

Optimization of PID Parameters of Flexible Gripper with PSO Using Various Objective Functions

Kusay Dib¹, Muhammet Aydın^{2,*}

¹Firat University, Faculty of Engineering, Department of Mechatronics Engineering, Elazig, Turkiye

²Firat University, Faculty of Engineering, Department of Mechatronics Engineering, Elazig, Turkiye

In this paper, a new flexible gripper for robots is designed. It is planned to use a DC motor to provide the movement of the wires in the structure of the designed flexible gripper. The speed control of DC motors is planned to be realized by the PID control method. The gain coefficients in the structure of PID control should be determined in an optimum way. For this purpose, the particle swarm optimization method was used to calculate the gain coefficients of PID control. Five different objective functions are applied to the system to obtain the best-performing gain coefficients. As a result, the optimum gain coefficients were found with the Integral Absolute Error objective function, and the motors were successfully controlled by the PID control method.

Keywords: Flexible gripper, PID control, Particle swarm optimization, Motor speed control, Objective function

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*Corresponding author: muhammeta@firat.edu.tr

1. Introduction

In the last decade, flexible robots have developed as a new subfield in the world of robotics. Robot engineers have been inspired by the efficient use of animals' flexible structures for different tasks. The mechanical design of animals requires flexibility in manufacturing and co-evolves with the nervous system to form an integrated neuromechanical system. These flexible materials not only provide advantages for dealing with non-structural environments but also impart great properties such as formability, high conformability, flexibility, dispersion, and stress mitigation [1]. Ecological niches determine the developmental course of hardness or hardening. Animals that do not require high speeds and stressors for specific tasks often develop flexible bodies. For example, the octopus can compress its body and caterpillars can cling to host plants for anchorage. Jellyfish pump their bodies with water. A few flexible robot systems modeled after various living systems are shown in Figure 1. These robots demonstrate the ability to perform the movements of the creatures they are inspired by.

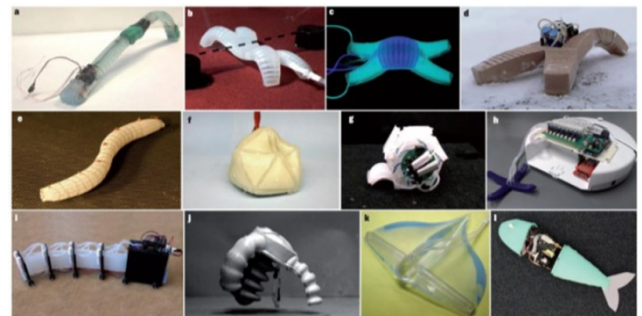


Fig.1. Mobile flexible robot systems modeled inspired by various living systems [2]

In the literature, there is a flexible robotic gripper consisting of a three-finger structure and a passive palm system that can reach a gripping force of 40 N, which is 10 times its weight at a very low operating pressure below 100 kPa in practice [3], a robotic gripper in which a wire is used in the fingers, the fingers do not coincide, there are two fingers on one side and one finger structure on the other side [4], a robotic gripper designed and manufactured with two opposing fingers [5], a robotic gripper designed using pneumatic chambers [6], a robotic gripper in which the finger structure

is moved by a stepper motor [7], a soft robotic gripper developed with a cable [8], robotic gripper developed for minimally invasive surgery [9], robotic gripper developed for grasping unidentified objects [10].

In this study, a new flexible robot gripper with a unique design of three fingers was designed. Wires are used in the structure of the designed robot gripper and the wires in each finger are guided by DC motors. The PID control method is used for the speed control of the DC motor. Particle swarm optimization was used to calculate the gain coefficients in the structure of the PID control method. Five different objective functions were tested and the gain coefficients that provide the best performance were obtained and the speed control of the motors was performed in the best way with the PID control method.

