

Design of Optimal PID, Fuzzy and New Fuzzy-PID Controller for CANSAT Carrier System Thrust Vector

A. Kosari *

Department of New Sciences and Technologies,
University of Tehran, Iran
E-mail: kosari_a@ut.ac.ir

*Corresponding author

H. Jahanshahi & A. A. Razavi

Department of New Sciences and Technologies,
University of Tehran, Iran
E-mail: hadi_jahanshahi@ut.ac.ir, a.razavi68@ut.ac.ir

Received: 4 February 2015, Revised: 7 March 2015, Accepted: 20 May 2015

Abstract: In this paper, multi-objective optimization based on Genetic Algorithm is used to find the design variables of PID, fuzzy and new Fuzzy-PID controllers applying for a thrust vector control of CANSAT carrier system. Motion vector control is considered according to the dynamic governing equation of the system which is derived using Newton's method and defined mission in delivering payload into the specific height and flight path angle. The cost functions of the system are position error from the set point and deviation of the vector angle of carrier system with carrier body, where these cost functions must be minimized simultaneously. Results demonstrate that this new Fuzzy-PID controller is superior to other controllers which are exerted in the thrust vector control of a CANSAT carrier system. This Fuzzy-PID is capable of doing the mission with decrease in settling time and rise time with respect to the convenient minimized objective function values.

Keywords: Multi-objective optimization, Genetic algorithm, PID-controller, Fuzzy controller, Fuzzy-PID controller, CANSAT carrier system

Reference: Kosari, A., Jahanshahi, H., and Razavi, A. A., "Design of Optimal PID, Fuzzy and New Fuzzy-PID Controller for CANSAT Carrier System Thrust Vector", Int J of Advanced Design and Manufacturing Technology, Vol. 8/No. 2, 2015, pp. 1-9.

Biographical notes: **A. R. Kosari** received his PhD in Aerospace Engineering from Sharif University of Technology in 2003. He is currently Assistant Professor at the Department of Aerospace and Mechatronic and System Engineering, Faculty of New Science and Technologies, University of Tehran, Tehran, Iran. His current research interest includes optimal control and Path Planning. **H. Jahanshahi** is MSc Student of Aerospace engineering at the University of Tehran, Iran. He received his BSc in Mechanical engineering from Sirjan University of Technology. His current research focuses on Fuzzy set and systems. **A. A. Razavi** is MSc student of Aerospace engineering at the University of Tehran, Iran. He received his BSc in Mechanical engineering from Ferdowsi University of Mashhad.

1 INTRODUCTION

CANSAT's are getting more popular each day in aerospace engineering curriculums because they enable students to have practical experience on virtual satellite launch operations and experience the whole process of design, test, launch and recovery. Demand for training of spacecraft engineering is increasing. As practical space engineering is a relatively very expensive field, there is an ongoing search for affordable training approaches. One of these approaches is "CANSAT Launch" concept which was introduced by an American Professor, Robert Twiggs [1]. He is a professor emeritus at Stanford University, who along with Jordi Puig-Suari of California Polytechnic State University is responsible for creating the CubeSat standard for miniaturized satellites and a standard for deployment of the satellites. He thought he could be regarded as the father of the miniature satellites due to his works with the pioneers of this idea [2]. CANSAT is a design-built-launch organization which is made by students. The main goal of the CANSAT is to educate future engineers and scientists. This program spread all over the world from the USA and takes its name (CANSAT) from the combination of "can" and "satellite" [3]. The key features of a CANSAT design may be expressed as:

- High Technology,
- Affordability and
- Light weight

The name of the satellite is determined by the size of the can. "CANSAT" is a nanoscale satellite model, weighting 350 to 1050g. These satellites are launched by the rocket and can reach a height of 150 to 2000m. After getting separated from the satellite rockets, it begins to perform its duties in the course of a free fall. These tasks are adapted to the recent space missions like terraforming and air bag missions [2]. Having the various sensors, circuits and mechanical components containing these satellites, the CANSAT is the smallest structure that could be called a miniature satellite. It should be noted that vehicles reach very low altitudes, up to a few thousand meters, which is much lower than that the smallest sounding rockets can reach [4]. This small satellite is left at a few hundred meters above the ground surface then returns to the earth by the recovery system. This height is sufficient for the payload operational test and figuring out that CANSAT can perform missions similar to those of real satellites but in a small limited scale. The CANSAT can handle different kinds of mission. The most important known missions existing for this system which are suggested for relevant competitions include:

- Atmosphere monitoring
- Imaging

In addition to the primary missions of such flying vehicles, mentioned above, recovering and landing on a certain location or expanding antenna mechanism are parts of the secondary mission of this system. In previous competitions, CANSAT was usually carried by balloons and then released at a specific height, but in new tournaments balloon is replaced by the carrying system. In this case carrying systems are launched vertically and CANSAT is released at the specific height with specific path angle to the earth local horizon, then at its highest point the carrying umbrella is opened and lands slowly. So, path controller design of carrying system for delivering CANSAT's payload at the specified height and determined flight condition plays an important role in the system design of this mission. Some researches carried out in the field of different carrying path controller designs (except CANSAT), are mainly based on nonlinear control methods.

