Automatic Indoor Air Quality Control of COVID-19 Patient Facilities Using Type-2 Fuzzy Controller

Indrajit Naskar¹, A K Pal²

¹, ² Heritage Institute of Technology, Dept. of AEIE, Kolkata, West Bengal, India
E-mail: indrajit.naskar@heritageit.edu, arabindakumarpal@gmail.com

Abstract. Big facilities can be used to set up cohort wards for severe and critical COVID-19 patients. The purpose of carbon dioxide and humidity control is to provide healthy air for breathing by both diluting the pollutants originating in the building and removing the pollutants from it. In this paper, for proper mechanical ventilation to maintain indoor air quality (IAQ), a Self-tuned Interval Type-2 Fuzzy PI controller (SIT2FPIC) is proposed. 49 fuzzy if-then rules are used to tune the Interval Type-2 Fuzzy PI controller (IT2FPIC) for proper functioning and to reduce the parameter variations. Correlations of CO₂ concentration and air humidity are studied to maintain the air quality in COVID-19 facilities. Mathematical models of CO₂ concentration and air humidity in hospitals or temporary COVID-19 facilities are developed considering the presence of COVID-19 patients, doctors, nurses, etc in the room. The control and monitoring of room air quality are very much essential for any infectious diseases like coronavirus. To maintain the air quality in terms of humidity and carbon dioxide, the proposed SIT2FPIC is applied to the mathematical model of humidity and carbon dioxide for the simulation study. The effectiveness of the proposed controller in mechanical ventilation in the treatment facilities is shown by a comparative study of different transient parameters. Effects of load variations in the model are also studied to check the usefulness of the proposed scheme.

1. Introduction

Now, the world is under the COVID-19 trap and also a new wave (second phase) is spreading rapidly. Lots of question arises from different corner of the world about routes of transmission for this pandemic disease [1]. After segregation of the different types of COVID-19 patient like mild, moderate, and severe, in addition to proper treatment through medicine, desired oxygen supply, and others also, there is a need to control the air quality in terms of humidity and carbon dioxide (CO₂) with sufficient and effective ventilation inside the room like hospitals, offices, schools, conference rooms [2]. In addition to this control, the effective application of other controls (including isolation and quarantine, social distancing, and hand hygiene) would be an additional important measure globally to reduce the likelihood of transmission and thereby protect healthcare workers, patients, and the general public [3]. To maintain the air quality, the controlling of concentration of O₂, CO₂ and humidity percentage present inside the patient room are one of the important issues [4]. Out of the above parameters, the controlling of humidity and CO₂ inside the room is of prime importance because the increasing of these two parameters enhances the possibility of respiratory distress which is a common symptom of COVID-19 patients.

In this paper, the mathematical model of humidity and carbon dioxide inside a patient's room is developed by considering the number of persons present in the room. Considering the dynamic nature
of the model due to model parameter variations, a fuzzy knowledge-based control scheme is suggested. To provide comfort to the patient by controlling the humidity and carbon dioxide of the room, a Self-tuned Interval Type-2 Fuzzy PI controller (SIT2F PIC) model is proposed. In this paper, the implementation of the proposed SIT2F PIC to the dynamic model of humidity and carbon dioxide of COVID-19 patient facility is observed and its performance is compared with other type-1 fuzzy controllers.

This study aims to provide a new solution in mechanical ventilation for indoor air quality control by type-2 fuzzy logic controller. In the following sections, mathematical modelling and controller design are covered respectively, in the sequel the Matlab simulation results are demonstrated, finally, the concluding remarks from this work as well as future work are presented.

2. COVID-19 Treatment Room and Mathematical Model

In the case of natural ventilation, natural forces (e.g., winds) drive outdoor air through the building openings such as windows, doors, solar chimneys, wind towers, and trickle ventilators. In mechanical ventilation, mechanical fans are used to control the ventilation. Fans can either be installed directly in windows or walls, or installed in air ducts for supplying air into, or exhausting air from a room [3]. Air from the room can be exhausted directly to the outdoors where the droplet nuclei will be diluted in the outdoor air. It's essential to exhaust air away from air-intake vents, persons, and animals. If for structural reasons dilution is not possible, exhausted air should be passed through a special high-efficiency particulate air (HEPA) filter that removes most (99.97%) of the droplet nuclei. Considering the severity of the disease and to restrict its transmission, it is advisable to use a HEPA filter at the outlet of the COVID-19 facilities. The Institute of Environmental Sciences and Technology dictates that a HEPA filter must trap 99.97% of particulates of 0.01 microns or larger, whereas the average size of coronavirus is around 0.123 micron [5]. Nowadays, HEPA filtration systems incorporate high-energy ultra-violet light with an anti-microbial coating to kill off the live bacteria and viruses trapped by the filter media, which assures a very high level of protection against airborne disease transmission [6, 7].