2. Material and Methods

2.1. Flexible gripper design

Flexible robotic grippers are flexible robotic devices made of elastomeric materials that can hold various objects with precision. However, in some cases, it can be difficult for the gripper to accurately detect and grasp the object. In this study, different object stimulation techniques and grip reliability enhancement methods that can be used for the development of a precision flexible gripper are discussed. As a result, the studies will cover technologies that will help precision flexible grippers to be used more reliably and effectively.

Figure 2 shows the flexible robot gripper with a new and different design. The flexible robot gripper consists of three fingers and wires pass through the inside of the fingers. The flexible movement of the fingers is caused by the DC motors at the bottom pulling the wires.



Fig.2. Flexible gripper design

In Figure 3, detailed measurements of the finger structure used in the robot gripper are given. All measurements are in mm dimension. The dashed lines in the design represent the places where the wires pass.

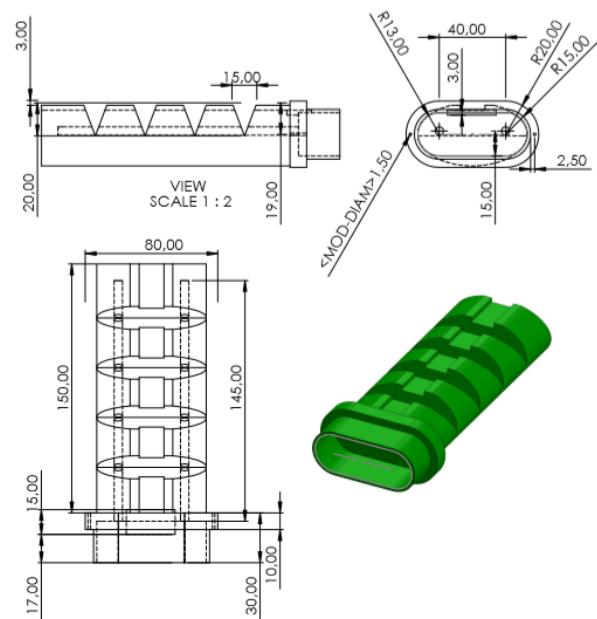


Fig.3. Flexible gripper finger design detail

2.2. PID control

PID control is a feedback control method widely used in industry. Despite the advances in modern control methods, PID controllers are widely used in industrial applications due to their simple and stable structure. The general structure of the controller and the system is shown in Figure 4.

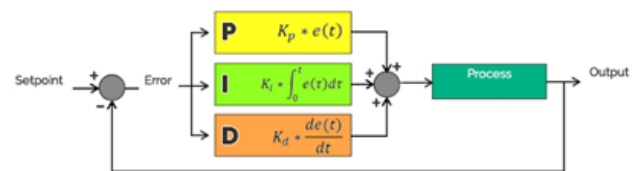


Fig.4. General structure of the PID controller

The PID control method is a combination of proportional, differential, and integral methods. The PID controller is also known as a three-mode controller. The PID control method is used in processes with fast and large load variations where one or two control methods cannot keep the error within acceptable limits. The difference between the output of the system to be controlled and the reference value, which is the input of the PID controller, is calculated as the error (e). The error value is multiplied by the proportional gain coefficient K_P , the derivative of the error by the derivative gain coefficient K_D , and the integral of the error by the integral gain coefficient K_I and the sum of the values obtained is applied as input to the system. The output of the system is again compared with the reference value, a new error value is calculated and the new output produced by the controller is applied as input to the system. This process is repeated until the error is zero. The K_P , K_D , and K_I parameters of the

controller are system-specific and there are many methods to determine these parameters. The most common method used is the Ziegler-Nichols method [11].

Proper control of the system with a PID controller is only possible with the correct determination of the controller parameters K_P , K_I , and K_D [12].

2.3. Particle swarm optimization

Optimization is the optimal use of the limited resources at hand. Optimization mathematically means finding the optimum value of an objective function within a given range of definitions. In terms of operations research and management, it can be defined as arranging a system to obtain the highest efficiency at the lowest cost [13]. Optimization consists of two sub-components: modeling and analysis. Modeling is the mathematical expression of a problem encountered in real life. Analyzing is to get the best result of the model by using various methods.

