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Trajectory Tracking of a Two – Link Gripping Mechanism

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The manufacturing industry frequently deals with the problem of gripping mechanism and their movement optimization. This paper presents an optimization methodology based on the whale optimization algorithm to design an optimal fuzzy PD controller of a two - link gripping mechanism (robot arm) as a part of mobile robot working cycle. The dynamical analysis of gripping mechanism investigates a coupling relation between the joint torques applied by the actuators and the position and acceleration of the robot arm. The proposed fuzzy controller optimizes the trajectory of the robot's end effector. Additionally, a simulation study was done for the specific initial case and the trapezoidal velocity profile was generated. Based on the predefined acceleration, movement of the robot arm is shown to be smooth and without an abrupt braking.

Keywords: Gripping mechanism, Trajectory tracking, Fuzzy controller, Whale optimization algorithm

1. INTRODUCTION

Robots take part in an important role in the current manufacturing industry. Per se, an essential feature of the Industry 4.0 are the autonomous production methods powered by robots that can complete tasks intelligently, with a focus on safety, flexibility, versatility, and collaboration [1].

Intelligent mobile robots can be used for many different purposes, for example, in the production process, one of them is internal transport – material handling. In that case we can consider an intelligent mobile robot as sort of a transportation machine – device. The main characteristic of all transportation machines is their working cycle (single or complex). Moreover, we will be considering intelligent mobile robot as „a single position machine" with a discontinue working regime. Single-position machine is a type of machine that will handle only one peace – product at a time and during handling it is on the machine the whole time [2].

Single working cycle of an intelligent mobile robot consists of: 1) Robot movement – from the starting point, to the position in front of the production machine, in reach of the gripping mechanism from where the transportation unit can be captured from the production machine; 2) Movement of the gripping mechanism - from starting (transport) position to the position needed for capturing the transportation unit; 3) Capturing of the transportation unit; 4) Reverse movement of the gripping mechanism with the transportation unit on it – from the position where the transportation unit is captured all the way to the starting (transport) position; 5) Reverse robot movement – from the position in front of the production machine to the starting point. 6) Activity 2), 3) and 4) are repeated, with the transportation unit releasing instead of capturing. However, if reverse robot movement is not finished at the same point i.e. starting point, then the working cycle is called complex.

Generally, the robot's motion in the environment is realized according to the predefined optimal path based on a defined criterion, and the current state of the robot is determined using preprocessed images obtained by a stereo vision system. In this paper, only a part of intelligent robot working cycle, which refers to movement of the gripping mechanism, will be considered and optimized.

Many different techniques can be and are utilized to control the trajectory of the robot: traditional feedback controls (proportional integral derivative (PID) like controls), adaptive control, robust control, sliding mode control, optimal control, fuzzy control, and many others, as well as, a combinations of previous techniques.

Fuzzy logic controller (FLC) is only one of the intelligent controllers and represents a widespread control technique since it has a satisfactory performance for nonlinear and complex systems. The advantages of a fuzzy PID controller for trajectory tracking control of a mobile robot, and its gripping mechanism are paramount in its rapidity, stability, anti-interference and tracking precision [3-5]. The fuzzy PID controller can be designed with a trial-and-error approach and the optimization can be done by using the cross-entropy method [6]. The varying fuzzy PID and proportional-derivative (PD) controllers tend to use either the Mamdani or Takagi-Sugeno type of the fuzzy systems [7]. Implementation of metaheuristic algorithms can deal with nonconvex, nonlinear, and multimodal problems subjected to linear or nonlinear constraints with continuous or discrete decision variables as global optimization algorithms. Differential evolution and genetic algorithms have been utilized to conduct the optimum design of a fuzzy controller for mobile robot trajectory tracking [8-10]. A 2 DOF planar robot was controlled for a given trajectory where the parameters of Mamdani type FLC were tuned with the particle swarm optimization [11]. The genetic algorithm is applied to improve the performance of the PID controller in terms of control precision and speed of convergence in paper [13]. A fuzzy sliding mode tracking controller for robot manipulators with uncertainty in the kinematic and dynamic models is designed and analyzed in paper [14]. Further, a sliding mode controller, an adaptive fuzzy approximator, is designed in such way that it controls the position tracking of a robot manipulator with two degrees of freedom. Initially, by utilizing an inverse dynamic method, it reduces the uncertainties bound and finally,

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sliding mode control eliminates the influence of the remaining uncertainties in closed-loop system stability [15]. In another paper a multiple-input multiple-output (MIMO) fuzzy logic unit was applied to the robot to track the desired trajectory with high accuracy. Moreover, in order to assess the performance of the proposed MIMO fuzzy sliding mode controller in the presence of parameter variations and external disturbances, a sudden load variation and noise were introduced to the robot system [16]. Feedback linearization controller is used to compute the required arm torque using the nonlinear feedback control law for a robotic manipulator with three degree of freedom. In addition, when all dynamic and physical parameters are known the FLC works remarkably, but given that a large amount of systems have uncertainties and the fuzzy FLC can reduce this kind of limitation [17]. However, various different approaches are included when combating the problem of the robotic arm, including the new methods using the neuro-fuzzy approach to estimate system uncertainties in paper [18].

The main goal of this paper is to design a fuzzy PD controller of a two-link gripping mechanism as a part of mobile robot working cycle. The whale optimization algorithm (WOA), as a novel optimization technique for solving optimization problems defined in [19], is used to determine the proper parameters of FLC in the trajectory tracking control of robot arm with two degrees of freedom (2-DOF).