In recent years, the development of Fuzzy-PID has become one of the major research areas in different engineering problems. The most significant applications and studies about fuzzy systems have concentrated on control areas, such as those in [5], [6]. Fuzzy systems are knowledge-based or rule-based systems formed via human knowledge and heuristics. They have been applied to a wide range of researching fields such as control, communication, medicine, management, business, psychology, and so forth. The most significant applications and studies of the fuzzy systems have concentrated on the control area, such as those in Refs. [7-12].

The development of fuzzy PID controllers for various engineering problems has been a major research activity in recent years. Along the way, the heuristic parameters of Fuzzy-PID controllers have to be determined via an appropriate approach. A very effective way to choose these factors is the use of evolutionary algorithms, such as the genetic algorithm (GA). A constrained optimization of a simple Fuzzy-PID system is designed for the online improvement of PID control performance while running the productive control [13]. In Ref. [14], Duan, Li and Deng proposed an inherent saturation of the Fuzzy-PID controller revealed due to the finite fuzzy rules.

In Ref. [15], Oh, Jang, and Pedrycz developed a design methodology for a fuzzy PD cascade controller for a ball-beam system using particle swarm optimization (PSO). In Ref. [16], an on-line tuning method is proposed for fuzzy PID controllers via rule weighing. Boubertakh, Tadjine, Glorennec, and Labiod proposed a new auto-tuning fuzzy PD and PI controllers using reinforcement-learning (QL) algorithm for SISO (single-input single-output) and TITO (two input two-output) systems [17]. Nie and Tan presented an improved version of the stable fuzzy adaptive control

structure, which comprises an approximation of the ideal controller and a supervisory controller [18]. In this paper a PID controller, then a fuzzy controller and finally a new Fuzzy-PID controller is exerted on the thrust vector of the CANSAT carrier system. In all of these controllers, genetic algorithm is applied to find the best controller gains.

2 CANSAT CARRYING SYSTEM DYNAMIC MODELLING

The first step in design of path control is identification and extraction of dynamic governing equations of the system. In mechanical systems (such as aerospace systems), there are various methods such as Newton, Lagrange, Keen and so forth for modelling of system dynamics. The best known of these methods is Newton's method which is used in this paper. Figure 1 shows a simplified model of a carrier system as θ is the carrier longitudinal vector angle with direction of vertical to the earth and Φ is the carrier thrust vector angle with direction of carrier body. Since in the CANSAT separation instance from its carrier, the CANSAT velocity vector image magnitude on the horizon plane needs to be zero, and also in the CANSAT operational time, this satellite is connected with ground station through radio waves, to reduce the signal to noise ratio (further distance equal to signal attenuation and noise increase), the control purpose of this problem is resetting the angle of θ on zero. Therefore, using Newton's laws, governing dynamic equations of the system can realize as follows:

$$\sum M_{CM} = I\alpha. \quad (1)$$

Where M_{CM} , I and α are the momentum around center of mass, rotational inertia, and carrier's angular acceleration around the axis perpendicular to the plane, respectively.

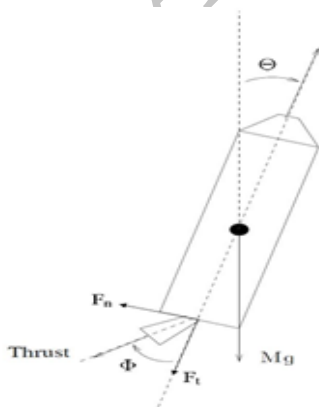


Fig. 1 Carrier system scheme

Finally governing dynamic equation of the system is made as follows:

$$\ddot{\theta} = \frac{1}{2I} lm(a + g) \tan(\phi). \quad (2)$$

Where b is calculated from the following equation:

$$b = \frac{1}{2I} lm(a + g). \quad (3)$$

If we take $\tan(\phi)$ as u , equation (1) becomes as follows:

$$\ddot{\theta} = bu. \quad (4)$$

where a is the acceleration along perpendicular axis, m is the mass of carrier, g is the gravity acceleration, and l is the length of carrier. The state variables are the system observable state vector which is described as follows:

$$x = [x_1, x_2, x_3] = [\theta, \dot{\theta}, \ddot{\theta}]$$

3 OPTIMIZATION APPROACH

There are several methods for engineering problems optimization. Our selected technique is using the genetic algorithm. One advantage of genetic algorithm method is dealing with function quantity. So, for choosing the function, there is no need to know its exact equation and it seems enough to find a way to calculate function value by entering problem variables, unlike other optimization methods that require having the objective function equation exactly. E.g. if we could find the function value for a special case with different kind of variables through graphical methods, there is no need to know the relation between function and variables, because the genetic algorithm method gives us the optimum value with good accuracy.