Particle Swarm Optimization (PSO), introduced by Kennedy and Eberhart, is one of the modern heuristic algorithms. It is a heuristic algorithm inspired by the behavior of bird flocks [14].

When birds search for food, they follow the bird closest to the food. The bird being followed is called the leader bird and the leader bird may change during the food search. The new bird in the flock that sees the food is chosen as the leader bird and all the birds in the flock continue their search for food by heading towards the new leader bird. The birds in the flock communicate among themselves to identify the leader bird and get closer to the food. Each bird in the flock is characterized as a particle and each bird represents a solution. The current position of each bird in the flock is considered as an input for the function whose solution is sought. Therefore, as the bird moves, each position of the bird is passed to the function and a solution is generated for the current position. The solution obtained is evaluated and the fitness value of the solution is determined. The fitness value is a measure of whether the result has been achieved or not. If the desired result is found by the specified criteria, the search ends, if the desired result is not found, the birds continue to wander in the search space [14].

PSO has gained superiority over most other search algorithms because it reaches the result quickly, is less likely to get stuck in local optima, and requires few parameters [15]. In PSO, each particle is initialized with random position and velocity values. In each iteration, the velocity and position values are updated and a fitness value is generated in the fitness function.

In addition, the local optimum value of the particles and the global optimum value of the swarm are updated in each iteration. At the end of a given iteration, the optimum value

of the swarm becomes the solution that PSO presents to the problem [16].

2.4. Determination of PID controller parameters

Optimization algorithms such as PSO find the parameters needed to minimize the given optimization problem. Therefore, it is necessary to define a function for the optimization of the PID parameters. This function is called "objective function". In the literature for optimization of PID algorithms, the sum of the absolute error (Integral Absolute Error (IAE)), the sum of the squared error (Integral Squared Error (ISE)), the sum of the squared time-weighted error (Integral Time-weighted Squared Error (ITSE)), functions such as the sum of the time-weighted absolute error (Integral Time-weighted Absolute Error (ITAE)), the sum of squared time-weighted error squares (Integral of Squared Time-weighted Error (ISTSE)) have been proposed [17]. These functions give the magnitude of the error that occurs with time and minimizing this function in the optimization problem means tuning the PID parameters to give the least error [18].

2.5. Speed control of DC motor using PSO method

To control the speed of the DC motor, the following DC motor model is considered.

$$\frac{\Theta(s)}{V(s)} = \frac{k_t}{(Js + b)(L_a s + R_a) + k_t K_b} \quad (1)$$

To control the DC motor in the best way, five different objective functions were used to find the optimum value of the PID control gain coefficients with the PSO method. The block diagrams of these objective functions are shown in Figure 5 in the simulation model created in the Matlab/Simulink environment.

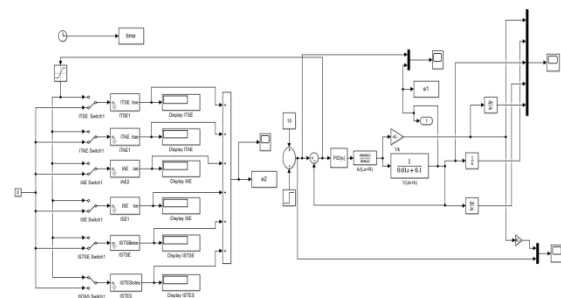


Fig.5. Simulation model created in Matlab/Simulink environment

3. Results and Discussion

First, the ITSE objective function was tested. The ITSE objective function expresses the sum of time-weighted error

squares. The mathematical expression of the ITSE objective function is given in equation 2.

$$f(ITSE) = \int te^2(t)dt \tag{2}$$

Figure 6 shows the block diagrams used to construct the ITSE objective function.

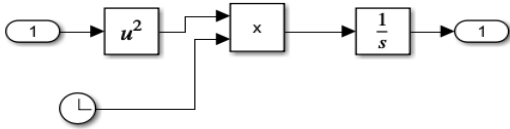


Fig.6. ITSE objective function simulation model

PID control coefficients were obtained after 50 iterations by using the ITSE objective function with PSO. As a result, the performance value was found as 16.577432176709010. The optimization graph obtained with the ITSE objective function using PSO is presented below.