A typical diagram of the COVID-19 treatment facility is sketched in (Figure 1) [3]. Different steps of air circulation are provided in the figure. In this design, one HEPA filter is used at the outlet to minimize the transmission. The Air extractor fan at the outlet is driven by the proposed controller according to the desired room CO2 concentration and air humidity. The vacuum created in the room is simultaneously filled through the inlet airway as shown in the diagram. In this study, different types of fuzzy expert system controllers are tested to provide the comfort conditions necessary for the treatment rooms [8-13].

![Figure 1. Basic block diagram of the specialized designed COVID 19 room](image-url)
Indoor Air Quality (IAQ) can be defined by its impact on human health, comfort, and productivity. The measure of IAQ is very vital especially in schools and hospitals [14, 15]. Poor IAQ in such establishments can aggravate health problems with patients. The CO₂ level in exhaled air about 38,000 ppm. When carbon dioxide is exhaled it is quickly mixed with the surrounding air and, if the ventilation is good, the concentration is quickly reduced to harmless levels as outdoor CO₂ levels are usually 350-450 ppm. But in general, in any crowded place, the CO₂ level varies between 1000 to 5000 ppm. The high CO₂ deprives the body of its needed oxygen, especially the brain, causes drowsiness, headaches, sleepiness, difficulty breathing, and increased heart rate, etc.

When CO₂ concentrations rise, air temperatures go up, and more water vapour evaporates and which increases the humidity of the room. Damp indoor spaces, humid air can increase the survival rate of viruses indoors and foster the growth and transmission of viruses and bacteria. The controlling of moisture can limit the spread of infectious diseases and crowded conditions with poor air circulation can promote this spread. Controlling CO₂ concentration and air humidity is very important in COVID-19 treatment facilities as most of the severe patients are affected with respiratory problems. In this section, CO₂ and humidity model is developed considering the parameter variations like the number of patients and supporting staff present in the room, and other disturbances.

**Carbon dioxide Model**

The rate of change of CO₂ concentration relies on the difference in the concentration of CO₂ at the air inlet and air outlet and also the number of occupiers of the room. When inlets and outlets are turned on, room air is discharged through the outlets, while air with a lower CO₂ concentration is flowing in the room at the same time. This concept of physics is utilized to develop the CO₂ model.

\[
\frac{d}{dt} \text{CO}_2(t) = k_1 (\text{c}_2(t) - \text{c}_1(t)) + k_2 (\text{c}_2(t) - \text{c}_2(t - \Delta t)) + \epsilon_1(t)
\]

Where,
- \(\text{c}_1(t)\) = number of persons present inside the room
- \(\text{c}_2(t)\) = concentration of CO₂ in the air at the air outlet
- \(\text{c}_2(t)\) = concentration of CO₂ in the air at the air inlet
- \(\epsilon_1(t)\) = disturbance for the carbon dioxide
- \(k_1, k_2\) are the constants >0

**Humidity Model**

The model for the humidity is obtained in a similar way to the model of the CO₂. It is assumed that the rate of change of humidity depends on the humidity of the air coming into the room and going out from the room. Also, consider the effect of CO₂ concentration in the room in each time interval \((\Delta t)\) and other unknown factors. The derived 1st order humidity equation is

\[
\frac{d}{dt} h(t) = c_1 (h(t) - h(t - \Delta t)) + \epsilon_2(t)
\]

Where,
- \(h(t)\) = air humidity which is measured at the air outlet
- \(h(t)\) = air humidity at the air inlet
- \(\epsilon_2(t)\) = disturbance for the humidity
- \(c_1, c_2\) and \(f_1\) are the constants >0
- \(\Delta t\) is the sampling interval and their corresponding sampled values are \(\text{CO}_2(t)\) and \(\text{CO}_2(t - \Delta t)\).
3. Design of Self-Tuned Interval Type-2 Fuzzy PI Controller (SIT2FPIC)

The developed SIT2FPIC design is described in different steps in this section. At first, an interval type-2 fuzzy system (IT2FS) is described and that is used to design an interval type-2 fuzzy PI controller (IT2FPIC). In the next step, a type-1 fuzzy rule-base scheme is incorporated to tune the IT2FPIC to design the proposed self-tuned interval type-2 fuzzy PI controller (SIT2FPIC).

