Development of Optimal Fuzzy-PID Controller for an Assistant Human Knee Exoskeleton System

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***Abstract*—In this paper, an optimal fuzzy-PID controller is proposed for a knee exoskeleton model for patients with knee problems caused by strokes, post-polio, osteoarthritis, etc. For this purpose, a fuzzy control logic based proportional integral derivative (Fuzzy-PID) controller is considered. The fuzzy controller in the proposed control structure is used to adjust the PID controller parameters for the knee exoskeleton model. The error between the targeted angle and actual angle of knee exoskeleton system and the change of this error are taken as the input variables of the fuzzy controller. The output variables are chosen as the parameters of PID controller. The membership functions of the fuzzy controller are optimized with a well-known optimization algorithm called class topper optimization. The performance of the proposed controller is examined under different scenarios and plotted on a graph.**

***Index Terms*—Knee exoskeleton model, Fuzzy controller, Optimization method, Optimal control**

I. Introduction

Exoskeletons are a new class of service robot that has recently gained great interest among researchers and engineers across several communities [1]. Exoskeletons are wearable robots that people can use to compensate for physical limitations when doing tasks like adjusting mobility, boosting strength, and carrying burden. Lower extremity exoskeletons are frequently used to assist subjects with gait training by assisting human motion. Knee exoskeletons are simple-design machines that are specifically designed and implemented to help people suffering from knee problems caused by injury, stroke, post-polio, osteoarthritis, etc. These machines are studied worldwide due to the increase of cases of knee impairments amongst people [2]. As these people are unable to perform their daily life activities and lead a normal life, knee exoskeleton helps in improving the physical as well as mental health of patients by helping them fight their knee dysfunctions and giving them the ability to walk normally again (not all cases) [3].

With the application of power to the knee joint, this device allows a greater control on the knee movement and gains on the movement. It helps in improving gait symmetry and the overall cycle. They are also therefore, often used in gait rehabilitation centre. In traditional physical therapies, physically demanding tasks are generally required to help patients with knee impairments [4]. These machines can also help these physical therapists in making their work easier and less time/energy consuming.

The most common structure in existing knee exoskeletons is the single-axis knee joint where its design utilizes a single hinge structure. When the knee angle is not too great, the single hinge joint is appropriate during the stance phase. During the swing phase, a polycentric knee centre of rotation is necessary because to the high knee angle. The passive knee exoskeleton for cycling assistance [5] and the quasi-passive knee exoskeleton for stair ascending both use the crossing four-bar knee joint [6]. In these two exercises, it is difficult to prevent a significant knee angle.

On the other hand, stance phase cannot be controlled sufficiently. In a normal knee-joint movement, the centre of rotation changes with every gait cycle (Polycentric motion) and this is one of the main drawbacks of the single-axis exoskeleton as it fails to completely and efficiently track the human knee-joint movement which also leads to the loss of energy [7]. To tackle this problem, a four-bar linkage is used as it reduces the relative motion. Therefore, it provides a more polycentric motion similar to a human knee joint and reduces the energy loss [8]. It is nearly similar to the human knee-joint movement. It also improves comfort and gives better gait movement. Four-bar linkages are thus more preferred over single-axis ones as it helps in minimizing these drawbacks [9]. The contributions of this chapter are as follows:

- The rotational movement of the knee exoskeleton system is improved with a Fuzzy-PID controller.
- An optimal fuzzy inference system is designed for the Fuzzy-PID controller.
- A systematic design procedure to optimize membership functions of the proposed controller is presented.
- A clustering nature based class topper optimization algorithm is used to optimize the fuzzy-PID controller.
- During any change in the system, the optimized fuzzy controller will auto adjust the gains of PID controller for the exoskeleton movement.

II. Mathematical modeling of Knee exoskeleton system

Knee exoskeletons are solely designed in order to carry out the flexion-extension movement of the human knee joint. Two main segments are considered when designing a knee exoskeleton as shown in Figure 1. These segments are connected to each other through the implementation of a four-bar mechanism [1]. It consists of two (upper and lower) supports

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and these are fixed. The knee joint has a one degree of freedom. The rotational movement of the knee exoskeleton system will be implemented using linear actuators [3].