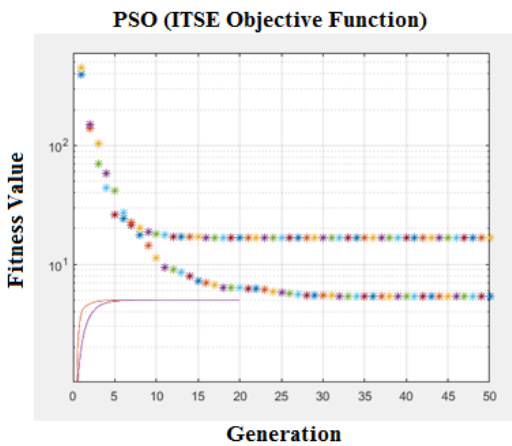


Fig.7. PSO optimization graph with ITSE objective function

As a result, the PID gain coefficients are calculated as $K_P=1.930797076179335$, $K_I=6.328557534074116$, and $K_D=-0.235721471990887$ respectively. When the speed control of the motor is realized by using these values in the structure of the PID control, the graph giving the speed of the motor according to time is obtained as given in Figure 8. When the graph is analysed, it is observed that the motor reaches the desired speed value after 7.654 seconds with an error of 0.01 rad/s.

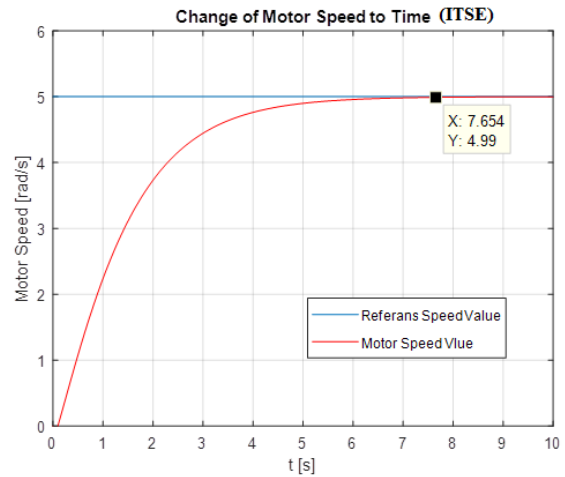


Fig.8. Change of motor speed to time (ITSE)

The objective function tested in the second stage was ITAE. The objective function for ITAE is shown in equation 3.

$$f(ITAE) = \int t|e(t)|dt \tag{3}$$

In addition, the objective function in equation 3 is modeled in a Matlab/Simulink environment as given below.

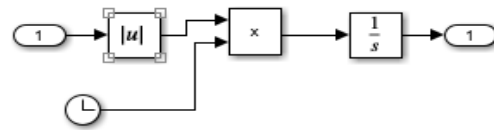


Fig.9. ITAE objective function simulation model

The PID control coefficients were optimized with the ITAE objective function after 50 iterations using PSO. The performance value obtained as a result of this process was determined as 8.452464896087200. Figure 10 shows the optimization graph of PSO with the ITAE objective function.

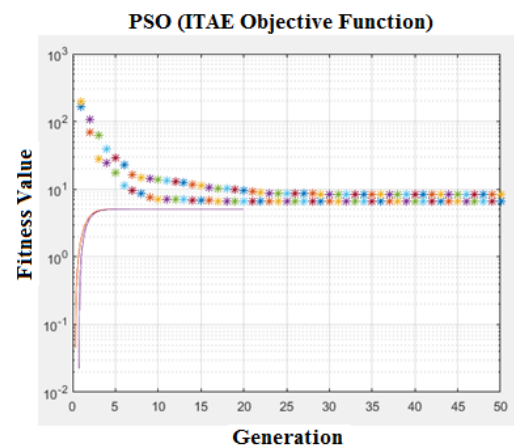


Fig.10. PSO optimization graph with ITAE objective function

As a consequence, $K_P = -1.5369655689375$, $K_I = 5.602065869875116$, and $K_D = -1.594452328966901$ were determined as the PID control gain coefficients, respectively. The graph in Figure 11 depicts the time-varying motor speed after motor speed control was accomplished using these values in the PID control framework. Analysis of the graph reveals that the motor takes 4.227 seconds to attain the desired speed value with a very minor inaccuracy of 0.01 rad/s.