Also, if we had a software for analyzing engineering problem which could get the variables and gave the answer, we could obtain the optimum value with genetic algorithm only by knowing the value of function for input variables with no requirement of awareness of solution processes. This is the unique advantage which could be rarely found in other optimization methods. In each optimization problem we deal with some goals which are mentioned as objective functions. These functions are those variables that need to be minimized or maximized. If we have only one objective function, we encounter single-objective optimization problem, but if we have more than one objective functions we involve in multi-objective or MOGA problem, where genetic algorithm tries to optimize the desired values simultaneously. MOGA is the abbreviation form of

multi objective based on genetic algorithm. The objective functions in this optimization are position error from the set position, and deviation of vector angle of carrier system with carrier body, described as follows:

$$O.F.1 = \int |\theta| d_t. \quad (5)$$

$$O.F.2 = \int |\phi| d_t. \quad (6)$$

4 PID CONTROLLER

System state vector is $[x_1, x_2, x_3]$ which are integral of carrier longitudinal vector angle with direction of vertical to the ground, carrier longitudinal vector angle with direction of vertical to the ground and derivation of carrier longitudinal vector angle with direction of vertical to the ground, respectively. In PID controller, advanced controller can be created considering parameters such as set point changes with respect to the current value of the process with factors like intensity and amount of changes with respect to time. In PID controllers, proportional-derivative-integral algorithm is used. As it comes from its name, the letter P goes for proportional, I means integral and D means Derivative. Proportional controller decreases settling time and error but increases overshoot.

Derivative controller decreases amount of overshoot and settling time and has less influence on rise time and steady state error. Integral controller decreases rise time but increases overshoot and settling time and removes steady state error. So at first, the response of open loop and the values which should be improved are determined. We use Proportional controller for rise time improvement, derivative controller for overshoot improvement and integral controller for steady state error. The gains of proportional, derivative and integral exerted in this controller according to the defined objective functions are calculated by using genetic algorithm.

5 FUZZY CONTROLLER

Controllers with fuzzy logic basis are considered a subset of intelligent control systems. Actually, intelligent control systems are combination of control engineering and artificial intelligence (programming, reasoning and learning), where fuzzy controllers are not excluded from this law. In other words, fuzzy controllers are strong combination of nonlinear controls (control engineering) and fuzzy logic (inference). There

are some inference methods in fuzzy logic. One of these methods is Mamdani fuzzy inference system. A Mamdani fuzzy inference system is made up of some limited if-then rules.

Fuzzy logic

The fact that carrier thrust force must be in a direction so that it could apply a torque in opposite of carrier's head angle direction until carrier angle to the vertical line become zero, is the simplest linguistic rule comes to the mind. This simple rule may lead to a periodic system if the system inertia is overlooked. Due to the Newton's laws, an object keep moving at its uniform speed when there is no force on it. Therefore, due to the inertia law, system keeps moving at the same speed and crosses the zero point until thrust applies an opposite torque to the carrier. To solve this problem, carrier angle velocity is entered in the problem in applied rules of making decision. So, the main rules of carrier path control are rewritten as follows:

- 1- If the carrier angle is negative and carrier angle velocity is negative, then thrust vector is positive big.
- 2- If the carrier angle is negative and carrier angle velocity is near to zero (without considering positive and negative), then thrust vector is positive small.
- 3- If the carrier angle is zero (without considering positive and negative) and carrier angle velocity is negative then thrust vector is positive small.
- 4- If the carrier angle is zero (without considering positive and negative) and carrier angle velocity is zero (without considering positive and negative) then thrust vector is positive zero.
- 5- If the carrier angle is zero (without considering positive and negative) and carrier angle velocity is positive then thrust vector is negative small.
- 6- If the carrier angle is positive and carrier angle velocity is near to zero (without considering positive and negative), then thrust vector is negative small.
- 7- If the carrier angle is positive and carrier angle velocity is positive, then thrust vector is negative big.

Fuzzification

Since governing equation of carrier dynamic system is continuous and differentiable, it's better to use Gaussian functions in fuzzification. The purpose of design is to make carrier angle to the vertical line zero, so it's necessary to have less criterion deviation in Gaussian function in the statement of 'if carrier angle is zero' than the other linguistic statements. The fuzzification membership functions of carrier angle to the vertical axis are shown in Fig. 2.

