Journal of Applied Mathematics and Computation (JAMC), 2018, 2(5), 188-200
http://www.hillpublisher.org/journal/jamc
ISSN Online:2576-0645
ISSN Print:2576-0653

# Fuzzy Logic Based Position Control of Triglide Robot

**Muhammet AYDIN [a,]*, Oğuz YAKUT[b]**

[a]Firat University, Department of Mechatronics Engineering, Elazig, Turkey
[b]Firat University, Department of Mechatronics Engineering, Elazig, Turkey

**How to cite this paper:** AYDIN, M. & YAKUT, O. (2018) Fuzzy Logic Based Position Control of Triglide Robot. *Journal of Applied Mathematics and Computation*, **2(5)**, 188-200.
http://dx.doi.org/10.26855/ jamc.2018.05.003

***Corresponding author**: Muhammet AYDIN, Firat University, Department of Mechatronics Engineering, Elazig, Turkey
Email: muhammeta@firat.edu.tr

## Abstract

In this paper, three degrees of freedom triglide parallel robot which is usually used in pick and place operations has been controlled. Triglide robot has been controlled by using fuzzy logic control method via a program written in Matlab being used dynamic equations with inverse and forward kinematic solutions of the robot. The derivative of error and error has been preferred as the input in the fuzzy logic structure. As the output, the control signal is generated from the fuzzy logic structure. The limit values of the membership functions of the fuzzy logic controller were found by optimization using the genetic algorithm via a program written in the Matlab package program. The controls have been repeated for three different reference points to demonstrate the success of the fuzzy logic controller on the triglide parallel robot. The system responses have been obtained graphically with the controls applied to the triglide parallel robot and the results have been examined. As a result, it is obviously seen that the system has reached the desired reference values approximately in 0.16 seconds with the fuzzy logic controller.

## Keywords

Dynamics, Genetic algorithm, Kinematics, Fuzzy Logic Control, Triglide.

## 1. Introduction

There are three basic robot structures, which are serial, parallel and hybrid structures. Serial robots have open kinematic chain structure, large workspace, and superior skill capability. Conversely, serial robots have some disadvantages such as low sensitivity, poor ability to exert force, the difficulty of the inverse kinematic solution, the high inertia of the moving parts and the inconvenience of being placed at the bottom of motors.

Although the information on parallel structures is based on the past, it has begun to be developed for robots in recent years. These constructions are the result of connecting moving and fixed platforms with kinematic chains. With the simultaneous triggering of the kinematic chains, the moving platform begins to move. In contrast to serial manipulators with open kinematic chains, parallel manipulators have a closed kinematic chain. Parallel robots have the advantages of high rigidity, ease of inverse kinematic solution, lightness, high accuracy, low inertia of moving parts and high agility. The ease of inverse kinematic solution provides easy to be able to control of parallel robots [1].

Parallel constructions can be preferred in micro robot applications because they are much less sensitive to scaling effects. This is the reason for preference in medical practice, especially in endoscopy applications [2].

Parallel robots move safely with close singularity. When the robot follows a straight path to a singular position, the forces required from the motors reach high values. Parallel robots provide sensitivity at lower prices when compared to serial robots with the same sensitivity. Some sensitivity sections can not be achieved with serial robots [3-6].

Three degrees of freedom parallel robots are often used in situations such as pick and place, machine operations.

Delta robot is one of the popular parallel manipulator types that have been working on over the years. In the Delta robot system, the end effector with three motors mounted on the fixed limb can be taken to any desired position. The arms connected to the motors are driven separately. The arms are connected to the end effector by parallelograms. Due to the use of parallelograms, the fixed platform and the moving platform are always in parallel. The rigidity of the system depends on the rigidity of the selected arms and the spaces in the joints. The smallest deviations in manufacturing quality affect the repeatability of the system at high levels. The triglide from the delta robot family is a simpler version of the delta robot and is a parallel robot with three degrees of freedom. There are three arms in the triglide parallel robot, which can be moved by linear motors.

Figure 1 shows the triglide parallel robot. The great advantage of the triglide robot is that it allows an infinite range of motion in the z-direction [6-8].

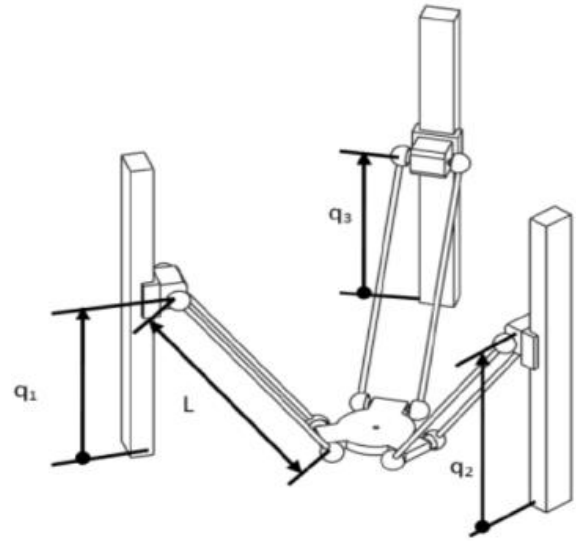


Figure 1.Triglide parallel robot [8].

In this paper, fuzzy logic control is provided by using dynamic equations with inverse and forward kinematic solutions for three degrees of freedom parallel robot, triglide. The coefficients of membership functions required for the applied fuzzy logic controller are optimized using the genetic algorithm technique. This has been done by using the genetic algorithms toolbox of the Matlab package program. In order to be able to demonstrate the success of the optimized fuzzy logic controller on the system, the controller was repeatedly performed for three different reference positions. Triangle membership functions in the fuzzy logic control structure were applied and the system responses were obtained graphically. Displacement error of the robot and error derivative have been given as inputs to the fuzzy structure. Numerical solutions were made with the program prepared in the Matlab environment and the graphical results of the system were obtained. The success of the controller, with graphical results, was analyzed by examination.

## 2. Kinematics for Triglide Parallel Robot

The fixed platform given in Fig. 2 has been chosen as the resulting circle of joining points of robot arms to fixed limbs. The midpoint of the top point of the fixed limb indicates the location of the fixed axis set. z-axis has been selected in the opposite direction of gravity.

The indices of the fixed and mobile platforms are determined by the numbering of the fixed limbs of the robot shown in Figure 1. The layout of the robot fixed limbs has been established to be 120 degrees angle between each fixed limb.