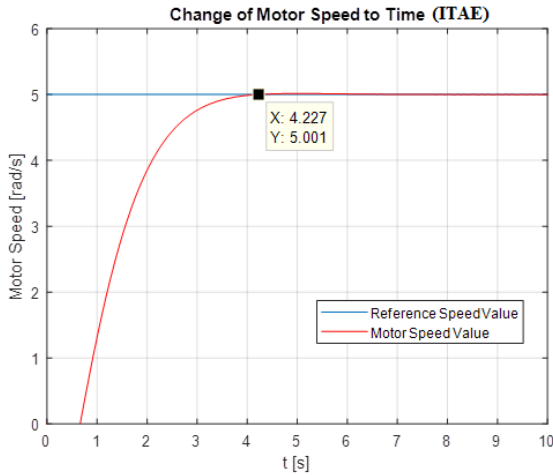


Fig.11. Change of motor speed to time (ITAE)

The IAE objective function was evaluated in the following phase. The total of the absolute mistakes is represented by the IAE objective function. Equation 4 contains the mathematical formulation of the IAE objective function.

$$f(IAE) = \int |e(t)|dt \quad (4)$$

The block diagrams used to build the IAE objective function are displayed in Figure 12.



Fig.12. IAE objective function simulation model

After 50 iterations, PSO and IAE objective functions were used to derive PID control coefficients. The performance value was thus determined to be 4.170398885812407. The graph of optimization that was produced using PSO and the ITAE objective function is shown below.

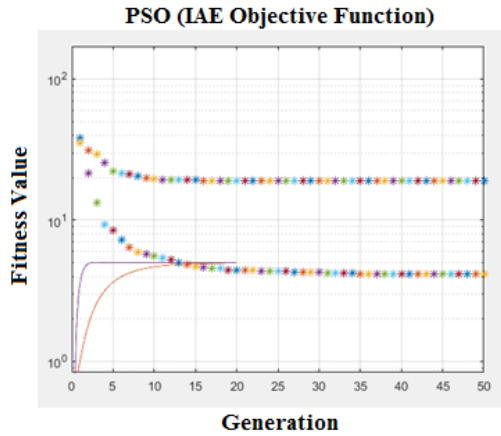


Fig.13. PSO optimization graph with IAE objective function

As an outcome, $K_P = 3.294302430836764$, $K_I = 12.222782529523670$, and $K_D = -0.918755771346210$ have been identified as the PID control gain coefficients, respectively. Using these parameters in the PID control structure, motor speed control was made possible, resulting in the graph in Figure 14 that illustrates the time-varying motor speed. The motor approaches its target speed value after 4.874 seconds with an error of 0 rad/s, according to the graph analysis.

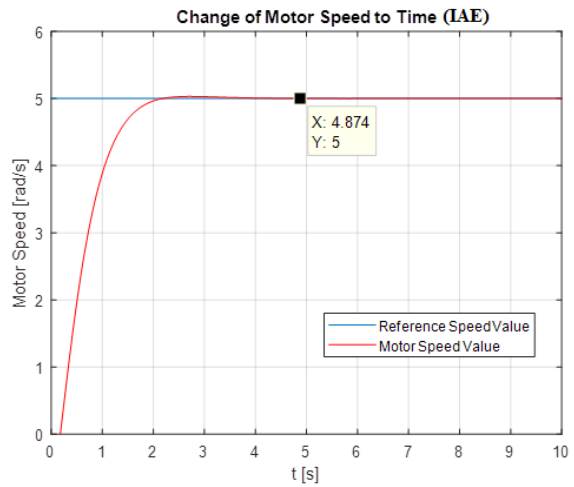


Fig.14. Change of motor speed to time (IAE)

The ISE objective function was then put to the test. Equation 5 contains the mathematical formulation of the ISE objective function.

$$f(ISE) = \int e^2(t)dt \quad (5)$$

The block diagrams that have been utilized to build the ISE objective function can be seen in Figure 15.