2. DYNAMICS OF A TWO-LINK GRIPPER

Figure 1 shows the real object - mobile robot with gripping mechanism. As the desired task is to optimize the motion of this mechanism with two link and two degrees of freedom, it can be approximated with the scheme as

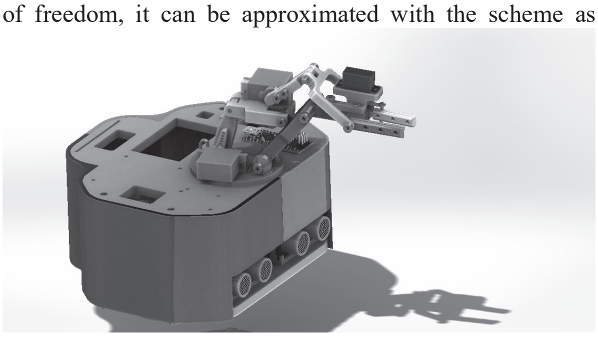

Figure 1: Real object: mobile robot with gripping mechanism

shown in Figure 2, where θ_i, and m_i are respectively the link angle, the length and the mass of the *i*-th link, $i = 1, 2$. Without considering the friction and the disturbances, the dynamic model of a rigid two-link robot can be written as follows [20]:

$$M(\mathbf{q})\ddot{\mathbf{q}} + C(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + G(\mathbf{q}) = \boldsymbol{\tau} \quad (1)$$

where $\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}} \in \mathbb{R}^{2\times1}$ are the robotic link position, the velocity and the acceleration vector, respectively; $\boldsymbol{\tau} \in \mathbb{R}^{2\times1}$ is the torque input vector; $M(\mathbf{q}) \in \mathbb{R}^{2\times2}$ is the positive definite inertia matrix; $C(\mathbf{q},\dot{\mathbf{q}}) \in \mathbb{R}^{2\times2}$ is the centripetal Coriolis force matrix; and $G(\mathbf{q}) \in \mathbb{R}^{2\times1}$ is the gravitational vector.

Assuming that the centres of masses are in the middle of the levers, the elements $M_{ij}(\mathbf{q})$ $(i = 1,2)$ of the inertia matrix $M(\mathbf{q})$ are as follows [20]:

$$\begin{aligned} M_{11} &= \frac{1}{3}m_1 l_1^2 + \frac{1}{3}m_2 l_2^2 + m_2 l_1^2 + m_2 l_1 l_2 \cos q_2 \\ M_{12} &= M_{21} = \frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 \cos q_2,\ \ M_{22} = \frac{1}{3}m_2 l_2^2 \end{aligned} \quad (2)$$

In the case of robot from Figure 2, $\mathbf{q}$ is the vector of angular displacements θ_1 and θ_2, $\mathbf{q} = [\theta_1 \quad \theta_2]^T$.

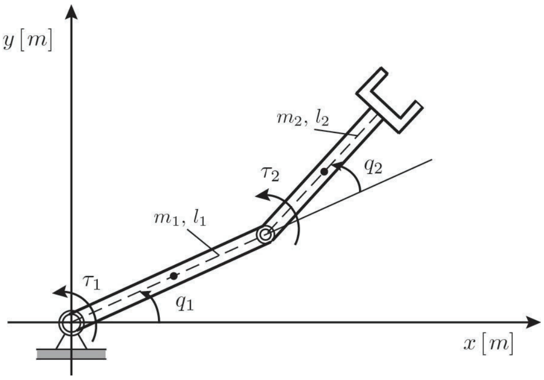

Figure 2: Scheme of the robotic gripper

The elements $C_{ij}(\mathbf{q},\dot{\mathbf{q}})$ $(i, j = 1,2)$ of the matrix $C(\mathbf{q},\dot{\mathbf{q}})$ are presented as,

$$\begin{aligned} C_{11} &= -\frac{1}{2}m_2 l_1 l_2 \dot{q}_2 \sin q_2 \\ C_{12} &= -\frac{1}{2}m_2 l_1 l_2 \sin q_2 (\dot{q}_1 + \dot{q}_2) \\ C_{21} &= -\frac{1}{2}m_2 l_1 l_2 \dot{q}_1 \sin q_2,\ C_{22} = 0 \end{aligned} \quad (3)$$

Finally, the elements of the gravitational torque vector $G(\mathbf{q})$ are given by:

$$\begin{aligned} G_1 &= \left(\frac{1}{2}m_1 l_1 + m_2 l_1\right) g \cos q_1 + \frac{1}{2}m_2 l_2 g \cos(q_1 + q_2) \\ G_2 &= \frac{1}{2}m_2 l_2 g \cos(q_1 + q_2) \end{aligned} \quad (4)$$

3. TRAJECTORY PLANING

In view of practical implementation, the trapezoidal velocity profile is one of the simplest motion profiles. It is composed of the ability to be accelerating to a constant velocity and decelerating to a rest state, and can therefore achieve fast motions. Its advantages are primarily that the time necessary to reach a constant speed is used and distributed so that the movement is smooth, without abrupt starting and stopping i.e. braking. The setting of this movement is actually done by setting the acceleration so that the speed decreases slightly until it reaches zero.

According to the time, the profile divides into three regions and outputs: the maximum acceleration, deceleration, or zero value as acceleration. As shown in Figure 3, in the constant acceleration region the acceleration is the maximum positive value $\ddot{q}_{\max}$ until the velocity reaches the maximum value, $\dot{q}_{\max}$. After that the constant velocity region where the acceleration and velocity are zero, and the maximum value as well, respectively, the velocity decreases to a zero with the maximum deceleration, $-\ddot{q}_{\max}$.