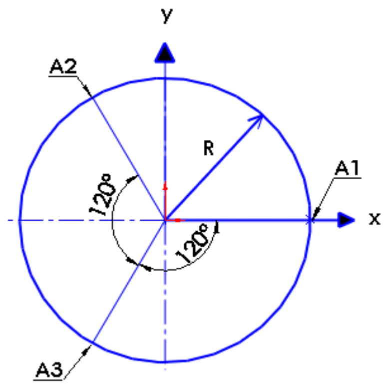


Figure 2. Fixed platform.

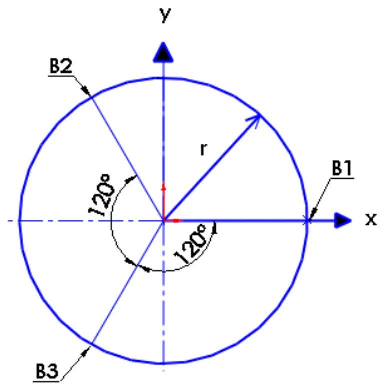


Figure 3. Mobile platform

The mobile platform shown in Figure 3 has been formed by the circle drawn from the points where the robot arms contact the end effector. The inverse kinematic equations of the robot obtained by Stan et al. were confirmed in previous studies, and forward kinematic equations of the robot were found analytically [8,9]. The forward and inverse kinematic solutions that were obtained are given below. There $q_1$, $q_2$ and $q_3$ are amount of displacements related to each arm of the robot. L indicates paralelogram length from joint to joint in the robot structure.
Inverse kinematic solutions;

$$q_1 = z_p + \sqrt{L^2 - (r - R + x_p)^2 - y_p^{\,2}} \tag{1}$$

$$q_2 = z_p + \sqrt{L^2 - \left(\frac{(R-r)}{2} + x_p\right)^2 - \left(\frac{\sqrt{3}(r-R)}{2} + y_p\right)^2} \tag{2}$$

$$q_3 = z_p + \sqrt{L^2 - \left(\frac{(R-r)}{2} + x_p\right)^2 - \left(\frac{\sqrt{3}(R-r)}{2} + y_p\right)^2} \tag{3}$$

Forward kinematic solutions;

$$x_p = \frac{2q_1^{\,2} - q_2^{\,2} - q_3^{\,2} - (4q_1 - 2q_2 - 2q_3)z_p}{6(R-r)} \tag{4}$$

$$y_p = \frac{q_2^{\,2} - q_3^{\,2} + 2(q_3 - q_2)z_p}{2\sqrt{3}(R-r)} \tag{5}$$

$$z_{p1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{6}$$

The terms a, b and c in Eq. (6) are explicitly expressed as follows.

$$a = 1 + \frac{(4q_1 - 2q_2 - 2q_3)^2}{36(R-r)^2} + \frac{(q_1 - q_2)^2}{3(R-r)^2} \tag{7}$$

$$b = \frac{2(-q_1 - q_2 - q_3)}{3} - \frac{(2q_1^{\,2} - q_2^{\,2} - q_3^{\,2})(2q_1 - q_2 - q_3)}{9(R-r)^2} + \frac{(q_2^{\,2} - q_3^{\,2})(q_3 - q_2)}{3(R-r)^2} \tag{8}$$

$$c = -L^2 + (R-r)^2 + \frac{(q_1^{\,2} + q_2^{\,2} + q_3^{\,2})}{3} + \frac{(2q_1^{\,2} - q_2^{\,2} - q_3^{\,2})^2}{36(R-r)^2} + \frac{(q_2^{\,2} - q_3^{\,2})^2}{12(R-r)^2} \tag{9}$$

## 3. Dynamics and 3D Design of Triglide Parallel Robot

Table 1 shows the coordinates of the center of gravity for the robot limbs. When the dynamic equations of the system are obtained, the Lagrange method has been used considering the center of gravity coordinates of the limbs. Frictions have been neglected when dynamic equations are taken out.

Table 1. Coordinates of the center of gravity of the triglide

| | |
|---|---|
| **1.Engine** | $(R, 0, q_1)$ |
| **2.Engine** | $\left(-\frac{R}{2}, \frac{R\sqrt{3}}{2}, q_2\right)$ |
| **3.Engine** | $\left(-\frac{R}{2}, -\frac{R\sqrt{3}}{2}, q_3\right)$ |
| **1.Parallelogram** | $\left(\frac{(x_p + r + R)}{2}, \frac{y_p}{2}, \frac{(z_p + q_1)}{2}\right)$ |
| **2.Parallelogram** | $\left(\frac{(2x_p - R - r)}{4}, \frac{(2y_p + R\sqrt{3} + r\sqrt{3})}{4}, \frac{(z_p + q_2)}{2}\right)$ |
| **3.Parallelogram** | $\left(\frac{(2x_p - R - r)}{4}, \frac{(2y_p - R\sqrt{3} - r\sqrt{3})}{4}, \frac{(z_p + q_3)}{2}\right)$ |
| **Mobile Platform** | $(x_p, y_p, z_p)$ |

The total kinetic energy has been calculated by considering motors, parallelograms and the mobile platform.

$$T = \left(\frac{1}{2}m_{engine} + \frac{1}{8}m_p\right)\left(\dot{q}_1^{\,2} + \dot{q}_2^{\,2} + \dot{q}_3^{\,2}\right) + \left(\frac{3}{8}m_p + \frac{1}{2}m_{mobile}\right)\left(\dot{x}_p^{\,2} + \dot{y}_p^{\,2} + \dot{z}_p^{\,2}\right) + \frac{1}{4}m_p\dot{z}_p(\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \tag{10}$$

In the same way, the total potential energy is taken out as in equation (11).

$$V = m_{engine} g(q_1 + q_2 + q_3) + m_p g\left(\frac{q_1 + q_2 + q_3}{2} + \frac{3z_P}{2}\right) + m_{mobile} g z_P \tag{11}$$