**Step 1: Design of Interval Type-2 Fuzzy System (IT2FS)**

The basic representation of the interval type-2 fuzzy membership function (MF) is illustrated in (Figure 2). Type-2 fuzzy sets are characterized by two triangular type MFs, $\hat{A}$ and $\hat{B}$. There are different shapes of MF’s but here triangular type MF is considered for its simplicity [16, 17]. $\hat{A}$ and $\hat{B}$ fuzzy sets are two input variables of fuzzy controller i.e., error (e) and change of error ($\Delta e$) respectively. Using the concept of the footprint of uncertainty (FOU), a triangular IT2FS is obtained by blurring a baseline triangular type-1 fuzzy system [18-20]. IT2FSs are bounded from up and down with two type-1 fuzzy MFs that are called upper membership function (UMF) and lower membership function (LMF), respectively. An upper MF and a lower MF are two type-1 MFs that bound for the footprint of the uncertainty of an interval type-2 MF. The upper MF is a subset that has the maximum membership grade of the FOU, and the lower MF is a subset that has the minimum membership grade of the FOU [21-24]. Five parameters are needed to represent a triangular IT2FS, (a, b, c, d, e) for error and $(a', b', c', d', e')$ for change of error where $(a, c, e)$ and $(a', c', e')$ determines the UMF for e and $\Delta e$ and $(b, c, d)$ and $(b', c', d')$ for e and $\Delta e$ respectively determines the subnormal LMF shown in (Figure 2).

![Typical type-2 triangular type membership functions](image)

The upper and lower MFs of $\hat{A}$ is denoted by $\mu_\hat{A}$ and $\mu_\hat{A}$ respectively.

$$\mu_\hat{A}(x) = \sup u |f_A(u) > 0$$

$$\mu_\hat{A}(x) = \inf u |f_A(u) > 0$$

The FOU of interval Type-2 Fuzzy System (IT2FS) is described by two MFs, upper MF (UMF) and lower MF (LMF) respectively.

$$\text{FOU}_\text{e} = [\mu_\hat{A}(x_1), \mu_\hat{A}(x_1)]$$

$$\text{FOU}_{\Delta e} = [\mu_\hat{B}(x_2), \mu_\hat{B}(x_2)]$$

In (Figure 2), when $e = x_1$, the vertical point at $x_1$ interacts the FOU (A) everywhere in the interval $[\mu_\hat{A}(x_1), \mu_\hat{A}(x_1)]$, and when $\Delta e = x_2$, the vertical point at $x_2$ interacts the FOU (B) everywhere.
in the interval $[μ|x|; μ|y|]$ [18–20]. This paper focuses on symmetric IT2FS, for which the FOU is symmetric about $x_1 = p$, $μ_{A}$ is symmetric about $x_1 = p$, $μ_{B}$ is symmetric about $x_2 = p$.

Similar to any type-1 fuzzy controller design, interval type-2 fuzzy controller also consists of all the basic blocks of type-1 fuzzy controller, such as fuzzifier, rule base & inference engine, defuzzifier, and besides a type reducer block is placed in between inference engine and defuzzifier as shown in (Figure 3) [25–29].

![Figure 3. Block diagram of IT2FS](image)

**Fuzzifier**

Fuzzy MF $\tilde{A}$ is defined by, $\tilde{A} = \{(x, u_A)|\mu_{\tilde{A}}(x, u_A)|x \in X, u_A \in \mathcal{B}, 0 \leq \mu_{\tilde{A}}(x, u_A) \leq 1\}$, in which $0 \leq \mu_{\tilde{A}}(x, u_A) \leq 1$.