The motor connected to the crank is operated and is used to control the torque as well as the rotation speed of the entire system using the four-bar linkage. The utilised four-bar linkage as well as the angle and length of each link, are depicted in Figure 2. The position vectors surrounding the entire four-bar linkage are simply added during loop closure. It can be represented as:

$$L_1 e^{j\theta_1} + L_2 e^{j\theta_2} + L_3 e^{j\theta_3} + L_4 e^{j\theta_4} = 0, \quad (1)$$

The link lengths are all constant, and there are four variables: L_1, L_2, L_3, L_4. The angle of the link is fixated and can be compared to the ground link. A motor is used to control the independent variable. Also, the function for constant link length and input angle are defined as follows:

$$\theta_3 = f_1(L_1, L_2, L_3, L_4, \theta_2); \quad (2)$$

$$\theta_4 = f_2(L_1, L_2, L_3, L_4, \theta_2). \quad (3)$$

Links 2 and 4 act as the input and output of the mechanism, respectively, hence the solutions should take into account both of these angles (θ_2 and θ_4). Now that equations (2) and (3) have been solved concurrently, equations (4) and (5) should be squared and added to eliminate angle θ_3:

$$(L_3 s_3)^2 = (-L_2 s_2 - L_4 s_4)^2; \quad (4)$$

where s_2 is $\sin\theta_2$, s_3 is $\sin\theta_3$, and s_4 is $\sin\theta_4$.

$$(L_3 c_3)^2 = ({L_1}^2 - L_2 c_2 - L_4 c_4)^2. \quad (5)$$

where c_2 is $\cos\theta_2$, c_3 is $\cos\theta_3$, and c_4 is $\cos\theta_4$.

Squaring and summing Eq. (4) and (5), we get

$${L_3}^2 = f(L_1, L_2, L_4, \theta_2, \theta_4). \quad (6)$$

By applying the trigonometric identity, the outcome is represented as follows:

$$k_1 c_2 + k_2 c_4 + k_3 = \cos(\theta_2 - \theta_4), \quad (7)$$

where $k_1 = \frac{L_1}{L_4}$, $k_2 = \frac{L_1}{L_2}$, $k_3 = \frac{{l_3}^2 - {L_1}^2 - {L_2}^2 - {L_4}^2}{2 L_2 L_4}$.

The accuracy points for the linkage bar are carefully selected with consideration given to the shank angle, and the equations are solved utilising the technique described in Freudenstein's work. Knowing k_i, the link lengths,L_i can be calculated.

Now, if $L_1 = 1$, then the remaining three links can be calculated. In order to find the desired lengths for the four links, the entire linkage is scaled up or down. The designed link lengths in this paper are considered from [1]. In this paper, L_1 is 29 mm, L_2 is 35 mm, L_3 is 15 mm, and L_4 is 45 mm.

A. Knee Exoskeleton Dynamics

The equation for the knee exoskeleton system is given by,

$$J\ddot{\theta} = -\tau g \cos\theta - B_1 sign\dot{\theta} - B_2\dot{\theta} - K(\theta - \theta_0) + \tau + \tau_h \quad (8)$$

whereJ = Js + Je, τg and K are the sum of inertias in the exoskeleton, the gravitational term, and the stiffness in thejoint respectively. θ is $[\theta_2, \theta_4]$. $B_1 = B_{1s} + B_{1e}$ is the solid friction parameter and $B_2 = B_{2s} + B_{2e}$ is the viscous friction parameters. $\tau$is the input torque of the actuator and τ_h is the input torque from human effort.

For modelling the knee exoskeleton system, state variables are $x_1 = \theta$, $x_2 = \dot{\theta}$, and U $= \tau$ is the control variable. Hence,

$$\dot{x} = F(x) + G_1(x)U \quad (9)$$

where,

$$F(x) = \begin{pmatrix} x_2 \\ f(x) \end{pmatrix};$$
$$f(x) = 1/J(-\tau g \cos\theta - B_1 sign\theta - K(\theta - \theta_{(0)}));$$
$$G_1(x) = \begin{pmatrix} 0 \\ 1/J \end{pmatrix};$$