After the Lagrange function is established, the equation of motion for the first arm of the robot is obtained as follows:

$$m_{engine}\ddot{q}_1 + \frac{3}{4}m_p\left(\ddot{x}_p\frac{\partial\dot{x}_p}{\partial\dot{q}_1} + \ddot{y}_p\frac{\partial\dot{y}_p}{\partial\dot{q}_1} + \ddot{z}_p\frac{\partial\dot{z}_p}{\partial\dot{q}_1}\right) + \frac{1}{4}m_p\left[\frac{\partial\dot{z}_p}{\partial\dot{q}_1}(\ddot{q}_1 + \ddot{q}_2 + \ddot{q}_3)\ddot{z}_p + \ddot{q}_1\right] + m_{mobile}\ddot{x}_p\frac{\partial\dot{x}_p}{\partial\dot{q}_1}$$

$$+m_{mobile}\ddot{y}_p\frac{\partial\dot{y}_p}{\partial\dot{q}_1} + m_{mobile}\ddot{z}_p\frac{\partial\dot{z}_p}{\partial\dot{q}_1} + A_1 = F_1 \tag{12}$$

$$A_1 = \frac{3}{4}m_p\left[\dot{x}_p\frac{d}{dt}\left(\frac{\partial\dot{x}_p}{\partial\dot{q}_1}\right) + \dot{y}_p\frac{d}{dt}\left(\frac{\partial\dot{y}_p}{\partial\dot{q}_1}\right) + \dot{z}_p\frac{d}{dt}\left(\frac{\partial\dot{z}_p}{\partial\dot{q}_1}\right)\right] + \frac{1}{4}m_p\frac{d}{dt}\left(\frac{\partial\dot{z}_p}{\partial\dot{q}_1}\right)(\dot{q}_1 + \dot{q}_2 + \dot{q}_3)$$

$$+m_{mobile}\left[\dot{x}_p\frac{d}{dt}\left(\frac{\partial\dot{x}_p}{\partial\dot{q}_1}\right) + \dot{y}_p\frac{d}{dt}\left(\frac{\partial\dot{y}_p}{\partial\dot{q}_1}\right) + \dot{z}_p\frac{d}{dt}\left(\frac{\partial\dot{z}_p}{\partial\dot{q}_1}\right)\right] - m_{mobile}\left(\dot{x}_p\frac{\partial\dot{x}_p}{\partial q_1} + \dot{y}_p\frac{\partial\dot{y}_p}{\partial q_1} + \dot{z}_p\frac{\partial\dot{z}_p}{\partial q_1}\right)$$

$$-\frac{1}{4}m_p\left[3\left(\dot{x}_p\frac{\partial\dot{x}_p}{\partial q_1} + \dot{y}_p\frac{\partial\dot{y}_p}{\partial q_1} + \dot{z}_p\frac{\partial\dot{z}_p}{\partial q_1}\right) + \frac{\partial\dot{z}_p}{\partial q_1}(\dot{q}_1 + \dot{q}_2 + \dot{q}_3)\right] + m_{engine}g + m_p g\left(\frac{1}{2} + \frac{3}{2}\frac{\partial z_p}{\partial q_1}\right)$$

$$+m_{mobile}\frac{\partial z_p}{\partial q_1} \tag{13}$$

Using abbreviations, equation (12) can be expressed as follows.

$$a_1\ddot{q}_1 + b_1\ddot{q}_2 + c_1\ddot{q}_3 = d_1 \tag{14}$$

If the same calculation methods applied to the first arm of the robot are performed to the other two arms of the robot, the following equations are obtained.

$$a_2\ddot{q}_1 + b_2\ddot{q}_2 + c_2\ddot{q}_3 = d_2 \tag{15}$$

$$a_3\ddot{q}_1 + b_3\ddot{q}_2 + c_3\ddot{q}_3 = d_3 \tag{16}$$

Acceleration expressions for each arm of the robot can be found as follows with the help of these three equations.

$$\ddot{q}_1 = \frac{d_3(b_1c_2 - b_2c_1) - d_2(b_1c_3 - b_3c_1) + d_1(b_2c_3 - b_3c_2)}{(a_1b_2c_3 - a_1b_3c_2 - a_2b_1c_3 + a_2b_3c_1 + a_3b_1c_2 - a_3b_2c_1)} \tag{17}$$

$$\ddot{q}_2 = \frac{d_2(a_1c_3 - a_3c_1) - d_3(a_1c_2 - a_2c_1) - d_1(a_2c_3 - a_3c_2)}{(a_1b_2c_3 - a_1b_3c_2 - a_2b_1c_3 + a_2b_3c_1 + a_3b_1c_2 - a_3b_2c_1)} \tag{18}$$

$$\ddot{q}_3 = \frac{d_3(a_1b_2-a_2b_1)-d_2(a_1b_3-a_3b_1)+d_1(a_2b_3-a_3b_2)}{(a_1b_2c_3-a_1b_3c_2-a_2b_1c_3+a_2b_3c_1+a_3b_1c_2-a_3b_2c_1)} \quad (19)$$

More information can be found in an earlier published paper on the dynamics of the triglide parallel robot, the above abbreviations are expressly stated in that paper [10].
The Triglide parallel robot has been designed as a solid model in the Solidworks program. Fig. 4 shows the appearance of this solid model. Triglide robot solid model dimensions have been used to be controlled the robot by the fuzzy logic method.