Fig.15. IAE objective function simulation model

After 50 iterations, PSO was used to optimize the PID control coefficients using the ISE objective function. This process yielded a performance value that was calculated to be 18.473181606955760. The PSO optimization graph with the ITAE objective function is shown in Figure 16.

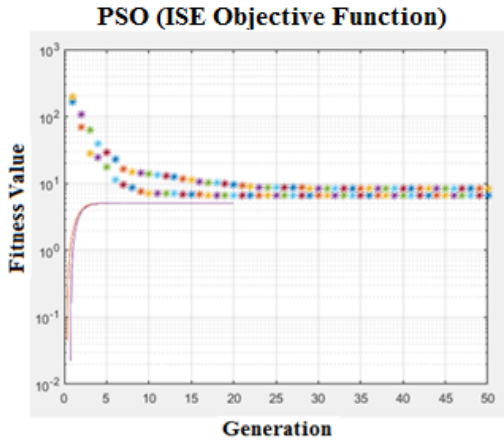


Fig.16. PSO optimization graph with ISE objective function

The PID gain coefficients are therefore determined as $K_P=2.444950921452875$, $K_I=7.564001933890495$, and $K_D=1.314806661865235$, respectively. The graph in Figure 17 shows the speed of the motor as a function of time when the speed control of the motor is implemented using these values in the PID control structure. When the graph is examined, it can be observed that the motor takes 7.012 seconds to attain the intended speed value with a 0.011 rad/s error.

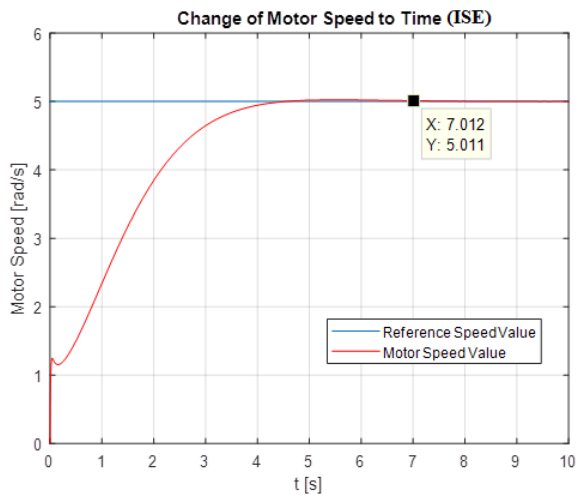


Fig.17. Change of motor speed to time (ISE)

The ISTSE objective function was examined in the last step. Equation 6 contains the mathematical formulation of the ISTSE objective function.

$$f(ITSE) = \int t^2 e^2(t) dt \quad (6)$$

Additionally, the Matlab/Simulink environment is used to represent the objective function in equation 6 as shown below.

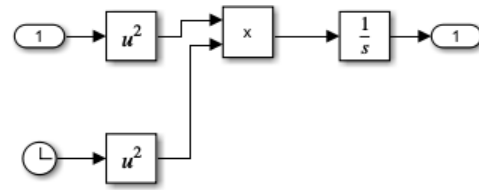


Fig.18. ISTSE objective function simulation model

After 50 iterations, PSO was used to optimize the PID control coefficients using the ISTSE objective function. This process generated a performance value that was determined as 4.876805969476571. The PSO optimization graph with the ISTSE objective function appears in Figure 19.