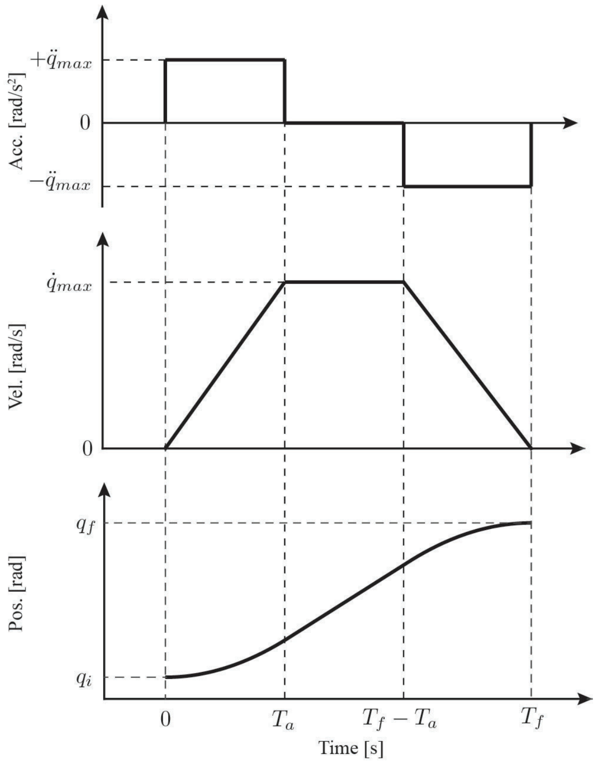

Figure 3:The trapezoidal velocity profile: the acceleration, velocity and position profiles

Using the following important parameters: the initial q_i and the final q_f, the total duration of the movement T_f and the time provided for acceleration T_a, the acceleration, velocity and position profiles can be described as:

$$\ddot{q}(t) = \begin{cases} +\ddot{q}_{\max} & 0 < t \le T_a \\ 0 & T_a < t \le T_f - T_a \\ -\ddot{q}_{\max} & T_f - T_a < t \le T_f \end{cases} \tag{5}$$

$$\dot{q}(t) = \begin{cases} \ddot{q}_{\max} \cdot t & 0 < t \le T_a \\ \ddot{q}_{\max} \cdot T_a & T_a < t \le T_f - T_a \\ \ddot{q}_{\max} \cdot \left(T_f - t\right) & T_f - T_a < t \le T_f \end{cases} \tag{6}$$

$$\dot{q}(t) = \begin{cases} q_i + 0.5 \cdot \ddot{q}_{\max} \cdot t^2 & 0 < t \le T_a \\ q_i + \ddot{q}_{\max} \cdot T_a \left(t - \dfrac{T_a}{2}\right) & T_a < t \le T_f - T_a \\ q_f - 0.5\ddot{q}_{\max} \cdot \left(T_f - t\right)^2 & T_f - T_a < t \le T_f \end{cases} \tag{7}$$

Clearly, from the acceleration output, the velocity and position profiles are generated by integration operations, while taking into account the initial conditions.

Maximum speed, maximum acceleration and the time provided for acceleration have the following relationship:

$$\dot{q}_{\max} = \ddot{q}_{\max} T_a \tag{8}$$

Using the following equation:

$$q_f - q_i = \left(\ddot{q}_{\max} \cdot T_a\right) \cdot \left(T_f - T_a\right) \tag{9}$$

the only unrevealed variable (maxima acceleration $\ddot{q}_{\max}$) can be obtained:

$$\ddot{q}_{\max} = \frac{q_f - q_i}{T_a\left(T_f - T_a\right)} \tag{10}$$

In all previous expressions it is logically assumed that $T_a \le T_f / 2$, that is, the acceleration period is shorter than half of the total time. In the case of equality, the shape of the function becomes a triangle [21].

4. FUZZY LOGIC CONTROLLER

In the following section, we will be using the fuzzy control technique in order to design a fuzzy controller which is able to move a two link robot to track a desired trajectory. Consequentially, we will be designing two fuzzy controllers, one for each separate link. Some of the essential elements when designing a fuzzy controller include, first and foremost, defining the input and output variables, secondly the choice of fuzzification and defuzzification process, and most importantly determining the rule-base of the controller.

In this paper, a proportional derivative (PD) type of FLC is utilized. The inputs of this type of controller are the error and the change in error, whilst the output is the control signal. Nevertheless, in the considered robot trajectory control, the input variables of the FLC are the error and error derivation of link position. The output variable of the fuzzy controller is the link control input, i.e. torque. All membership functions for the controller inputs and outputs are defined on the common normalized interval [-1, 1]. For all of the membership functions we use symmetric triangular functions (except for the two membership functions at the ends, which are trapezoidal) with an equal base and 50% overlap with neighbouring membership functions as shown in Figure 4 and Figure 5.

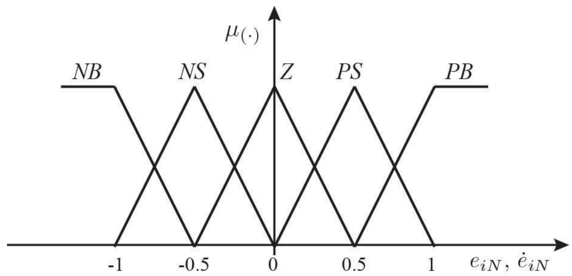

Figure 4: The input membership functions

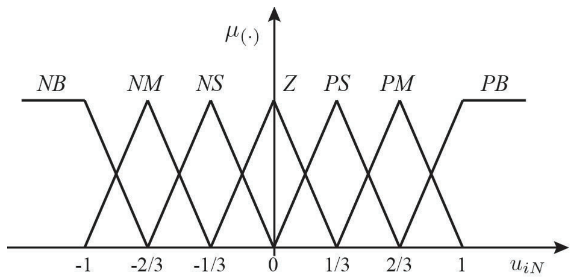

Figure 5: The output membership functions

Further, fuzzy controllers both of the links share a common membership function, where e_{iN} and $\dot{e}_{iN}$, for all $i = 1, 2, ...$ represent the normalized error and the normalized derivative of the error, respectively. The normalized control signals are represented by u_{iN}, for all $i = 1, 2$ respectively, for the link 1 and link 2.

