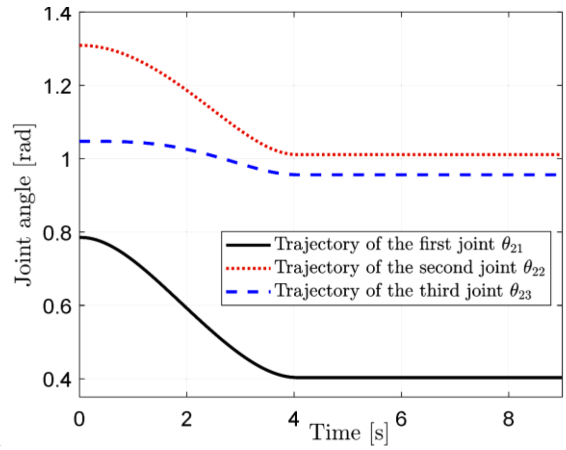

Fig 5. The motion trajectory of jonints angles of the second arm - robot

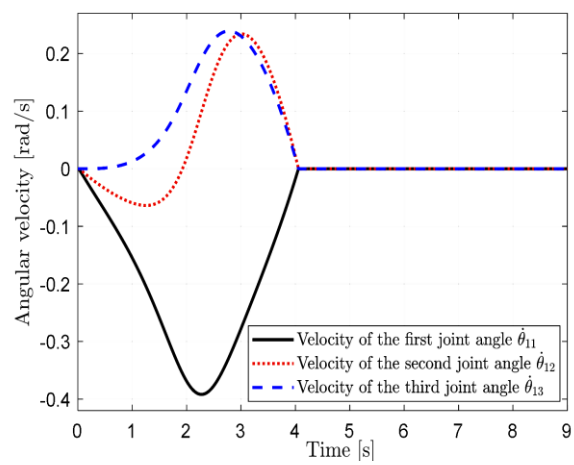

Fig 6. Velocities of joints of the first arm - robot

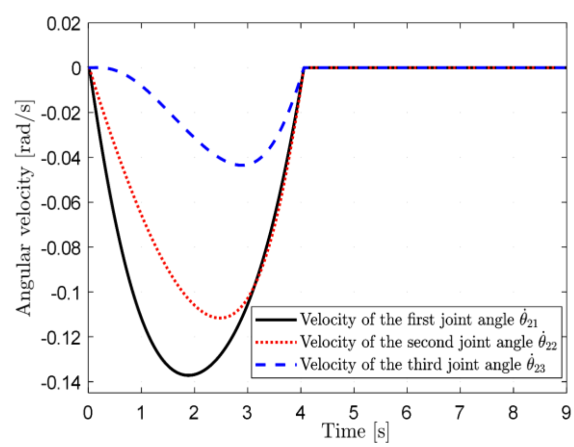

Fig 7. Velocities of joints of the second arm-robot

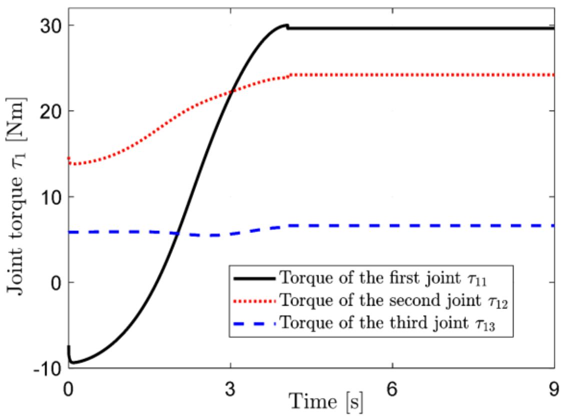

Fig 8. The joints torque of the first arm-robot

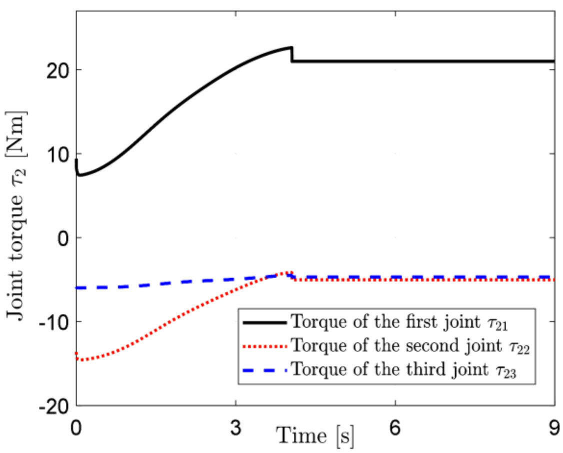

Fig 9. The joints torque of the second arm-robot

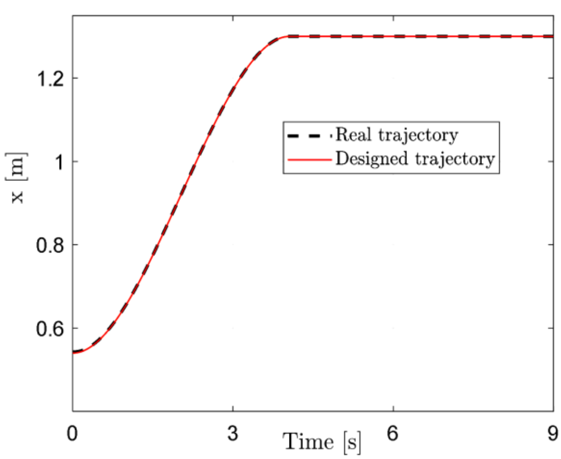

Fig 10. The motion trajectory along *x*-axis of the object

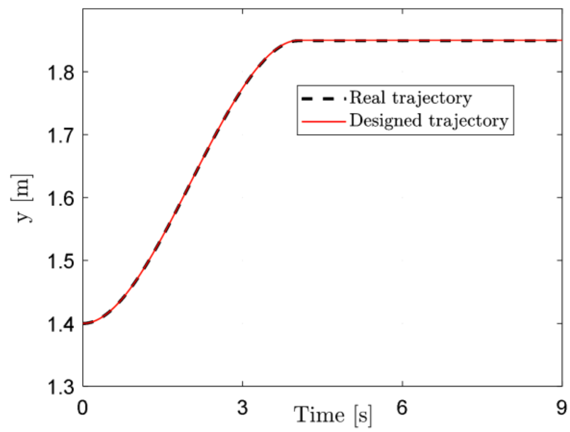

Fig 11. The motion trajectory along *y*-axis of the object