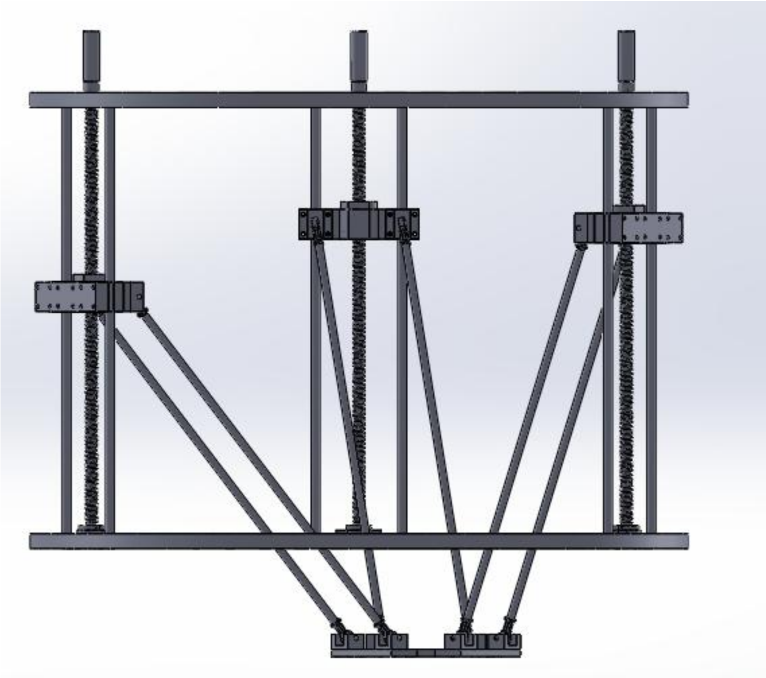

Figure 4. Solid model of the triglide parallel robot

## 4. Control of Triglide Robot by Fuzzy Logic Control Method

The notion of fuzzy logic works like the mechanism of human emotion and inference. Contrary to other classical control methods, fuzzy logic controls by taking intermediate values between two values into consideration. The output of a fuzzy controller consists of blurring the input and output values using the associated membership functions. The input value with a clear value will have a different meaning through the membership function that is associated. Therefore, the output of the fuzzy logic controller depends on the membership values of the different membership functions.
Fuzzy logic and fuzzy notion are overlooked although a lot of people put into practice in their daily life. For example, some questions in the surveys can not have a clear answer. They often offer intermediate choices to people with multiple answer choices such as 'not very satisfied', 'not satisfied', 'satisfied' and 'quite satisfied', which are often blurry or ambiguous. The majority of the questionnaires are similar. These uncertain answers can not be created by machines, but people can create and apply these answers. A computer can not answer surveys like people could do. Because computers have no concept of intermediate values. They can only operate with 0 or 1, or high or low. These data, which can be processed by all machines, are called crisp or classical data. With the administration of a human, computers can be allowed to process these ambiguous data. If some fuzzy logic methods and information about fuzzy logic systems are transferred by humans to computers and machines, then this ambiguous data can be solved.
The fuzzy logic idea which was discovered by L. A. Zadeh come out of at the University of California at Berkeley in 1962 [11]. This discovery was not valid until professor E. H. Mamdani at the University of London implemented to fuzzy logic control practically. Almost ten years after the invention of fuzzy theory, in 1974 Mamdani applied fuzzy

logic for the first time to control the automatic steam engine [12]. Subsequently, in 1976, Blue Circle Cement and SIRA in Denmark improved an industrial application to control cement kilns [13]. In 1982, this system was in operation
Plenty of fuzzy applications have been published and reported since the 1980s, such as industrial manufacturing, automatic control, automobile production, banks, hospitals, libraries and academic education. Fuzzy logic and fuzzy logic control techniques nowadays can be found application possibilities in every field of society.
In recent years, there are many studies related to robot control with the fuzzy logic method. Some of these are mobile robot trajectory control, motion control of an autonomous robot, control of spherical rolling robots, robot manipulator control, tracking control for robot fingers, control of hexapod robots, constrained multi-legged robot system control, nonlinear networked control of robots and control of flying robots [14-24].
In this paper, the fuzzy logic method has been implemented to Triglide parallel robot for position control. The success of the controller is determined by calculating the optimal value of the specified coefficients of membership functions. Those coefficients of the fuzzy logic controller are optimized by using the genetic algorithm. Fig. 5 shows the block diagram of the notation that the coefficients of the controller are optimized by the genetic algorithm technique.

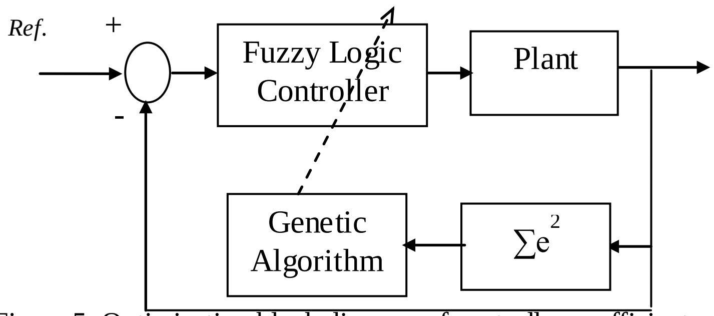

Figure 5. Optimization block diagram of controller coefficients.

To optimize the coefficients of membership functions is benefited from genetic algorithm toolbox in the Matlab package programme. A function that takes the sum of the squares of the errors obtained from the outputs of the system for a randomly determined reference point to zero is defined as the objective function for the genetic algorithm. After the optimum values of the coefficients belonging to the controller are determined by this method, the controller is made ready for application by being disabled the genetic algorithm.
Since our robot is 3-axis, each fuzzy logic structure is applied to each motor. The rule table, membership functions for inputs and output are shown in Table 2, Fig. 6, 7, and 8, respectively. Triangle membership functions have been used for each input and output.

Table 2. Rule table with each membership function for u control signal outputs

| e \ de/dt | $NB_{de}$ | $Z_{de}$ | $PB_{de}$ |
|---|---|---|---|
| $NB_e$ | $Z_u$ | $NB_u$ | $NB_u$ |
| $Z_e$ | $NB_u$ | $Z_u$ | $PB_u$ |
| $PB_e$ | $PB_u$ | $PB_u$ | $PB_u$ |

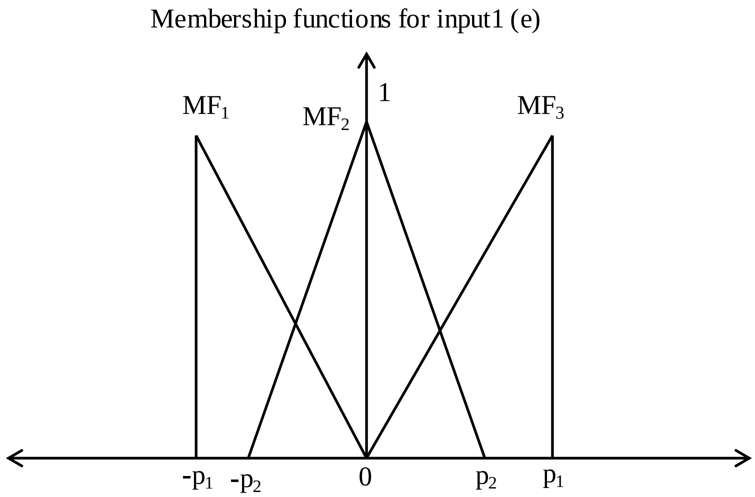

Figure 6. Membership functions for input1 (e)

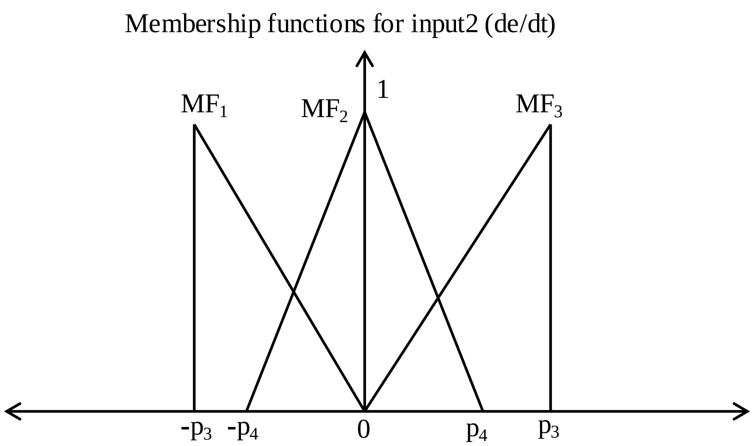

Figure 7. Membership functions for input2 (de/dt)