Where, $u_A$ denotes the primary membership function (PMF) of $\tilde{A}$ and $\mu_{\tilde{A}} \in [0,1]$ is called secondary membership function (SMF), $\mathcal{B} \subseteq [0,1]$ is PMF of $x$.

Similarly, $\tilde{B} = \{(x, v_B)|\mu_{\tilde{B}}(x, v_B)|x \in X, v_B \in \mathcal{B}, 0 \leq \mu_{\tilde{B}}(x, v_B) \leq 1\}$, in which $0 \leq \mu_{\tilde{B}}(x, v_B) \leq 1$, $\mathcal{B}$ denotes the PMF of $\tilde{B}$ and $\mu_{\tilde{B}} \in [0,1]$ is SMF, $\mathcal{B} \subseteq [0,1]$ is PMF of $x$.

The collection of all PMF of type-2 fuzzy system is known as FOU, FOU (A) = $\bigcup_{x \in X} \mathcal{B}$, and FOU (B) = $\bigcup_{v \in X} \mathcal{B}$.

A type-2 fuzzy system transforms into an interval type-2 fuzzy system when the grades or all SMF is equal to 1, i.e.

$\mu_{\tilde{A}}(x, u_A) = 1$ and $\mu_{\tilde{B}}(x, v_B) = 1$.

$A = \{(x, u_A)|\mu_{\tilde{A}}(x, u_A) = 1)|x \in X, u_A \in \mathcal{B}, 0 \leq \mu_{\tilde{A}}(x, u_A) \leq 1\}$

$B = \{(x, v_B)|\mu_{\tilde{B}}(x, v_B) = 1)|x \in X, v_B \in \mathcal{B}, 0 \leq \mu_{\tilde{B}}(x, v_B) \leq 1\}$

Unlike type-1 fuzzy system, in IT2FS, meet and join operation could be used instead of union and intersection [28–31].
Knowledge base
The distinction between type-1 and type-2 is related to the nature of the membership function, which is not important while forming rules, hence the structure of the rules the same in type-2. The structure of the Mamdani interval type-2 fuzzy rule for the IT2FPIC is written as follows.

If $e_{PI}(k)$ is $A$ and $\Delta e_{PI}(k)$ is $B$ then $u_{PI}(k)$ is $C$.

Where $A$, $B$ and $C$ are the interval type-2 fuzzy membership functions. The inference engine combines the fired rules and gives a mapping from input IT2FS to output IT2FS [21-27].

Inference engine
In the type-2 fuzzy system, the inference engine combines the rules and gives a mapping from the input type-2 fuzzy system to the output type-2 fuzzy system. The inference process for a single rule is shown in Fig. 2.

Two firing levels and firing interval are computed as follows:

Lower firing level, $f = \min\{\mu_A(x), \mu_B(x)\}$ and upper firing level, $f = \min\{\mu_A(x), \mu_B(x)\}$.

The firing interval, $F = [f, f]$.

Type reducer / Defuzzifier
To combine the firing interval $F$ and rule consequent in the last step a type reducer is applied. The most commonly used one is the center of sets (COS) type reducer [24-31].

$$\sum_{n=1}^{N} f_n y_n = \bigcup_{y_n \in Y_n} \sum_{n=1}^{N} f_n \sum_{i=1}^{N} \sum_{j=1}^{N} [y, y]$$

Lastly, the defuzzified value of IT2FS is calculated as, $y[x] = \frac{1}{\Delta e}$.

Step2: Design of Interval Type-2 Fuzzy PI Controller (IT2FPIC)
Block diagram of IT2FPIC is depicted in (Figure 4) and the different MFs are used to develop this controller are presented in (Figures 5 to 7). The design procedure of the interval type-2 fuzzy system is already discussed in the previous section [32]. IT2FPIC for CO$_2$ is designed by using the input and output MFs depicted in (Figures 5 and 7) respectively. Similarly, IT2FPIC for humidity is developed by applying the input and output MFs presented in (Figures 6 and 7) respectively. The 7x7 If-Then rule base utilized in type-2 controller design is revealed in Table 1. $G_e$ and $G_{\Delta e}$ are the normalization factors for $e$ and $\Delta e$ respectively. $G$ is the de-normalization factor for output of the type-2 fuzzy controller, $u$.