Table 1: Fuzzy IF-THEN rules for the robot trajectory control

e_N \ $\dot{e}_N$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NM	NS	Z
NS	NB	NM	NS	Z	PS
Z	NM	NS	Z	PS	PM
PS	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PB

In a standard fuzzy partition, each fuzzy set determines the value of the linguistic variable. The fuzzy linguistic variables NB, NM, NS, Z, PS, PM and PB represent the negative big, negative medium, negative small, zero, positive small, positive medium and positive big values. Hence, the fuzzy IF-THEN rules for the robot trajectory control are given in Table 1.

In addition, the use of normalized domains requires a scale transformation, i.e. input normalization, which maps the physical values of the input variables into a normalized domain. Furthermore, output denormalization maps the normalized value of the control output variable into its respective physical domain. In stating the above, the relationships between scaling factors and the input and output variables are as follows:

$$e_{iN} = S_{e_i} \cdot e_i,\ \dot{e}_{iN} = S_{de_i} \cdot \dot{e}_i,\ u_i = S_{u_i} \cdot u_{iN},\ i = 1, 2 \quad (11)$$

where e_i, $\dot{e}_i$ and u_i are error, the derivative error and control input, respectively. Practically, the proposed FLCs are implemented in Matlab/Simulink, with the product inference engine and center average defuzzification method. Simulink model of the two link robot system with fuzzy control is shown in Figure 6.

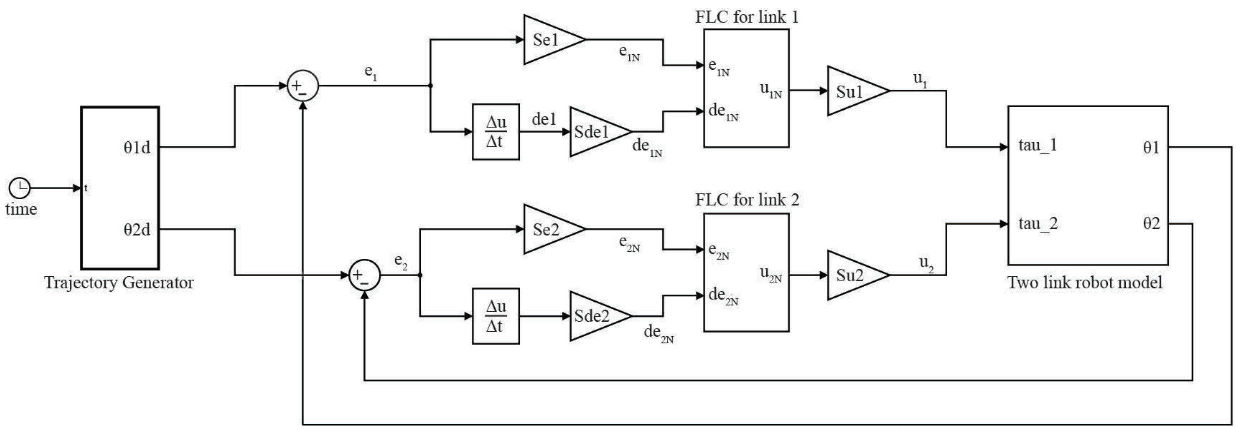

Figure 6: Simulink model of the 2-DOF gripping mechanism with fuzzy control

5. OPTIMIZATION OF FLC

5.1. Whale optimization algorithm

The highly utilised and implemented WOA was first suggested by Seyedali Mirijalili and Andrew Lewis in their paper [19]. The WOA has proven to be outstanding at resolving a variety of modes, multimodal and problems that are not linear. The foremost supremacies of this algorithm, and all metaheuristic algorithms in general, are that it has random distribution, which avoids getting stuck in the local minimum. The hunting method which they deeply rely on is the bubble-net feeding method. Using this method they dive deep, a couple of meters deep into the ocean and then start swimming upwards to the surface creating a bubbles in a spiral shape while encircling the prey.

5.1.1. Encircling the prey

Since the whales can recognize the location of the prey, the WOA algorithm assumes that the current best solution is the target prey, or very close to it. Stressing this, after the best search agent is defined the other search agents will try to update their position towards it. The mathematical model of encircling the prey is proposed using the following equations (where $\mathbf{D}$ is the distance vector and $\mathbf{X}$ is the vector utilized to update the position):

$$\mathbf{D} = \left| \mathbf{C}\mathbf{X}^*(t) - \mathbf{X}(t) \right| \quad (12)$$

$$\mathbf{X}(t+1) = \mathbf{X}^*(t) - \mathbf{A}\mathbf{D} \quad (13)$$

where t indicates the current iteration, $\mathbf{A}$ and $\mathbf{C}$ are coefficient vectors, $\mathbf{X}^*$ is the position vector of the best solution obratined so far, $\mathbf{X}$ is the position vector [19].