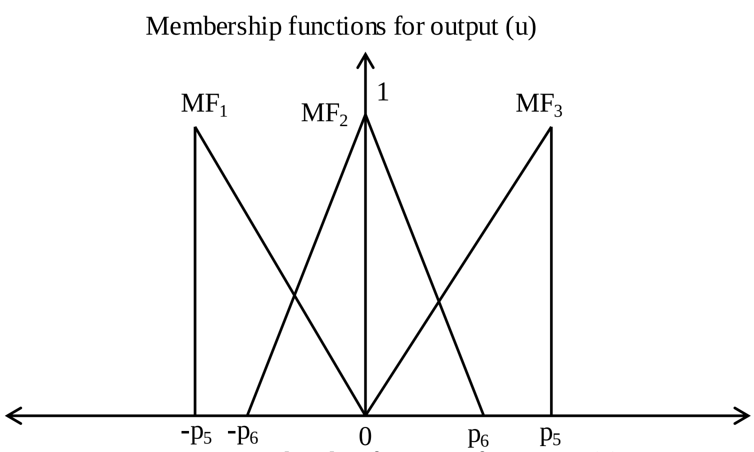

Figure 8. Membership functions for output (u)

The values of the coefficients of membership functions used in these fuzzy structures are calculated by the genetic algorithm and obtained as in Tab. 3. The values of $p_1$, $p_2$, $p_3$, $p_4$, $p_5$, and $p_6$, which are optimized by the genetic algorithm, are given below.

Table 3. Values of the Coefficients of membership functions

| $p_1$ | $p_2$ | $p_3$ | $p_4$ | $p_5$ | $p_6$ |
|---|---|---|---|---|---|
| 0.1542 | 0.1134 | 8.5995 | 32.6079 | 13.8226 | 6.2298 |

These coefficients were applied to the fuzzy logic controller for 3 different reference positions and the system responses were obtained graphically. In the first application, when the fuzzy logic control is applied to take the end effector of the robot to reference positions x=0.2 m, y= - 0.1m and z= 0.5 m, the displacement responses of the system are obtained graphically as shown in Fig. 9. Fig. 10 shows the graph of the control forces that must be applied to each motor.

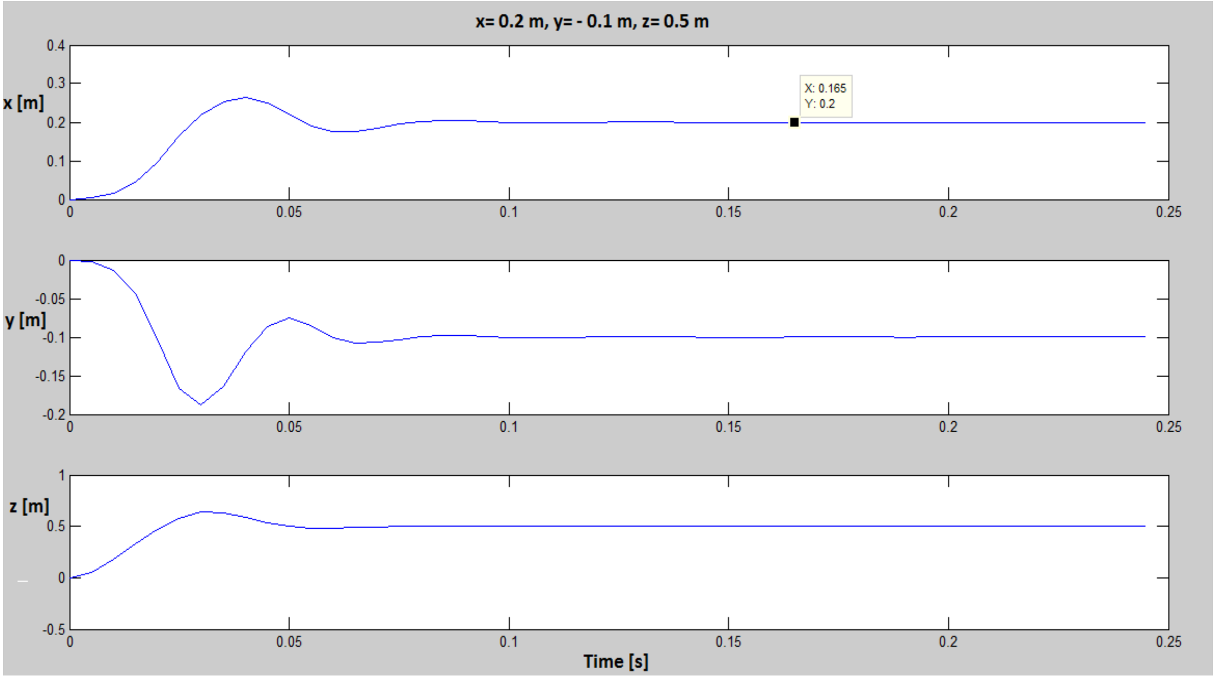


Figure 9. Displacement responses of the system for x=0.2 m, y= - 0.1 m and z= 0.5 m.