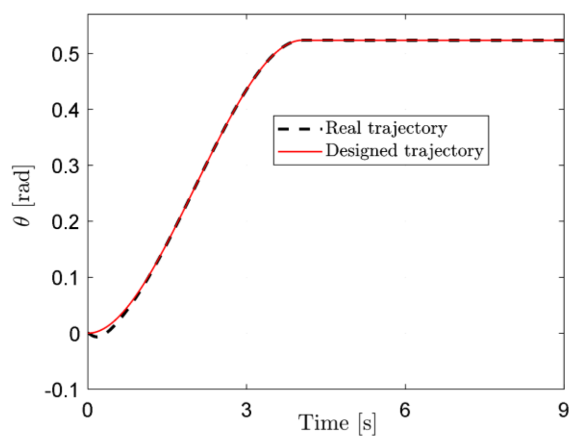

Fig 12. The motion trajectory rotational of the object

The fifth – order polynomial trajectory of the object with the optimal time T_f = 2,5771 s. The optimal trajectory of the position and rotational angle of the object is determined as follows:

$$x = 0{,}54 + 0{,}4440t^3 - 0{,}2585t^4 + 0{,}0401t^5$$

$$y = 1{,}4 + 0{,}2629t^3 - 0{,}1530t^4 + 0{,}0238t^5$$

$$\theta = 0{,}3059t^3 - 0{,}1781t^4 + 0{,}0276t^5$$

The simulation result GA algorithm with the constraints of torque of the joints, joints angle, angular velocity as shown in Fig. 13 to Fig. 21.

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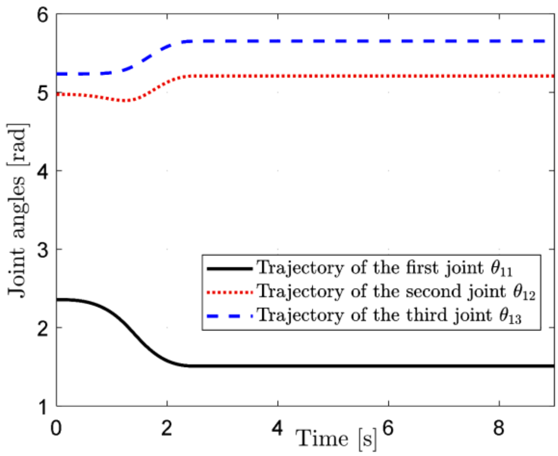