5.1.2. Exploitation phase: Hunting using the Bubble-net method

Moreover when stating the mathematical modeling of the exploitation phase it is found that there are two diverse approaches to it; the shrinking encircling mechanism and spiral updating position. An universal assumption suggests that there is a 50% chance that the whale will chose between one of these two approaches, when updating the position. The first approach is related to decreasing linearly the value of a from 2 to 0 over the course of iterations. Hence, the random values for $\mathbf{A}$ are between $[-1,1]$, where the new position of the agent is located between the current best agent and the original position. The second approach is based on the calculations of the position of the prey and the whale.

The mathematical model for these approaches is henceforward, depicted as the following equation:

$$\mathbf{X}(t+1)=\begin{cases}\mathbf{X}^*(t)-\mathbf{AD} & if \quad p<0.5\\ \mathbf{D}'\cdot e^{bl}\cdot\cos(2\pi l)+\mathbf{X}^*(t) & if \quad p>0.5\end{cases} \quad (14)$$

where p is a random number in $[0,1]$, b is a constant for defining the shape of the logarithmic spiral, l is a random number in $[-1,1]$ and $\mathbf{D}'=|\mathbf{X}^*(t)-\mathbf{X}(t)|$ indicates the distance of the i -th whale from the prey [19].

5.1.3. Exploitation phase: Search for the prey

The whales search for the prey randomly according to the position of each others locations. The parameter $\mathbf{A}$ is used to force the search agent to move far away from a reference whale. The position update here is based on the position of a randomly chosen search agent, instead of the best agent so far. The mechanism and $|\mathbf{A}|>1$ emphasizes the exploration and allows the WOA algorithm to perform a global search, henceforward it favors exploration and local optima avoidance. In other words the agent is diverging and moving away from the prey, unlike the converging and the best solution selection when using $|\mathbf{A}|<1$ [19]. The mathematical model is as ensuing:

$$\mathbf{D}=|\mathbf{C}\mathbf{X}_{rand}-\mathbf{X}| \quad (15)$$

$$\mathbf{X}(t+1)=\mathbf{X}_{rand}-\mathbf{AD} \quad (16)$$

5.2. Optimization of FLC using the whale optimization algorithm

In a general sense, fuzzy controllers have a large number of parameters that can be adjusted in an attempt to gain an optimal dynamical response. Those parameters are the shape of the membership functions, the number of the linguistic variables for input and output values of the set of rules, scaling factors, etc. Moreover, in using the predetermined membership functions for the input and output values defined in section 4, and on Figure 4 and Figure 5, as well as, the set of rules (Table 1), it becomes obvious that the performance of the fuzzy PD controller depends on the input and output scaling factors, in turn the design of the fuzzy controller can be simply be attributed to the choice of the input/output scaling factors.

In this paper we have been focused only on the tuning of the scaling factors, considering that is correspondent to the gains of the controller. Further, for the design of the optimal fuzzy PD controller the WOA optimization algorithm was used. Moreover, the mentioned parameters are all coded into one whale, i.e. one agent, that is presented with a vector which contains, in our case, six parameters. For the objective function we utilized the algebraic sum of ITAE (integral of time-weighted absolute error) performance criterion of both links, as defined in the ensuing equation:

$$J=\int_0^\infty t\cdot\left[|e_1(t)|+|e_2(t)|\right]dt \quad (17)$$

6. EXPERIMENTAL RESULTS

Finally, in order to demonstrate the methodology previously discussed, a 2-DOF robot, that is depicted in Figure 2, is used in order to perform the following simulation. The physical parameters for the gripping mechanism are $m_1=0.00799$ kg, $m_2=0.00521$ kg, $l_1=0.05831$ m and $l_2=0.0422$ m.

The desired end-effector trajectory of the 2-DOF manipulator is specified according to trapezoidal velocity profile defined in Section 3. The initial position of the robotic gripper is determined by the mechanism itself. In our case, the initial link configuration is defined as $q_0=[1.3963 \quad -0.5236]^T$ rad and lastly, the initial end-effector position is $x_0=0.0373$ m, $y_0=0.0898$ m.

The control task is to move that point from its initials to the finals coordinates defined by angles $q_f=[0.7854 \quad -0.7854]^T$ rad, and the end-effector position $x_f=0.0834$ m, $y_f=0.0412$ m.

The time required to reach this position is set to be $T_f=6$ s, the maximum acceleration $\ddot{q}_{\max}$ and the time provided for acceleration T_a are calculated based on the equation (10) and the following,

$$T_a=\frac{T_f}{3}=2\text{ s},\ |\ddot{q}_{\max 1}|=0.0763\ \frac{\text{m}}{\text{s}^2},\ |\ddot{q}_{\max 2}|=0.0330\ \frac{\text{m}}{\text{s}^2}$$

In the proposed WOA algorithm the population is set to 10, while the total number of iterations is set to 30. Furthermore, in this optimization method, one agent represents one potential optimal fuzzy controller. All of the parameter values that were used in the implementation of the WOA were taken from the original paper [19]. The convergence curve of the objective function value is depicted in Figure 7.