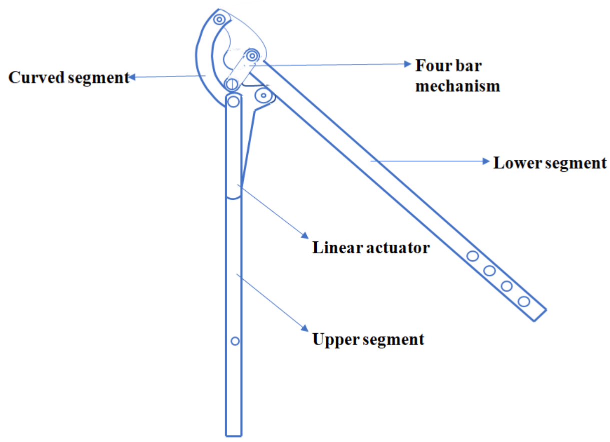


Fig. 1: Knee exoskeleton segments [1].

III. Problem Formulation

For this investigation, the proposed Knee Exoskeleton model from the preceding section is applied. Fig. 3 displays the Knee exoskeleton system's control structure. This device formulates a patient-focused control loop for the knee system by combining a traditional PID structure with a fuzzy controller with optimal membership functions. The error between the targeted angle and actual angle of knee exoskeleton system and the change of this error are taken as the input variables of the fuzzy controller. The output variables are chosen as the parameters of PID controller. Membership functions associated with the fuzzy input-output variables are optimized with a

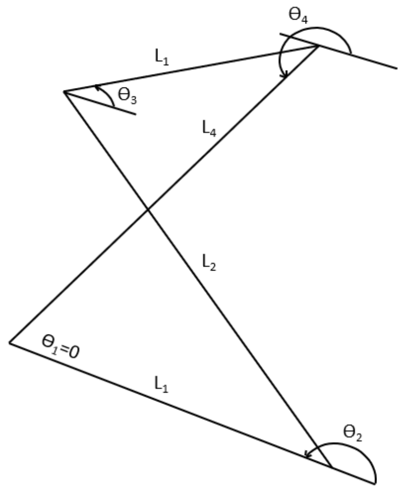


Fig. 2: Four bar linkage [1]

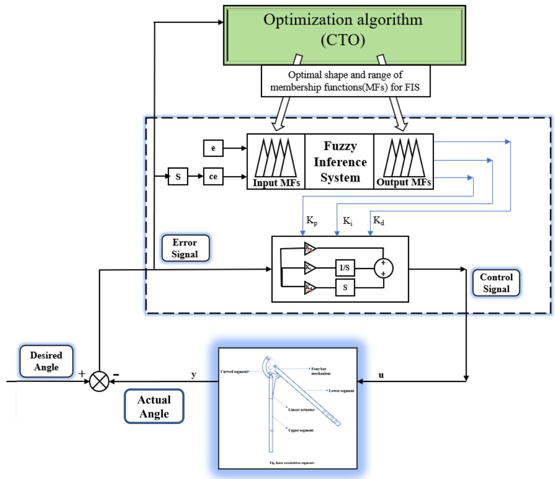


Fig. 3: Fuzzy-PID control scheme for Knee Exoskeleton System.

metaheuristic algorithm. The optimal fuzzy controller will automatically adjust the PID controller gains if there is a system disruption. The PID controller's parameters (proportional gain (K_p), integral gain (K_i), and derivative gain (K_d)) are auto adjusted by the optimal fuzzy controller.

The optimal MFs for fuzzy inputs and outputs are evaluated based on an objective function for the knee exoskeleton system. When optimising the membership functions of a fuzzy controller, an integral time absolute error between the desired angle and the actual angle of the knee exoskeleton system is taken into account:

$$\Im_1 = \int_0^T t|e|dt, \tag{10}$$

where $e_{\min} \le e \le e_{\max}$, $ce_{\min} \le ce \le ce_{\max}$, $k_{p\,\min} \le k_p \le k_{p\,\max}$, $k_{i\,\min} \le k_i \le k_{i\,\max}$, $k_{d\,\min} \le k_d \le k_{d\,\max}$.

The initial ranges of all such variables are selected on the basis of trial and error method for simulating the proposed control scheme for the Knee Exoskeleton model.