Fig 13. The motion trajectory of jonints angles of the first arm-robot

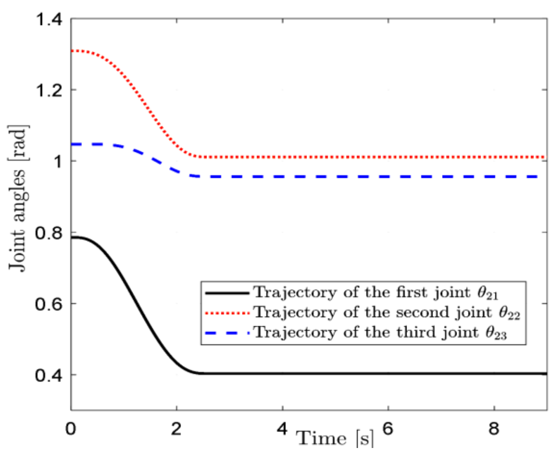

Fig 14. The motion trajectory of jonints angles of the second arm-robot

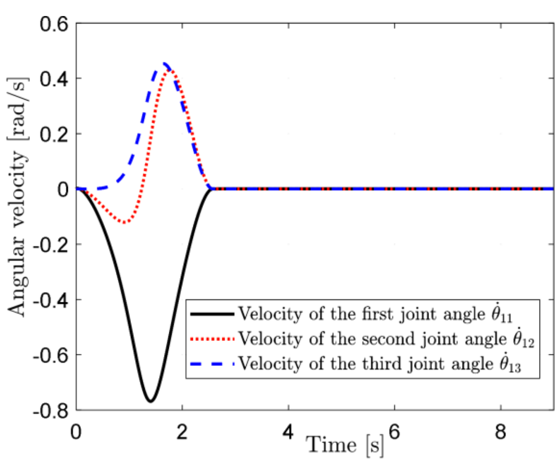

Fig 15. Velocities of joints of the first arm-robot

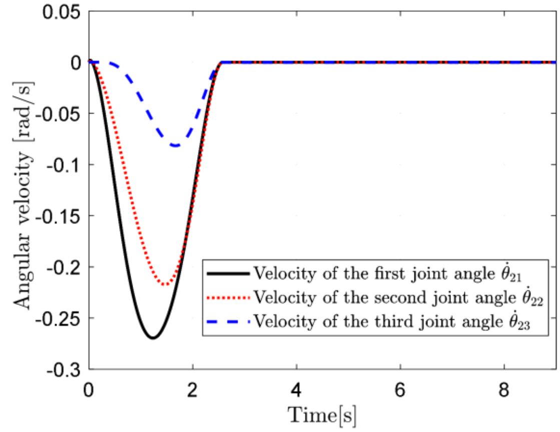

Fig 16. Velocities of joints of the second arm-robot

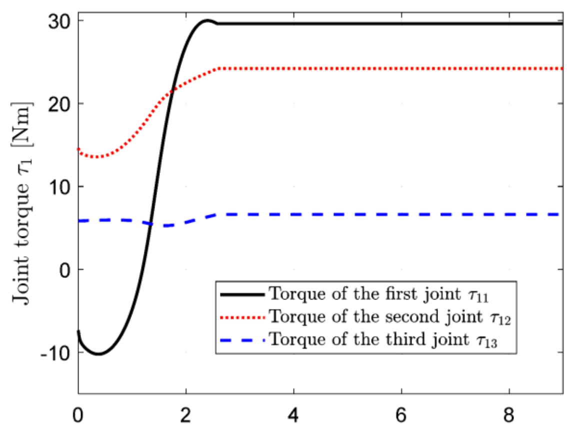

Fig 17. The joints torque of the first arm-robot

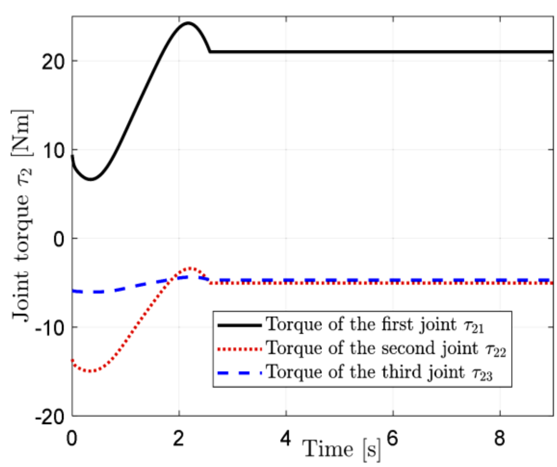

Fig 18. The joints torque of the second arm-robot

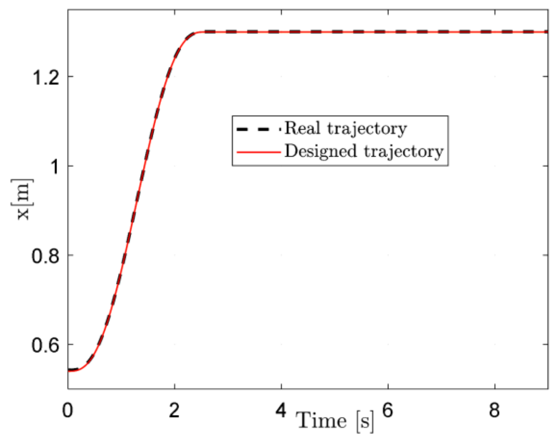

Fig 19. The motion trajectory along *x*-axis of the object

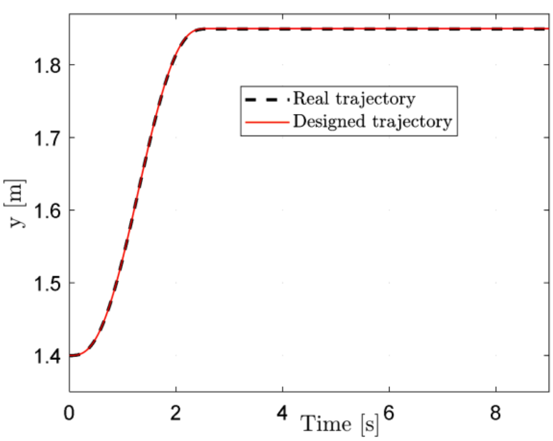

Fig 20. The motion trajectory along *y*-axis of the object

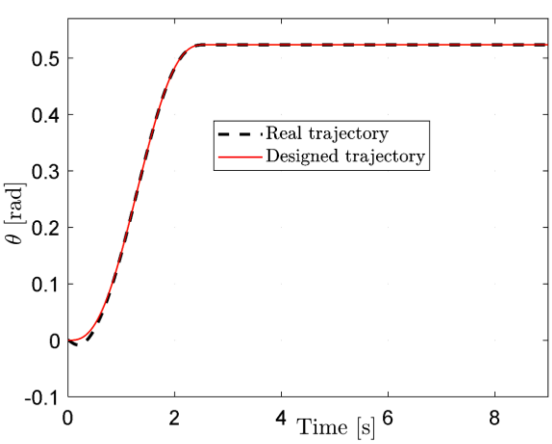

Fig 21. The motion trajectory rotational of the object

From Fig. 4 to Fig. 21 it is possible to see that all the torques, the joints velocity, joints angle are within their limits. The joint 1 torque of dual-arm is a peak, it reaches the limit of torque (Fig. 8 and Fig. 17). It showed that the objective function gives well results, the GA algorithm has been worked well, did not suffer from premature convergence error.

The tracking performances of the position (Fig. 10 – Fig. 12 and Fig. 19 – Fig. 21) of the object can be achieved in *x*, *y* and rotational angle direction. The position and the rotational angle of the object converge to the desired trajectories, the degree of adjustment is zero, and the static deviation is zero.

6. CONCLUSION

The problem of designing the optimal trajectory planning of the object in the dual-arm system with the consideration of adding a controller to the system has been studied in this paper. Based on GA, the object movement times optimization process has been solved. Now, the object's polynomial optimal trajectory has been constructed. In the optimization process, the torque acting on the robot joints is taken from the controller output, and the joint angle and angular velocity are taken from the actual measured value. These torques, position, and velocity values are fed into the GA to check for torque and motion-limiting constraints. Therefore, the obtained trajectory is optimal and realistic, the optimal trajectory of the object has been

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constructed without violating any constraints on the robot actuator. Thus, the paper has solved two problems simultaneously: The problem of optimization of the planning trajectory and the tracking trajectory.

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