![Figure 4. Block diagram of IT2FPIC](image-url)
The ranges selected for inputs (e, Δe) and output (u) for the entire proposed ventilated room design for COVID patients with CO2 and humidity control using fuzzy based controller are [-800ppm, +800ppm] and [-1, +1] for CO2 control and the ranges are [-100%, +100%] and [-1, +1] for humidity control respectively. As the standard CO2 concentration in the atmosphere is 400ppm and it increases sometimes up to 1000ppm due to air pollution. Here, each fuzzy model consists of only 49 fuzzy if-then rules as shown in Table 1. In this case, the specified spaces are uniformly divided into 7 fuzzy regions and assigned MFs accordingly. The term sets (shown in Table 1) for e, Δe, and u are linguistically represented as {NB, NM, NS, ZE, PS, PM, PB}.
Step3: Design of Self-tuned Interval Type-2 Fuzzy PI Controller (SIT2FPIC):

![Block diagram of the proposed SIT2FPIC for CO2 and Humidity control](image)

**Figure 8.** Block diagram of the proposed SIT2FPIC for CO2 and Humidity control

![MFs (e, Δe) for CO2](image)

**Figure 9.** MFs (e, Δe) for CO2

![MFs (e, Δe) for humidity](image)

**Figure 10.** MFs (e, Δe) for humidity

![Output MF (β) of CO2 and humidity](image)

**Figure 11.** Output MF (β) of CO2 and humidity

In this section, IT2FPIC is tuned by a type-1 fuzzy system. From (Figure 8), it is revealed that the same inputs (e, Δe) are used in type-1 fuzzy system design but their MFs are different as shown in (Figures 9 and 10). The output (β) of the type-1 fuzzy system with the range [0, 1] for the CO₂ and humidity control is also mapped into 7 fuzzy regions as {ZE, VS, S, SB, MB, B, VB} as shown in (Figure 11). The corresponding 49
fuzzy rules are presented in Table 2. The output of the type-1 fuzzy system (β) is varied according to the process parameter variations (ε, Δε), and this output (β) is used to modify/tune the output of IT2FPIC (u) as shown in (Figure 8).

4. Result
The proposed SIT2FPIC is utilized to control the air quality of the specially designed COVID patient’s treatment facility by fan drive. In this paper, IAQ is maintained by controlling CO2 concentration and % humidity and assumed temperature is constant in the room. The desired CO2 and % humidity are fixed at 800ppm and 60% respectively. However, the controller can perform at other set-points also. The performance of the proposed controller is compared with the type-1 fuzzy PI controller (T1FPIC) and self-tuned type-1 fuzzy PI controller (ST1FPIC). The T1FPIC is a simple fuzzy controller designed with 7x7 fuzzy if-then rules. The T1FPIC is modified to ST1FPIC by incorporating the same self-tuning strategy, applied in the proposed type-2 controller design. The control output of T1FPIC, ST1FPIC, and proposed SIT2FPIC are individually subjected to the ventilated room for effective humidity and CO2 control to provide the desired comfort to the patients and to minimize the transmission of coronavirus. The responses of the different controllers are investigated under step input as shown in (Figures 12 and 13). MATLAB Simulation experiments to maintain IAQ of COVID-19 treatment facilities by mechanical ventilation illustrated the merits of the proposed control scheme over other fuzzy controllers. (Figures 12 and 13) represent very smooth responses of humidity and CO2 in the case of SIT2FPIC compared to others. Especially, in the case of respiratory distress patients, it is very much essential to maintain indoor air quality; because any type of fluctuation may increase breathing problems. It is seen in Table 3 that to maintain the air quality, to provide comfort to the COVID patients, the output response of the proposed controller does not exceed the desired value. The percentage overshoot and settling time are found to be minimum in the case of SIT2FPIC.