Defuzzification

As it mentioned in above part, governing equation of carrier dynamic system is continuous and differentiable. So, it's better to use Gaussian functions (which are differentiable) in defuzzification. Moreover, using Gaussian functions result in smooth performance of output rather than using other functions such as triangular or trapezoidal functions. Due to symmetric property of the system, Gaussian functions are considered homogeneous and symmetric. The defuzzification membership functions of thrust angle are shown in Fig. 3.

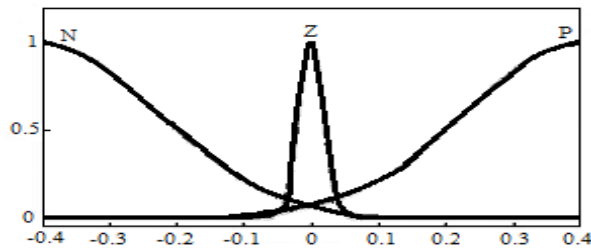


Fig. 2 Fuzzification of carrier angle to the vertical axis

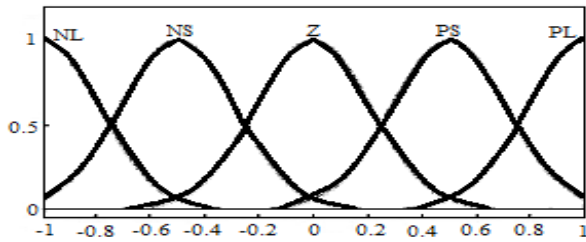


Fig. 3 Defuzzification of thrust angle

Taking Laplace transform from Eq. 4, and selecting control parameter U as follows:

$$U(s) = (w_i^D + \Delta w_i^0 s)(-\theta(s)). \quad (7)$$

Closed loop transfer function of the system becomes:

$$\frac{\theta(s)}{U(s)} = \frac{b\Delta w_i^0 s + bw_i^D}{s^2 + b\Delta w_i^0 s + bw_i^D}. \quad (8)$$

Fuzzy gain used in this controller according to the defined objective functions, position error from the set point, and deviation of the vector angle of carrier system with carrier body is calculated by genetic algorithm.

6 FUZZY-PID CONTROLLER

In the proposed new Fuzzy-PID controller, two fuzzy inference motors are utilized. The first is the Single

Input Fuzzy Inference Motor (SIFIM) that has only one input. Since all of the desired values in the stabilization control are zeros, the variables are reversely inputted into the Norm block. For each normalized variable (Norm block output), a SIFIM is defined. The second is the Preferer Fuzzy Inference Motor (PFIM) that represents the control priority order of each Norm block output.

$$SIFIM-i: \{R_i^j : \text{if } x_i = A_i^j \text{ then } u_i = C_i^j\}_{j=1}^m. \quad (9)$$

SIFIM- i mention the single input inference motor which accept the i^{th} input among inputs and R_i^j is the j^{th} rule of the i single input inference motor. A_i^j and C_i^j are the membership functions. Each input item usually has a different role in implementation of control. To express the different effects of each input item in the implementation of system, single input fuzzy inference motor defines a dynamic importance degree (w_i^D) for each input item.

$$w_i^D = w_i + B_i \times \Delta w_i. \quad (10)$$

Where w_i , B_i and Δw_i are control parameters which are described by fuzzy rules. SIFIM- i block calculate f_i as follows:

$$f_i = \frac{VB_i \times f_1 + PO_i \times f_2 + ZB_i \times f_3}{VB_i + PO_i + ZB_i}. \quad (11)$$

The membership functions of SIFIMs are shown in Fig. 4. f_1 , f_2 and f_3 (fuzzy rules of SIFIMs) noted in the above equation, are exploited from the Table 1. Other type of fuzzy inference motors are PFIMs. PFIMs guarantee CANSAT carrier control system when it is derived from desired values in one or more of the coordinate system directions. PFIM- i calculate Δw_i as follows:

$$\Delta W_1 = \Delta W_2 = \Delta W_3 = \frac{W_1 \times HS + W_2 \times HM + W_3 \times HB}{HS + HM + HB}. \quad (12)$$

The membership functions of SIFIMs are shown in Fig. 4, and fuzzy rules of PFIMs are shown in Table 2. After calculating f_i and Δw_i , it is possible to define new Fuzzy-PID controller as the following:

$$f = \hat{K}_{i\theta} \int \hat{\theta} d_t + \hat{K}_{p\theta} \hat{\theta} + \hat{K}_{d\theta} \frac{d\hat{\theta}}{d_t}. \quad (13)$$