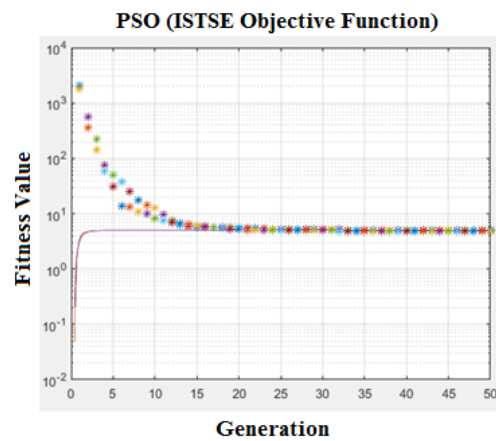


Fig.19. PSO optimization graph with ISTSE objective function

Finally, the PID gain coefficients are derived as follows: $K_P=1.083175042269747$, $K_I=9.096427827835454$, and $K_D=-2.332473877749748$. The graph showing the motor speed according to time is obtained as shown in Figure 20 when the speed control of the motor is realized by applying these values in the PID control structure. When the graph is examined, it can be observed that the motor takes 5.235 seconds to attain the desired speed value with a 0.005 rad/s error.

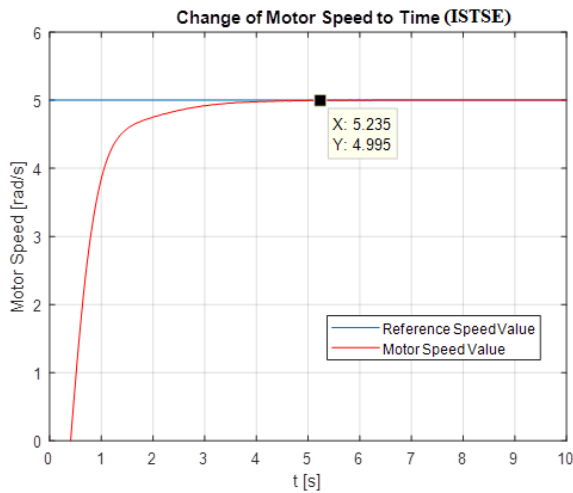


Fig.20. Change of motor speed to time (ISTSE)

When the results of these five objective functions are analyzed, it is the IAE that gives the best result. As a result of using this objective function, the sum of the squares of the errors, which is the performance criterion, was obtained as 4.17. In control systems, the aim is to make the error zero or to try to reach the closest value to zero. Using this objective function, the optimum PID gain coefficients were obtained by the particle swarm optimization method and the sum of the squares of the errors, which is the closest value to zero, was obtained as 4.17 by finding the best one among the five objective functions with IAE.

4. Conclusion

As a result of this study, a new flexible robot gripper with a unique three-finger design was designed. The wires used in the structure of the designed robot gripper directed the movement of each finger. The movement of the wires was provided by DC motors. For this reason, the importance of speed control of the DC motor has emerged. The speed control of the DC motor was realized with the PID control method. For this purpose, particle swarm optimization was used to calculate the gain coefficients in the structure of the PID control method. Five different objective functions were tested and the gain coefficients that provide the best performance were obtained and the speed control of the motors was realized in the best way with the PID control method. IAE gave the best result from the five objective functions. In IAE, the sum of the squares of the errors was obtained as 4.17 with the best performance value. In addition, the aim is to control the motor at the desired speed of 5 rad/s and to realize this with the least error. After 4.874 seconds, the motor achieved the desired speed value with zero error with the PID control gain coefficients found with this objective function.