Figure 12. Output response of different controllers for humidity control
Figure 13. Output response of different controllers for CO2 control

Table 3. Performance study in terms of settling time and %peak overshoot

| Controlled Parameters | Controllers | t<sub>s</sub> (sec) | %OS    |
|-----------------------|-------------|---------------------|--------|
| Humidity              | Proposed SIT2FPIC | 2.5510              | 0.0300 |
|                       | ST1FPIC     | 6.0965              | 5.6904 |
|                       | T1FPIC      | 2.8940              | 23.2825|
| Carbon dioxide        | Proposed SIT2FPIC | 6.8269              | 0.3697 |
|                       | ST1FPIC     | 15.6716             | 4.2223 |
|                       | T1FPIC      | 11.4787             | 25.1468|
Variations of load and disturbances are very common in any HVAC or IAQ monitoring [33]. In (Figures 14 and 15), negative and positive load variations in CO₂ and humidity processes are studied. It is found that the proposed SIT2FPIC can counteract the load variations very effectively.

**Figure 14.** Output response of different controllers for humidity control with varying load

**Figure 15.** Output response of different controllers for CO₂ control with varying load
5. Conclusion
This paper mainly focuses on indoor air quality monitoring by controlling the indoor CO₂ concentration and air humidity of any COVID-19 treatment facilities. A building with proper mechanical ventilation arrangement is designed for this purpose. The mathematical model of CO₂ and humidity is framed using the concept of physics. In the next section, for proper IAQ control a fuzzy-based tuning technique for an interval type-2 fuzzy PI controller is suggested. Here, the output of the proposed controller is continuously modified on-line in terms of a multiplying factor $\beta$, obtained through the proposed fuzzy tuning scheme. The study reveals that the implementation of the proposed SIT2FPIC on ventilated rooms showed much-improved performance compared to other fuzzy controllers. The presented simulation results have confirmed the ability of the new system to handle the critical ventilation problems. This work can be extended for future work as distributed network sensors throughout the buildings to monitor different gas levels as well as odors to provide the necessary ventilation for all the rooms. The proposed ventilation scheme can be implemented to monitor and control the oxygen supply to the patients suffering from respiratory diseases and also in neonatal ventilation. Drug administration and medicine dosage optimization may be the other use of the self-tuned type-2 fuzzy controller.