Where f is the control action. $\int \hat{\theta} d_t$, $\hat{\theta}$, $\frac{d\hat{\theta}}{d_t}$ are the fuzzy forms of $\int \theta d_t$, θ , $\frac{d\theta}{d_t}$, respectively, and should be

obtained by SIFIM. In other words,

$$\int \hat{\theta} d_t = f_1; \hat{\theta} = f_2; \frac{d\hat{\theta}}{d_t} = f_3. \text{ Furthermore, in Eq. 13,}$$

$\hat{K}_{i\theta}$, $\hat{K}_{p\theta}$, and $\hat{K}_{d\theta}$ are the fuzzy variables calculated by the following equations:

$$\hat{K}_{i\theta} = K_{i\theta}^b + K_{i\theta}^r \Delta W_1. \quad (14)$$

$$\hat{K}_{p\theta} = K_{p\theta}^b + K_{p\theta}^r \Delta W_2. \quad (15)$$

$$\hat{K}_{d\theta} = K_{d\theta}^b + K_{d\theta}^r \Delta W_3. \quad (16)$$

Where $K_{i\theta}^b$, $K_{p\theta}^b$ and $K_{d\theta}^b$ are the base variables $K_{i\theta}^r$, $K_{p\theta}^r$, and $K_{d\theta}^r$ are the regulation variables. The base and regulation variables can be obtained by trial and error process. However, the best solution to have an optimal control, is the use of optimization approaches such as evolutionary algorithms, especially genetic algorithm.

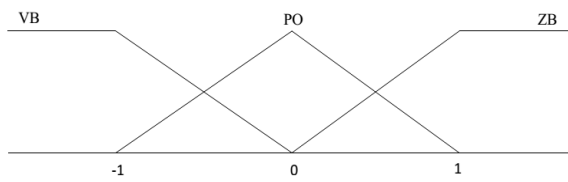


Fig. 4 Membership functions of SIFIM

Table 1 Fuzzy rules of SIFIMs

if	Then
VB_i	$f_1 = 1$
PO_i	$f_2 = 0$
ZB_i	$f_3 = -1$

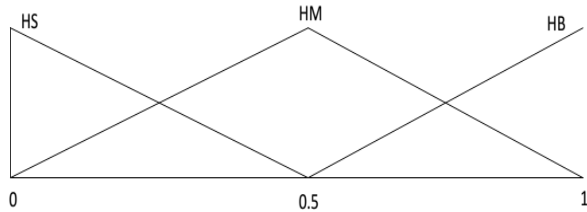


Fig. 5 Membership functions of PFIM

Table 2 Fuzzy rules of PFIMs

if	Then
$ \theta $ HS	$W_1 = 1$
$ \theta $ HM	$W_2 = 0.5$
$ \theta $ HB	$W_3 = 1$

7 SIMULATION AND RESULT

For PID, fuzzy and Fuzzy-PID controller, gain values and objective function values related to these gains are shown in Tables 3, 4, 5, 6, 7 and 8, respectively. The time responses of carrier position to the vertical direction, carrier angular velocity and carrier thrust vector angle with carrier body direction for PID, fuzzy and Fuzzy-PID controllers are shown in Figures 6, 7, 8, 9, 10, 11, 13, 14 and 15 respectively. Also, Simulation of fuzzy controller for carrier system in MATLAB, is shown in Fig. 12. The system parameters used for simulation are, $m = 100 \text{ kg}$, $g = 10 \text{ m/s}^2$, $l = 1 \text{ m}$,

$a = 100 \text{ m/s}^2$, $I = 1000 \text{ kgm}^2$ and the norm block factor is 1.

The initial values are $x = [x_1, x_2, x_3] = [0, 0.2^{\text{rad}}, 0]$ and the algorithm configuration of the genetic algorithm (exist in the environment of MATLABR2012a) is as follows. The crossover fraction = 0.8, population size = 200, selection function = tournament, mutation function = constraint dependent, crossover function = intermediate, crossover ratio = 1, migration direction = forward, migration fraction = 0.2, migration interval = 20, distance measure function = distance crowding, Pareto front population function = 0.35, and stopping criteria is defined as function tolerance = 10^{-4} .