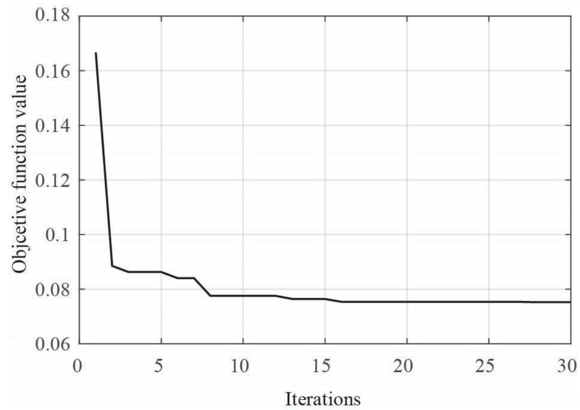

Figure 7: The convergence curve of the objective function value

In addition, after the optimization the obtained parameters for the scaling factors are:

$$S_{e_1}=1.8505,\ S_{de_1}=0.0784,\ S_{u_1}=0.9218$$

$$S_{e_2}=1.5,\ S_{de_2}=0.0025,\ S_{u_2}=1.4385$$

In the following two pictures, we have shown the comparison between the real trajectory and the desired trajectory of the link 1 (Figure 8) and link 2 (Figure 9).

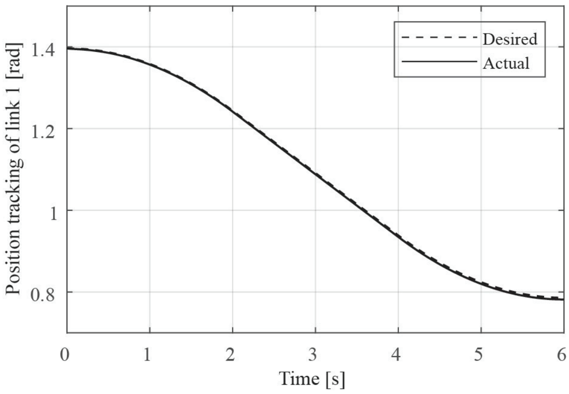

Figure 8: A comparison between the desired and real trajectory of link 1

There we can also observe that the real and desired trajectory curves both almost match, with very slight deviations, nearly neglectable.

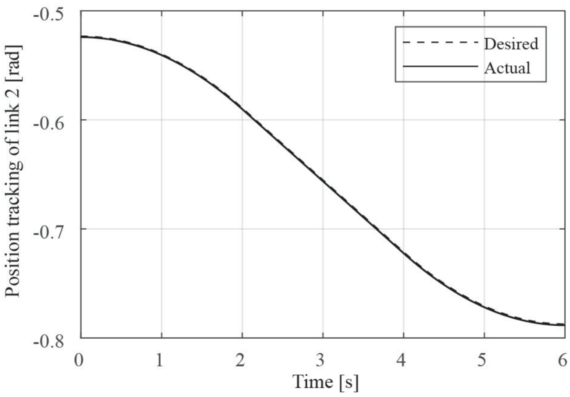

Figure 9: A comparison between the desired and real trajectory of link 2

Moreover, the errors of position tracking for link 1 and link 2, are given in Figure 10 and Figure 11, respectively.

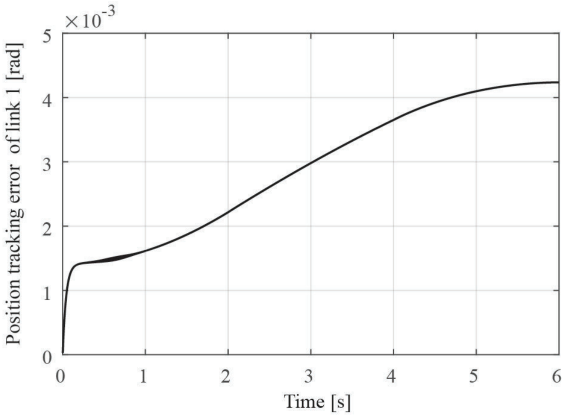

Figure 10: Position tracking error of link 1

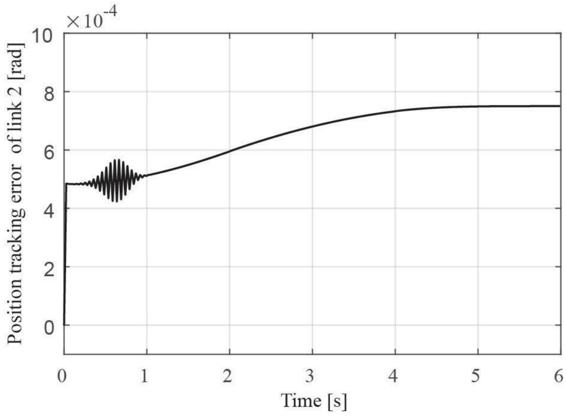

Figure 11: Position tracking error of link 2

The error for the position tracking of the first link is less than 0.005 rad, while for the second link it is less than 0.001 rad. Finally, in Figure 12 and Figure 13 we have depicted the control torque of both link 1 and link 2.

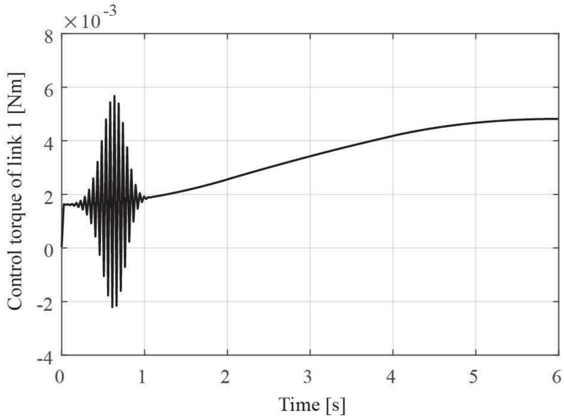

Figure 12: Control torque of link 1

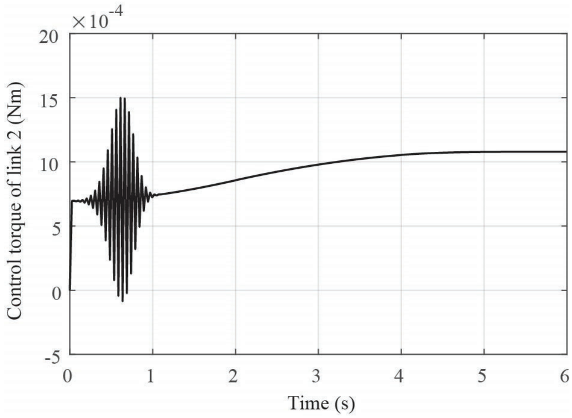

Figure 13: Control torque of link 2

Furthermore, the robustness of the designed fuzzy controllers is tested, as follows. Hence, in order to test the robustness, the mass of the robotic arm of each link is increased three times, as in [11].