Reference
[1] Smart hospital projects, 2020 Retrofit measures for COVID-19 Pan American Health Organization 1-17
[2] WHO Publication/Guidelines 2009 Natural Ventilation for Infection Control in Health-Care Settings 1-133
[3] International Laboratory for Air Quality and Health (ILAQH) Queensland University of Technology 2020 How can airborne transmission of COVID-19 indoors be minimized? Environment International journal homepage: www.elsevier.com/locate/envint, 142 1-7
[4] ANSI/ASHRAE/ASHE Standard 170 2008 Ventilation of Health Care Facilities 1-20
[5] Grasselli G, Zangrillo A and Zanella A et al 2020 Baseline characteristics and outcomes of 1591 patients infected with SARS-CoV-2 admitted to ICUs of the Lombardy region, Italy JAMA 323(16) 1574-1581
[6] Gupta Shakti Kumar, kant Lt Col sunil, Chandrashekhar R, Satpathy Satyendar 2007 Modern Trends in Planning and Designing of Hospitals: Principles and Practice Jaypee Brothers Medical Publishers (P) Ltd. p. 199. ISBN 978-8180619120, 1-14
[7] Barnette Sonya 2015 Specification for HEPA Filters Used by DOE Contractors-DOE Technical Standards Program Retrieved US Department of energy, 1-27
[8] Fadli Pradityo and Nico Surantha 2019 Indoor Air Quality Monitoring System with Fuzzy Logic Control Based On IOT International Journal of Scientific & Technology Research 8 1824-1829
[9] Attia Abdel-Hamid, Sohair F. Rezeka and Saleh Ahmed M 2015 Fuzzy logic control of air-conditioning system in residential buildings Elsevier B.V. Alexandria Engineering Journal 1-9
[10] Agamy Hossam, Abdelhakim Mostafa, Mosleh Mosaid, Elserafy Kamel, Abdelrahman Nasr, and Mohamed Nasr, 2020 Neural Fuzzy Control of the Indoor Air Quality Onboard a RO-RO Ship Garage Int. J. Fuzzy Syst. 22, 1020-1035
[11] Saritas Ismail, Etik Nazmi, Allahverdi Novruz, and Sert Ibrahim Unal 2007 Fuzzy Expert System Design for Operating Room Air-Condition Control Systems International Conference on Computer Systems and Technologies 1-8
[12] Mohammad Abdel, Kareem Jaradat and Md. A. Al-Nimr 2009 “Fuzzy Logic Controller Deployed for Indoor Air Quality Control in Naturally Ventilated Environments Journal of Electrical Engineering 60 12-17
[13] Sam Matiur, Rahman Mohammad Fazle, Rabbi Omar, Altowjri Mahdi, Alqahtani Tasriva Sikandar, Izzeldin Ibrahim Abdelaziz, Md. Asraf Ali, and Kenneth Sundaraj 2018 Fuzzy Logic based improved ventilation system for the pharmaceutical industry International journal of engineering & technology 640-645
[14] Fiedoruk K G 2013 Correlations of air humidity and carbon dioxide concentration in the kindergarten Energy and Buildings 62 45-50
[15] Fiedoruk K G 2019, Indoor Air Quality in the Bedroom of a Single-Family House-A Case Study Proceedings 16, 38; doi: 10.3390/proceedings 2019016038
[16] Lee, C C 1990 Fuzzy logic in control systems: fuzzy logic controller-Parts I, II. IEEE Trans.on Syst. Man, Cyber 20 404-435,
[17] Mudi R K and Pal N R 1998 A self-tuning fuzzy PD controller IETE Journal of Research (Special Issue on Fuzzy Systems) 44 177-189
[18] Zadeh L A 1975 The concept of a linguistic variable and its application to approximate reasoning Inform Sci. 8 199-249
[19] Mizumoto, M. and Tanaka K 1981 Fuzzy sets of type-2 under algebraic product and algebraicsum Fuzzy Sets Syst 5 277-290
[20] Liang, Qilian and Mendel Jerry M. 2000 Interval Type-2 Fuzzy Logic Systems: Theory and Design IEEE transactions on fuzzy systems 8 535-550
[21] Karnik N N and Mendel J M 2001 Operations on type-2 fuzzy sets Fuzzy Sets Syst. 122 327-348
[22] Mendel Jerry M 2007 Advances in type-2 fuzzy sets and systems Science direct Information Sciences, 177 84-110
[23] Manceur M, Essounbouli N and Hamzaoui A 2012 Second-order sliding fuzzy interval type-2 control for an uncertain system with real application IEEE transactions on fuzzy systems 20 262-275
[24] Lynch C, Hagras H and Callaghan V 2005“Embedded type-2 FLC for the speed control of marine and traction diesel engines Proceedings of IEEE International Conference on Fuzzy Systems 347-353
[25] Maldonad01 Y and Castillo01 O 2012 Genetic design of an interval type-2 fuzzy controller for velocity regulation in a dc motor International Journal of Advanced Robotic Systems 1-8
[26] Ahmad M El-Nagar and M. El-Bardini 2014 Practical implementation for the interval type-2 fuzzy PID controller using a low-cost microcontroller Ain Shams engineering journal 5 475-487
[27] Biglarbegian M, Melek W, Senior W and Mendel Jerry M 2010 On the stability of interval type-2 TSK IEEE transactions on Systems, Man, and Cybernetics—part b: cybernetics 40(3) 798-818
[28] Lin Yang-Yin, Chang Jyh-Yeong, Pal Nikhil R and Lin Chin-Teng 2013 A mutually recurrent interval type-2 neural fuzzy system (mrit2nfs) with self-evolving structure and parameter IEEE Transactions on Fuzzy Systems 21 492-509
[29] Ahmad M., El-Nagar and M. El-Bardini 2017 Parallel realization for self-tuning interval type-2 fuzzy controller Engineering Applications of Artificial Intelligence journal 61 8-20
[30] Lu Xingguo and Ming Liu 2016 Optimal design and tuning of PID-type interval type-2 fuzzylogic controllers for delta parallel robots International Journal of Advanced Robotic Systems 1 1-12
[31] Dongrui Wu and Woei Wan Tan, 2006 A simplified type-2 fuzzy logic controller for real-time control ISA Transactions 45 503-516
[32] Naskar Indrajit and Pal A K 2017 Type-2 Fuzzy Controller with Type-1 Tuning Scheme for Overhead Crane Control Communications in Computer and Information Science book series (CCIS) 776 567-576
[33] Pal A K and Mudi R K 2008 Self-tuning fuzzy PI controller and its application to HVAC systems International Journal of computational cognition 6 25-30