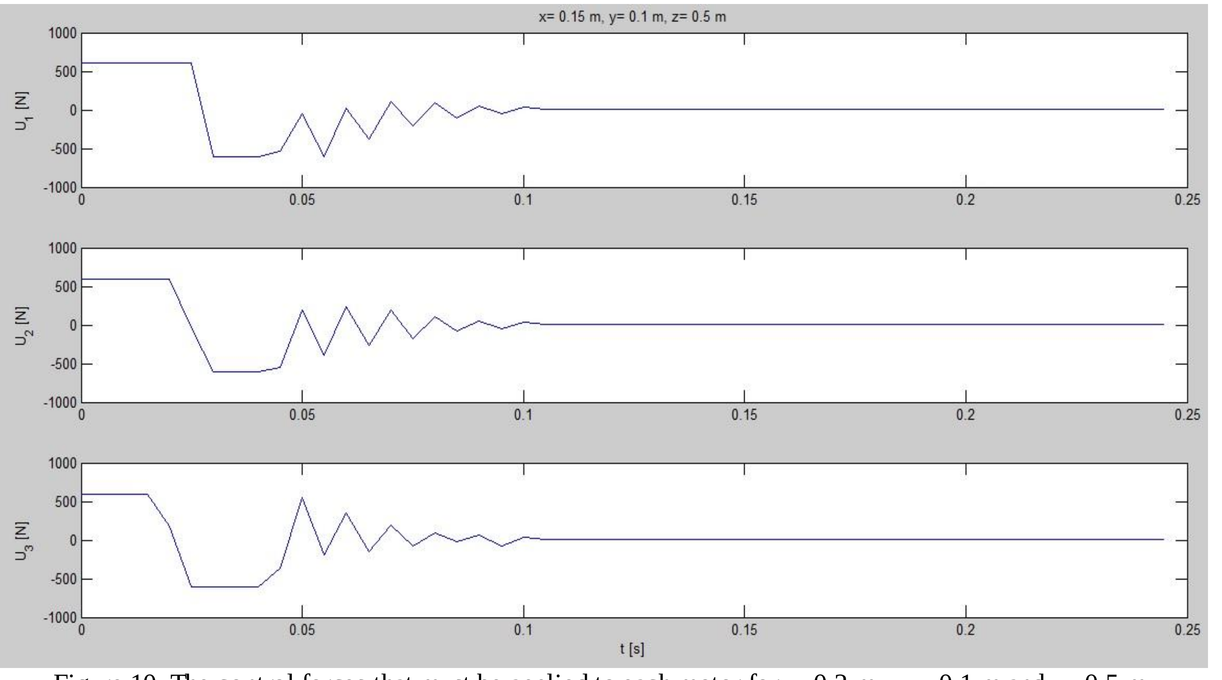


Figure 10. The control forces that must be applied to each motor for x=0.2 m, y= - 0.1 m and z= 0.5 m.

Similarly, in the second application, fuzzy logic control was applied to get the end effector of the triglide to reference positions x = 0.2 m, y = - 0.1 m and z = - 0.7 m. According to this, Fig. 11 shows the displacement responses of the system and graphical results showing the time-dependent variation of the control forces are given in Fig. 12.

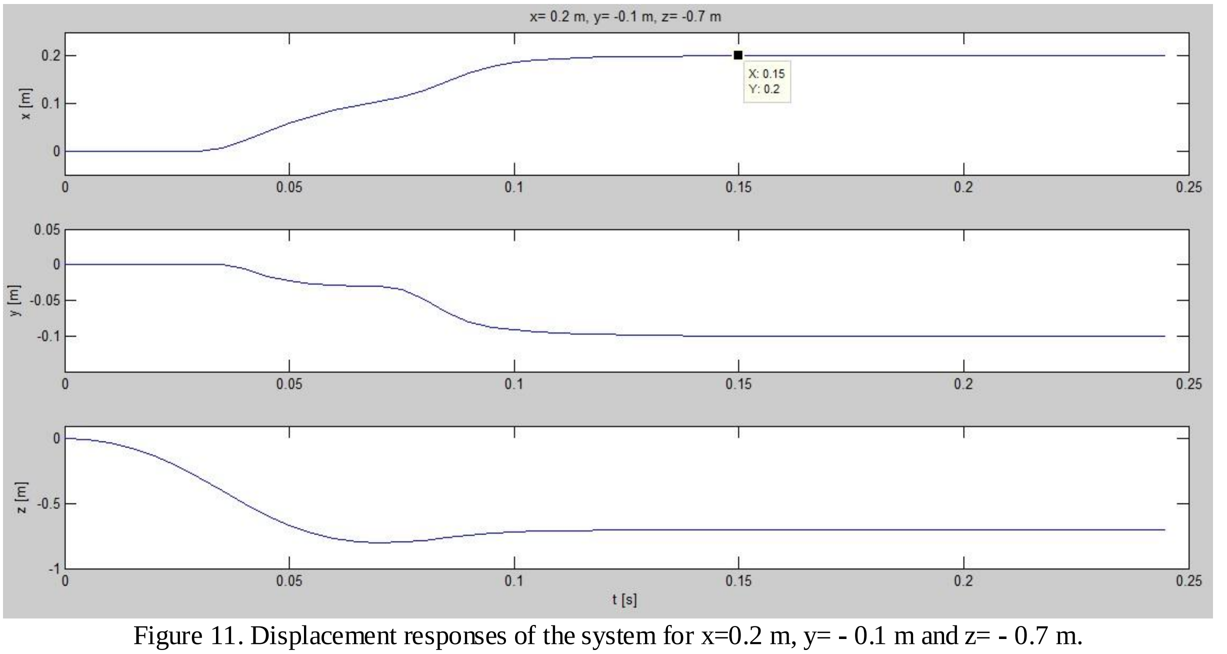


Figure 11. Displacement responses of the system for x=0.2 m, y= - 0.1 m and z= - 0.7 m.