Table 3 Design variables of optimum point for PID controller

Design variable	value
K_p	2.1427
K_d	0.9781
K_i	4.0713

Table 4 Objective functions of optimum point for PID controller

objective function	Value
$O.F.1 = \int \theta d_t$	0.1354
$O.F.2 = \int \phi d_t$	0.0198

Table 5 Design variables of optimum point for fuzzy controller

Design variable	Value
w_i^D	1.7943
Δw_i^0	2.1097

Table 6 Objective functions of optimum point for fuzzy controller

objective function	Value
$O.F.1 = \int \theta d_t$	0.0917
$O.F.2 = \int \phi d_t$	0.1961

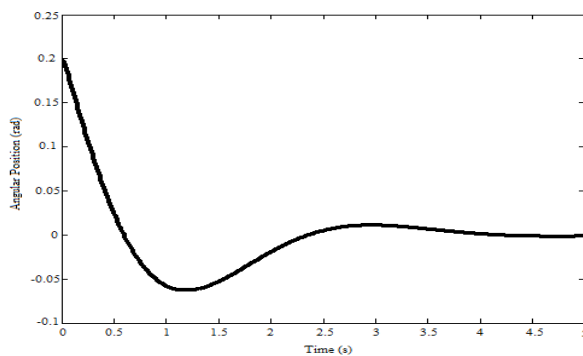


Fig. 6 Time response of angular position of PID controller for optimum point

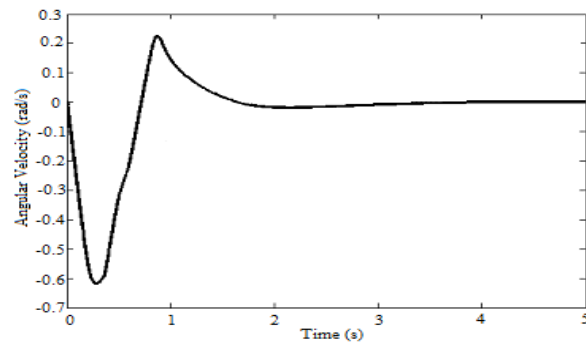


Fig. 10 Time response of angular velocity of fuzzy controller for optimum point

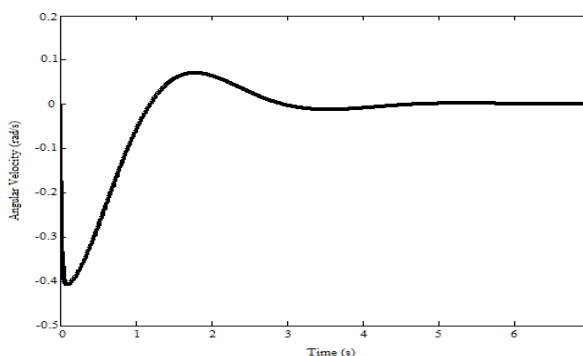


Fig. 7 Time response of angular velocity of PID controller for optimum point

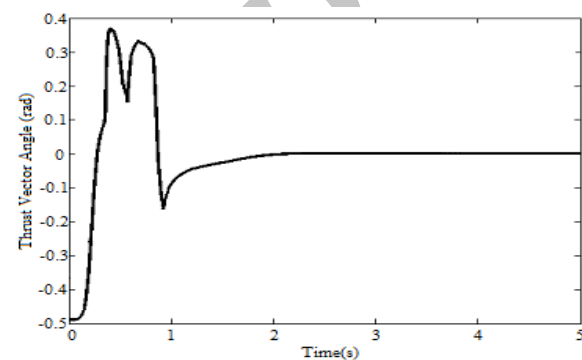


Fig. 11 Time response of thrust vector angle of fuzzy controller for optimum point