The parameters of the fuzzy controller, which were optimized using the WOA algorithm, have remained unchanged, and comparisons of real and desired trajectories are given in Figure 14 and Figure 15.

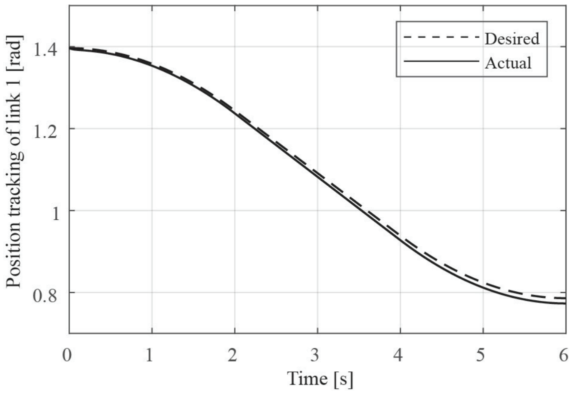

Figure 14: A comparison between the desired and real trajectory of link 1 (increased mass of links three times)

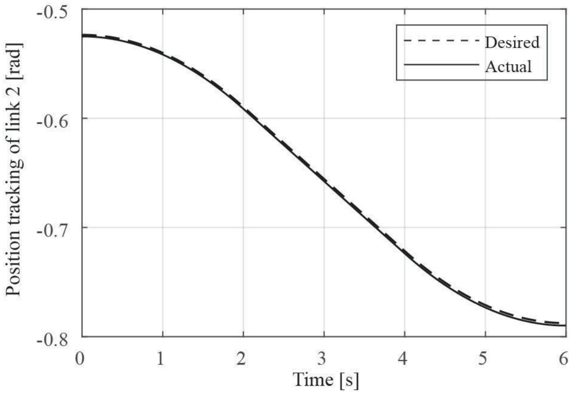

Figure 15: A comparison between the desired and real trajectory of link 2 (increased mass of links three times)

In the pictures above we can clearly notice that even though we enlarged the mass of link 1 and link 2, the optimized algorithm works exceptionally well.

In addition, the errors of position tracking for link 1 and link 2, where the given links have a mass that has been increased three times in order to test the robustness, are given in Figure 16 and Figure 17, respectively.

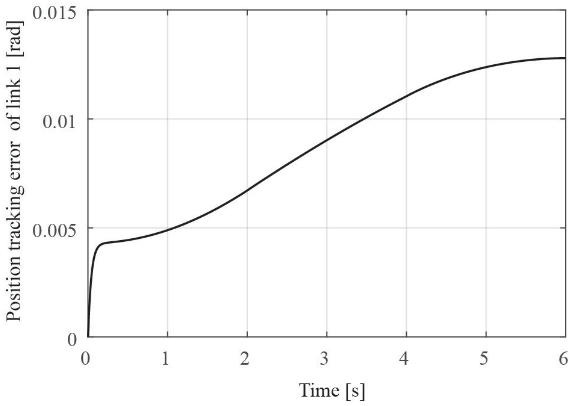

Figure 16: Position tracking error of link 1 (increased mass of links three times)

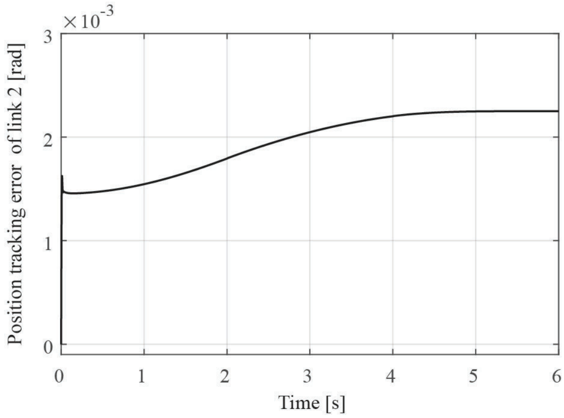

Figure 17: Position tracking error of link 2 (increased mass of links three times)

Here the error for the position tracking of the first link is about $0.015\,\text{rad}$, while for the second link it is about $0.001\,\text{rad}$.

7. CONCLUSION

In this paper, fuzzy controllers were proposed for the trajectory tracking control of a two-link gripping mechanism as a part of mobile robot working cycle. The whale optimization algorithm was used to optimize the scaling factors of the proposed fuzzy PD controller. Namely, optimal input/output gains for the fuzzy PD controller were generated according to ITAE performance criterion. Numerical simulations were done to analyze the trajectory tracking performance of the designed controller. Moreover, the robustness of the controllers was tested in the case of the mass changes. The simulation results have shown that the proposed controller was capable of dealing with the nonlinearities of the robot and the changing of its parameters. One possible area of the future work can be simultaneous optimization of the scaling factors as well as parameters of input and output membership functions.