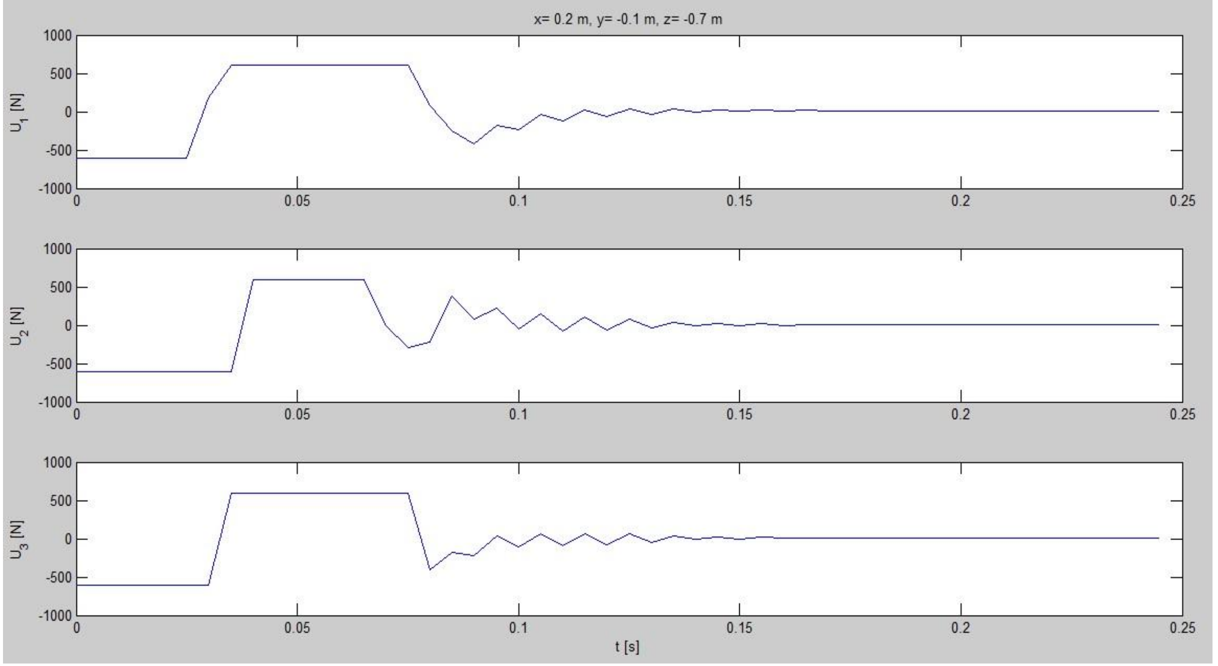

Figure 12. The control forces that must be applied to each motor for x=0.2 m, y= - 0.1 m and z= - 0.7 m.

In the third application, when the fuzzy logic control is applied to take the end effector of the robot to reference positions x= - 0.2 m, y= 0.2 m and z= - 1.2 m, the displacement responses of the system are obtained graphically as shown in Fig. 13. Fig. 14 shows the graph of the control forces that must be applied to each motor.

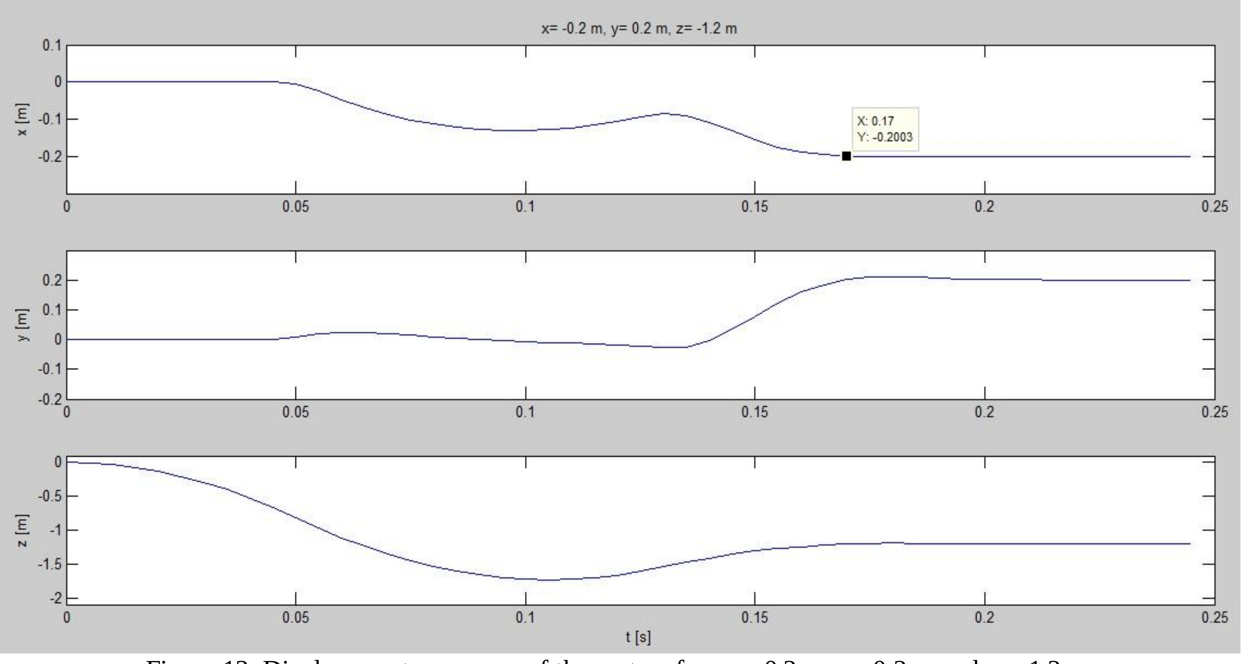

Figure 13. Displacement responses of the system for x= - 0.2 m, y= 0.2 m and z= -1.2 m.

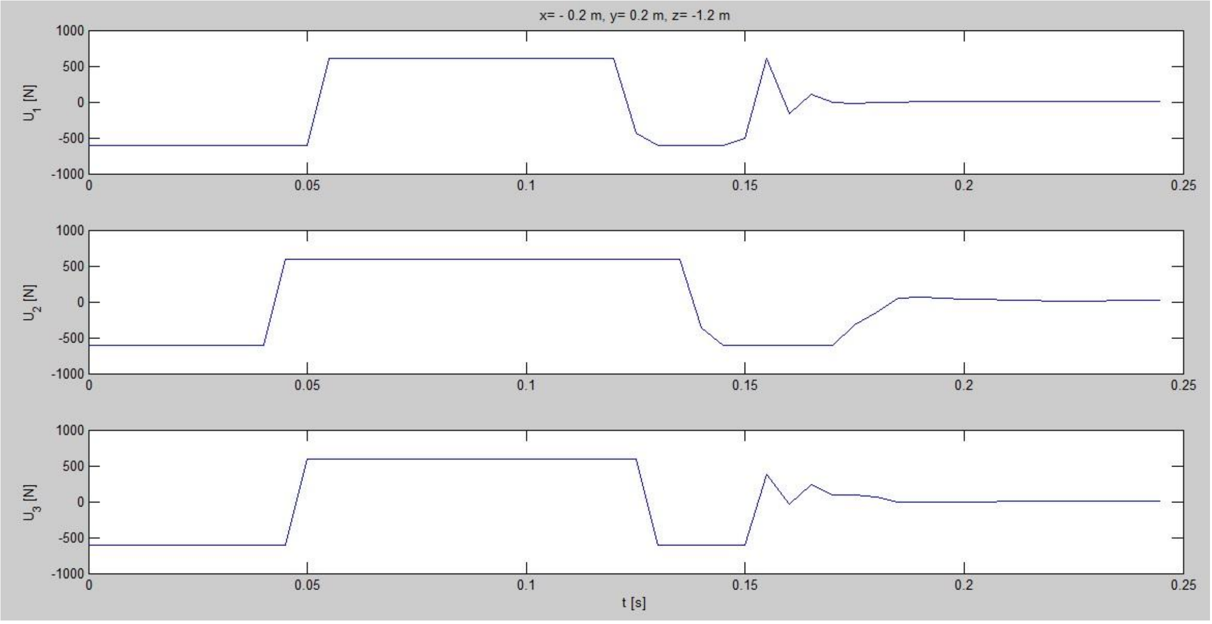

Figure 14. The control forces that must be applied to each motor for x= - 0.2 m, y= 0.2 m and z= - 1.2 m.