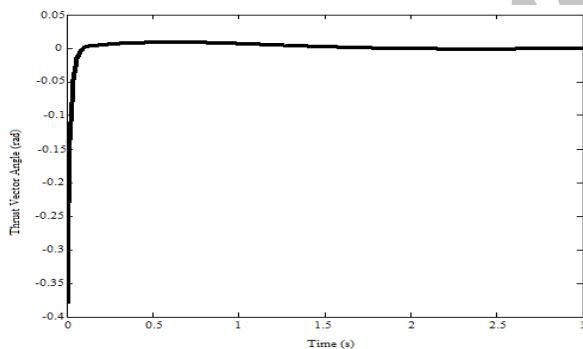


Fig. 8 Time response of thrust vector angle of PID controller for optimum point

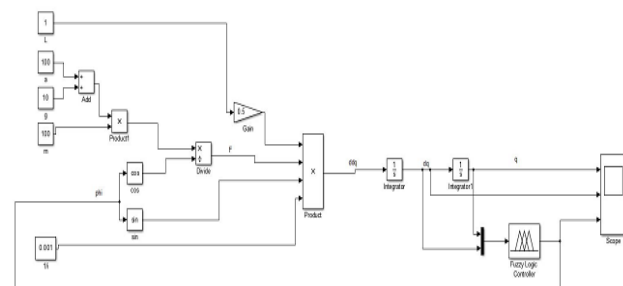


Fig. 12 Simulation of fuzzy controller for carrier system in MATLAB/SIMULINK

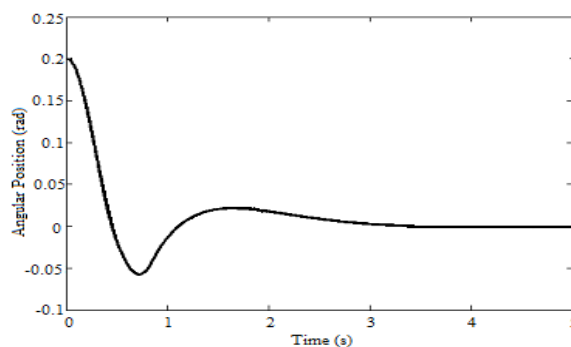


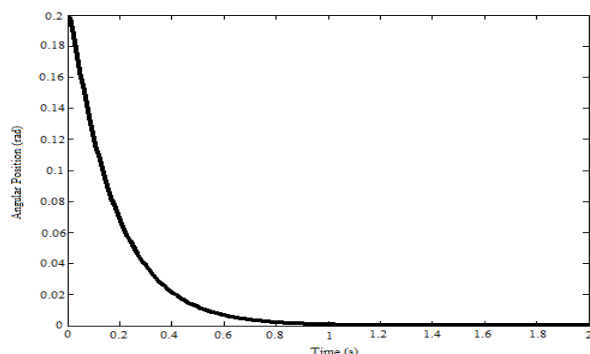
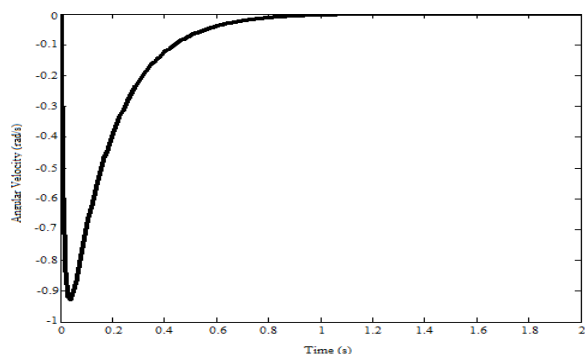
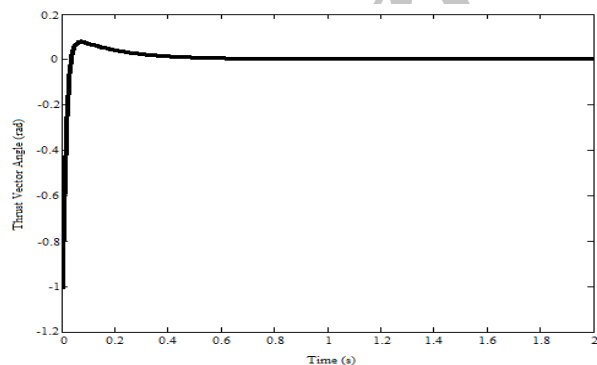
Fig. 9 Time response of angular position of fuzzy controller for optimum point

Table 7 Design variables of optimum point for Fuzzy-PID controller

Design variable	Value
$K_{i\theta}^b$	0.3841
K_{θ}^b	7.9144
$K_{d\theta}^b$	1.5354
$K_{i\theta}^r$	-0.4193
K_{θ}^r	0.2136
$K_{d\theta}^r$	0.9018

Table 8 Objective functions of optimum point for Fuzzy-PID controller

objective function	Value
$O.F.1 = \int \dot{\theta} d_t$	0.0385
$O.F.2 = \int \dot{\phi} d_t$	0.0362

**Fig. 13** Time response of angular position of Fuzzy-PID controller for optimum point**Fig. 14** Time response of angular velocity of Fuzzy-PID controller for optimum point**Fig. 15** Time response of thrust vector angle of Fuzzy-PID controller for optimum point

8 CONCLUSION

In this work, the multi-objective optimization was successfully used for an optimum design of PID, fuzzy and new Fuzzy-PID controllers for the CANSAT carrier system where the dynamic is derived by using Newton's

method. The objective functions for this system are position error from set point and deviation of vector angle of carrier system to carrier body.

An integral term is augmented to the state variables due to steady state error elimination and rise time decrease.

In PID and fuzzy and Fuzzy-PID controller, design variables are calculated by using genetic algorithm with respect to defined objective functions. Mamdani inference system with some defined if-then rules and Gaussian membership functions for fuzzification and defuzzification parts are used in fuzzy controller. The new Fuzzy-PID controller utilizes two average inference engines called SIFIM and PFIM where the first engine get one input from each Norm block and give f_i as outputs, and the second one guarantee CANSAT carrier control system in large derivation from desired values in one or more of coordinate system directions and give the ΔW_i as outputs. The reported results demonstrated that the proposed methodology for Fuzzy-PID controller can control CANSAT carrier system effectively rather than applied PID and fuzzy controllers. It is recommended to identify accurate dynamic of system and choose convenient fuzzy rules to improve performance of controllers.