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REFERENCES

[1] M.A.K. Bahrin, M.F. Othman, N.H.N. Azli and M.F. Talib, "Industry 4.0: A review on industrial automation and robotic," Journal Teknology, Vol. 8(6-13), pp. 137–143, (2016)

[2] U. Bugarić, D. Popović and S. Tošić, "Methodology for analysis of working cycle," XVII International Conference on "Material Flow, Machines and Devices in Industry", Belgrade (Serbia), pp. 4–5, (2002)

[3] Q. Xu, J. Kan, S. Chen and S. Yan, "Fuzzy PID Based Trajectory Tracking Control of Mobile Robot and its Simulation in Simulink," International Journal of Control and Automation, Vol. 7(8), pp. 233–244, (2014)

[4] M. Tong, W. Lin, X. Huo, Z. Jin and C. Miao, “A model-free fuzzy adaptive trajectory tracking control algorithm based on dynamic surface control,” International Journal of Advanced Robotic Systems, Vol. 17(1), pp. 1–11, (2020)

[5] M. S. Abood, I. K. Thajeel, E. M. Alsaedi, M. M. Hamdi, A. S. Mustafa and S. A. Rashid, “Fuzzy Logic Controller to control the position of a mobile robot that follows a track on the floor,” 4th International Symposium on Multidisciplinary Studies and Innovative Technologies , Istanbul (Turkey), 22-24 October 2020, pp. 1–7, (2020)

[6] T.A. Mai, T.S. Dang, D.T. Duong, V.C. Le and S. Banerjee, “A combined backstepping and adaptive fuzzy PID approach for trajectory tracking of autonomous mobile robots,” Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 43, (2021)

[7] B. Jiang, H. R. Karimi, S. Yang, C. Gao and Y. Kao, “Observer-Based Adaptive Sliding Mode Control for Nonlinear Stochastic Markov Jump Systems via T-S Fuzzy Modeling: Applications to Robot Arm Model,” IEEE Transactions on Industrial Electronics, Vol. 68(1), pp. 466–477 (2021)

[8] H. Nejat Pishkenari, S.H. Mahboobi and A.Alasty, “Optimum synthesis of fuzzy logic controller for trajectory tracking by differential evolution,” Scientia Iranica, Vol. 18 (2), pp. 261–267, (2011)

[9] R.M. da Silva, M.A de Souza Leite Cuadros and D.F.T. Gamarra, “Comparison of a Backstepping and a Fuzzy Controller for Tracking a Trajectory with a Mobile Robot,” Intelligent Systems Design and Applications, Vol. 941, pp. 212–221, (2019)

[10] J. Zhao, L. Han, L. Wang and Z. Yu, “The fuzzy PID control optimized by genetic algorithm for trajectory tracking of robot arm,” 12th World Congress on Intelligent Control and Automation, Guilin (China),12 June-15 June 2016, pp. 556–559, (2016)

[11] Z. Bingul and O. Karahan, “A Fuzzy Logic Controller tuned with PSO for 2 DOF robot trajectory control,” Expert Systems with Applications Vol. 38, pp. 1017–1031, (2011)

[12] H. Feng, Cb. Yin, Ww. Weng, W. Ma, Jj. Zhou, Wh. Jia and Zl. Zhang, “Robotic excavator trajectory control using an improved GA based PID controller,” Mechanical Systems and Signal Processing, Vol. 105, pp. 153–168 (2018)

[13] A. Alouache and Q. Wu, “Genetic Algorithms for Trajectory Tracking of Mobile Robot Based on PID Controller,” 14th International Conference on Intelligent Computer Communication and Processing, Cluj-Napoca (Romania), 6-8 September 2018, pp. 237–241, (2018)

[14] F. Piltan, A.R. Nabaee, M.M. Ebrahimi and M. Bazregar, “Design Robust Fuzzy Sliding Mode Control Technique for Robot Manipulator Systems with Modeling Uncertainties,” International Journal Information Technology and Computer Science, Vol. 8, pp. 123–135, (2013)

[15] M.R. Soltanpour, P. Otadolajam and M.H. Khooban, “Robust control strategy for electrically driven robot manipulators: adaptive fuzzy sliding mode,” IET science measurement and technology, Vol. 9 (3), pp. 322–334, (2015)

[16] Y. Hacioglu, Y.Z. Arslan and N. Yagiz, “MIMO fuzzy sliding mode controlled dual arm robot in load transportation,” Journal of the Franklin Institute, Vol. 348 (8), pp. 1886–1902, (2011)

[17] F. Piltan, M.H. Yarmahmoudi, M. Mirzaie, S. Emamzadeh and Z. Hivand, “Design Novel Fuzzy Robust Feedback Linearization Control with Application to Robot Manipulator, ” International Journal of Intelligent Systems and Applications, Vol. 5(5), pp. 1–10, (2013)

[18] D.C. Theodoridis, Y. Boutalis and M.A. Christodoulou, “A New Adaptive Neuro-Fuzzy Controller for Trajectory Tracking of Robot Manipulators,” International Journal of Robotics and Automation, Vol. 26(1), pp. 64–75, (2011)

[19] S. Mirjalili and A. Lewis, “The Whale Optimization Algorithm,” Advances in engineering software, Vol. 95, pp. 51–67, (2016)

[20] L. Sciavicco and B. Siciliano, “Modeling and control of robot manipulators,” Springer-Verlag, London (England), (2000)

[21] https://www.ucg.ac.me/skladiste/blog_13269/objava_8796/fajlovi/35_industtrijska781.pdf, University of Montenegro, pp. 87-102, (last accessed 30/05/21)