References

- [1] Kim, S., Laschi, C. and Trimmer, B., Soft robotics: a bioinspired evolution in robotics, *Trends in biotechnology*, 31:5 (2013) 287–294. <https://doi.org/10.1016/j.tibtech.2013.03.002>.
- [2] Rus, D. and Tolley, M. T., Design, fabrication, and control of soft robots, *Nature*, 521:7553 (2015) 467–475. <https://doi.org/10.1038/nature14543>.
- [3] Zhou, J., Chen, S. and Wang, Z., A soft-robotic gripper with enhanced object adaptation and grasping reliability, *IEEE Robotics and automation letters*, 2:4 (2017) 2287–2293. <https://doi.org/10.1109/LRA.2017.2716445>.
- [4] Manti, M., Hassan, T., Passetti, G., D'Elia, N., Laschi, C. and Cianchetti, M., A bioinspired soft robotic gripper for adaptable and effective grasping, *Soft Robotics*, 2:3 (2015) 107–116. <https://doi.org/10.1089/soro.2015.0009>.
- [5] Alizadehyazdi, V., Bonthron, M. and Spenko, M., An electrostatic/gecko-inspired adhesives soft robotic gripper, *IEEE Robotics and Automation Letters*, 5:3 (2020) 4679–4686. <https://doi.org/10.1109/LRA.2020.3003773>.
- [6] Batsuren, K. and Yun, D., Soft robotic gripper with chambered fingers for performing in-hand manipulation, *Applied Sciences*, 9:15 (2019) 2967. <https://doi.org/10.3390/app9152967>.
- [7] Liu, C. H., Chung, F. M., Chen, Y., Chiu, C. H., and Chen, T. L., Optimal design of a motor-driven three-finger soft robotic gripper, *IEEE/ASME Transactions on Mechatronics*, 25:4 (2020) 1830–1840. <https://doi.org/10.1109/TMECH.2020.2997743>.
- [8] Wang, R., Zhang, X., Zhu, B., Zhang, H., Chen, B. and Wang, H., Topology optimization of a cable-driven soft robotic gripper, *Structural and Multidisciplinary Optimization*, 62 (2020) 2749–2763. <https://doi.org/10.1007/s00158-020-02619-y>.
- [9] Rateni, G., Cianchetti, M., Ciuti, G., Menciassi, A. and Laschi, C., Design and development of a soft robotic gripper for manipulation in minimally invasive surgery: a proof of concept, *Meccanica*, 50 (2015) 2855–2863. <https://doi.org/10.1007/s11012-015-0261-6>.
- [10] Liu, C. H., Chen, T. L., Chiu, C. H., Hsu, M. C., Chen, Y., Pai, T. Y. and Chiang, Y. P., Optimal design of a soft robotic gripper for grasping unknown objects, *Soft robotics*, 5:4 (2018), 452–465. <https://doi.org/10.1089/soro.2017.0121>.
- [11] Ziegler, J.G. and Nichols, N.B., Optimum Settings for Automatic Controllers, *Journal of Dynamic Systems, Measurement, and Control*, 115 (1993) 220.
- [12] Erkol, H. O., GA ve PSO ile Kontrol Parametrelerinin Optimizasyonu, *Karaelmas Fen ve Mühendislik Dergisi*, 7 (2017) 179–185.
- [13] Fiğlalı, A., Optimizasyona giriş, *Optimizasyon Seminerleri Dizisi*, (2008) 2–27, Kocaeli.
- [14] Coello Coello, C.A. and Reyes-Sierra, M., Multi-

- Objective Particle Swarm Optimizers: A Survey of the State-of-the-Art, *International Journal of Computational Intelligence Research*, 2:3 (2006) 287-308.
- [15] Ortakçı, Y. and Göloğlu, C., Parçacık Sürü Optimizasyonu İle Küme Sayısının Belirlenmesi, (2012) 1-6.
- [16] Ortakçı, Y., Parçacık Sürü Optimizasyonu Yöntemlerinin Uygulamalarla Karşılaştırılması, Master's Thesis (2011) Karabük Üniversitesi.
- [17] Campo, A. B., PID control design, *IntechOpen*, (2012).
- [18] Maiti, D., Acharya, A., Chakraborty, M., Konar, A. and Janarthanan, R., Tuning PID and Fractional PID Controllers using the Integral Time Absolute Error Criterion, *Proceedings of the 2008 4th International Conference on Information and Automation for Sustainability, ICIAFS 2008*, (2008) 457-462. <https://doi.org/10.1109/ICIAFS.2008.4783932>.