## 5. Conclusion

When the results of the inspection with the fuzzy logic of the triglide parallel robot are examined, it is seen that x, y, and z reach the desired reference values in intervals of about 0.17 seconds.

It is seen that the control force graphs obtained using the fuzzy logic controller are practically applicable. In this study, the triglide parallel robot was controlled by a fuzzy logic controller using the kinematic and dynamic solutions obtained from previous studies. When the fuzzy logic controller is applied to the system, the coefficients of membership functions of the controller are optimized with the genetic algorithm. This paper will provide the contribution to the literature on the control of the triglide robot by the fuzzy logic control method.

## Acknowledgements

This work was funded by a research grant from Firat University Scientific Research Projects Unit (FUBAP – MF.16.06).

## References

[1] Sciavicco, L. and Siciliano, B. (2000) Modeling and Control of Robot Manipulator (2thed.). Springer.

[2] Merlet, J.P. (2006) Parallel Robots (2th ed.). Springer, pp. 75-76.

[3] Proceedings of IEEE International Conference on Robotics and Automation (1992) "On the infinitesimal motion of parallel manipulators in singular configurations" Nice, France, Merlet, J.P., No. 1, pp. 320–325.

[4] Bi, Z. M. and Lang, S. Y. T. (2009), "Joint workspace of parallel kinematic machines", Robotics and Computer Integrated Manufacturing, No. 25, pp. 57-63.

[5] Merlet, J. P. (1995), "Determination of the orientation workspace of parallel manipulators", Journal of Intelligent and Robotic Systems, No. 13, pp. 143–160.

[6] SCOReD 2007 : The 5th Student Conference on Research and Development (2007)"Forward kinematics of 3 degrees of freedom delta robot" Malasia, Mustafa, M., Misuari, R. and Daniyal, H.

[7] Merlet, J. P. (2006) Parallel Robots (2th ed.). Springer, pp. 31-34.

[8] HSI 2008 (2008) "Evolutionary approach to optimal design of 3 dof translation exoskeleton and medical parallel robots" Krakow, Poland, Stan, S.D., Manic, M., Matieş, V. and Balan, R., pp. 720-725.

[9] TOK 2012 (2012) "Üç serbestlik dereceli Triglide paralel robotun ters ve düz kinematic çözümlerinin analitik olarak elde edilmesi" Nigde, Turkey, Aydın, M. and Alli, H.

[10] In: Proc. of the International Conference on Advances in Mechanical and Automation Engineering (2016) "The Obtaining of Dynamic Equations for Three Degree of Freedom Parallel Robot "Roma, İtaly, Aydın M, Alli H.

[11] Zadeh L. A. (1965), "Fuzzy Sets", Information and Control, No. 8, pp. 338-353.

[12] Mamdani E. H., Assilion S (1974) "An Experiment in Linguistic Synthesis With a Fuzzy Logic Controller", International Journal of Man-Machine Studies, No. 7, pp.1-13.

[13] Holmblad L. P., Ostergaard J. J. (1982) "Control of Cement Kiln by Fuzzy Logic", Fuzzy Information and Decision Processes, pp. 389-399.

[14] Castillo O., Neyoy H., Soria J., Melin P., Valdez F. (2015) "A new approach for dynamic fuzzy logic parameter tuning in Ant Colony Optimization and its application in fuzzy control of a mobile robot", Applied Soft Computing, No. 28, pp. 150–159.

[15] Abdessemed F., Faisal M., Emmadeddine M., Hedjar R., Al-Mutib K., Alsulaiman M., Mathkour H. (2014) "A Hierarchical Fuzzy Control Design for Indoor Mobile Robot", International Journal of Advanced Robotic Systems, 2014, No. 11:33.

[16] Kayacan E., Kayacan E., Ramon H., Saeys W. (2013) "Adaptive Neuro-Fuzzy Control of a Spherical Rolling Robot Using Sliding-Mode-Control-Theory-Based Online Learning Algorithm", IEEE Transactions On Cybernetıcs, 43:1.

[17] Siradjuddin I., Behera L., McGinnity T. M., Coleman S. (2014) "Image-Based Visual Servoing of a 7-DOF Robot Manipulator Using an Adaptive Distributed Fuzzy PD Controller", IEEE/ASME Transactions On Mechatronics, 19:2.

[18] Zhou Q., Li H., Shi P. (2015) "Decentralized Adaptive Fuzzy Tracking Control for Robot Finger Dynamics", IEEE Transactions On Fuzzy Systems, 23:3.

[19] Juang C-F., Chen Y-H., Jhan Y-H. (2015) "Wall-Following Control of a Hexapod Robot Using a Data-Driven Fuzzy Controller Learned Through Differential Evolution", IEEE Transactions On Industrial Electronics, 62:1.

[20] Li Z., Xiao S., Ge S. S., Su H. (2016) "Constrained Multilegged Robot System Modeling and Fuzzy Control With Uncertain Kinematics and Dynamics Incorporating Foot Force Optimization", IEEE Transactions On Systems, Man, And Cybernetics: Systems, 46:1.

[21] Li H., Wu C., Yin S., Lam H-K.(2016) "Observer-Based Fuzzy Control for Nonlinear Networked Systems Under Unmeasurable Premise Variables", IEEE Transactions On Fuzzy Systems, 24:5.

[22] Takahashi Y., Ishii T., Todoroki C., Ma eda Y. I., Nakamura T. (2015) "Fuzzy Control for a Kite-Based Tethered Flying Robot", Journal of Advanced Computational Intelligence and Intelligent Informatics, 19:3.

[23] Sancheza M. A., Castillo O., Castro J. R. (2015) "Generalized Type-2 Fuzzy Systems for controlling a mobile robot and a performance comparison with Interval Type-2 and Type-1 Fuzzy Systems", Expert Systems with Applications, No. 42, pp. 5904–5914.

[24] Melin P., Astudillo L., Castillo O., Valdez F., Garcia M. (2013) "Optimal design of type2 and type-1 fuzzy tracking controllers for autonomous mobile robots under perturbed torques using a new chemical optimization paradigm", Expert Systems with Applications, No. 40, pp. 3185–3195.