REFERENCES

- [1] Aydemir, M. E., Dursun, R. C., and Pehlevan, M., "Ground Station Design Procedures for CANSAT", the 6th International Conference on Recent Advanced in Space Technologies (RAST), Istanbul, Turkey, June 2013, pp. 909-912.
- [2] Soyer, S., "Small Space Can: CANSAT," in 5th International Conference on Recent Advanced in Space Technologies (RAST), Istanbul, Turkey, June 2011, pp. 789-793.
- [3] Çabuloğlu, C., Aykiş, H., Yapacak, R., Çalışkan, E., Ağırbaş, Ö., Abur, Ş., Soyer, S., Türkmen, H., Ay, S., Karataş, Y., Aydemir, M. E., and Çelebi, M., "Mission Analysis and Planning of a CANSAT", The 5th International Conference on Recent Advanced in Space Technologies (RAST), Istanbul, Turkey, June 2011, pp. 794-799.
- [4] Okninski, A., Marciniak, B., Bartkowiak, B., Kaniewski, D., Matyszewski, J., Kindracki, J., and Wolanski, P., "Development of the Polish Small Sounding Rocket Program", Acta Astronautica, Vol. 108, 2015, pp. 46-56.
- [5] Zadeh, L. A., "Fuzzy algorithms", Information and Control, Vol. 12, 1968, pp. 94-102.
- [6] Zadeh, L. A., "Outline of a new approach to the analysis of complex systems and decision processes", IEEE Transactions on Systems, Man and Cybernetics, Vol. 3, 1973, pp. 28-44.
- [7] Nasser, H., Kiefer-Kamal, E. H., Hu, H., Belouettar, S., and Barkanov, E., "Active vibration damping of

- composite structures using a nonlinear fuzzy controller", *Composite Structures*, Vol. 94, 2012, pp. 1385-1390.
- [8] LI, P., JIN, F. J., "Adaptive Fuzzy Control for Unknown Nonlinear Systems with Perturbed Dead-zone Inputs", *Acta Automatica Sinica*, Vol. 36, 2010, pp. 573-579.
- [9] Lygouras, J. N., Botsaris, P. N., Vourvoulakis, J., and Kodogiannis, V., "Fuzzy logic controller implementation for a solar air-conditioning system", *Applied Energy*, Vol. 84, 2007, pp. 1305-1318.
- [10] Jee, S., Koren, Y., "Adaptive fuzzy logic controller for feed drives of a CNC machine tool", *Mechatronics*, Vol. 14, 2004, pp. 299-326.
- [11] Sinha, A. S. C., Lyshevski, S., "Fuzzy control with random delays using invariant cones and its application to control of energy processes in microelectromechanical motion devices", *Energy Conversion and Management*, Vol. 46, 2005, pp. 1305-1318.
- [12] Zuperl, U., Cus, F., and Milfelner, M., "Fuzzy control strategy for an adaptive force control in end-milling", *Journal of Materials Processing Technology*, Vol. 164-165, 2005, pp. 1472-1478.
- [13] Mansour, S. E., Kember, G. C., Dubay, R., and Robertson, B., "Online optimization of fuzzy-PID control of a thermal process", *ISA Transactions*, Vol. 44, 2005, pp. 305-314.
- [14] Duan, X. G., Li, H. X., and Deng, H., "Robustness of fuzzy PID controller due to its inherent saturation", *Journal of Process Control*, Vol. 22, 2012, pp. 470-476.
- [15] Oh, S. K., Jang, H. J., and Pedrycz, W., "Optimized fuzzy PD cascade controller: A comparative analysis and design", *Simulation Modelling Practice and Theory*, Vol. 19, 2011, pp. 181-195.
- [16] Karasakal, O., Guzelkaya, M., Eksin, I., Yesil, E., and Kumbasar, T., "Online tuning of fuzzy PID controllers via rule weighing based on normalized acceleration", *Engineering Applications of Artificial Intelligence*, Vol. 26, 2013, pp. 184-197.
- [17] Boubertakh, H., Tadjine, M., Glorennec, P. Y., and Labiod, S., "Tuning fuzzy PD and PI controllers using reinforcement learning", *ISA Transactions*, Vol. 49, 2010, pp. 543-551.
- [18] Nie, M., Tan, W. W., "Stable adaptive fuzzy PD plus PI controller for nonlinear uncertain systems", *Fuzzy Sets and Systems*, Vol. 179, 2011, pp. 1-19.