IV. Class Topper Optimization (CTO)

The class topper optimization (CTO) is based on a metaheuristic optimization algorithm [10]. The primary principle behind this algorithm is that the intelligence and learning ability of the students in a class can be used to define a topper in the class. Each student in a class aspires to perform better at each exam phase in order to achieve and become the topper in that class.Students in each section of the class typically have the same learning style [11]. In this way, the technique gradually converges on global solutions. According to CTO, the best student in that section (section topper) teaches the other students in that section. On the other side, section winners enhance their results by learning from the overall winner. As a result, at every exam stage, all candidates will be advancing their skills. The best student is a class topper or the global optimum. A class could have some sections. In each segment, the pupils' learning behaviour is consistent. Typically, a section's top student, known as the section topper, teaches the rest of the students in that section (ST). Class topper refers to the top student among section toppers (ST) in a class (CT) [12].

Assume that there are (SEC) sections in a class with (S) students in each section. The test will be run (j) times in total. Pupil capacity (Prf) has been enhanced as follows by the CTO:

$$Ex^S{}_{(j+1)} = Whf * Ex^S{}_{(j)} + Ca * rd * (CT_j - S(j)), \tag{11}$$

$$Prf^S{}_{(j+1)} = Prf^S{}_{(j)} + Ex^S{}_{(j+1)}, \tag{12}$$

where $Ex^{ST}{}_{(j+1)}$ is marks obtained by S at $(j+1)^{th}$ test, Whf is weight factor, Ca is acceleration factor, rd is random gain, $Prf^S{}_{(L,j)}$ is the score of S^{the} pupil at j^{th} test. For class level, $S(j)$ is $ST(j)$ and in section level.

A. Advantage of CTO

The reason of choosing of CTO is the clustering nature of the algorithm. In this algorithm the complete search space is devided into some sections or local search space which allows to find global solution easily. The exploration and exploitation process can be balanced efficiently by searching local optimal solutions in each section (local search space). Compering among them, the global solution can be found.

V. Steps for creating fuzzy type-1 systems using CTO

Step 1: Prepare a fuzzy inference system (FIS)

Initially, an inference system is prepared for the fuzzy type-1 system.

Inputs of FIS: The FIS receives inputs from the knee exoskeleton system's error (e) and change in error (ce) between the desired and actual knee positions. For FIS inputs, the following membership functions (MFs) are used:

$$MBF_{inputs} = [NL, NM, NS, ZE, PS, PM, PB] \quad (13)$$

where NL denotes negative large, NM denotes negative medium, NS denotes negative small, ZE denotes zero, PS denotes positive small, PM denotes positive medium, PB denotes positive big.

The FIS takes triangular forms for its input MFs. Trial and error is used to choose the initial error ranges and change in errors.

Outputs of FIS: As outputs of the initial FIS, the PID controller's parameters (k_p, k_i, and k_d) are used. The following are the MFs for each output variable of the first FIS: :

$$MBF_{inputs} = [NL, NM, NS, ZE, PS, PM, PB] \quad (14)$$

The output MFs of the FIS are assumed to have triangular beginning forms. For the knee exoskeleton system, the initial ranges of membership functions for each output variable (k_p, k_i and k_d) of the initial FIS system are determined based on trial and error method.

Rule base for FIS: With the knowledge of the fundamental PID controller performance for a system, a set of 36 rules for each output variable of the original FIS is created. The rule base for the outputs (k_p, k_i and k_d) is presented in Table **??**.

Step 2: Initialization of membership functions

Assign range of membership functions of fuzzy variables: Assign range of each membership function for each fuzzy variable (inputs and outputs) as follows: For input variables: $MF_{e_{\min}} \leq MF_e \leq MF_{e_{\max}}$ and $MF_{ce_{\min}} \leq MF_{ce} \leq MF_{ce_{\max}}$.

For output variables: $MF_{k_{p\,\min}} \leq MF_{k_p} \leq MF_{k_{p\,\max}}$, $MF_{k_{i\,\min}} \leq MF_{k_i} \leq MF_{k_{i\,\max}}$, $MF_{k_{d\,\min}} \leq MF_{k_d} \leq MF_{k_{d\,\max}}$

Step 3: Generate initial range of MFs

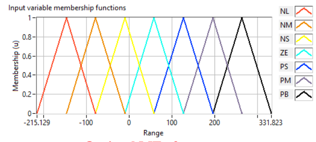
Create a population of random ranges that fall within the designated boundary for each fuzzy input and output variables. The following processes have been used to build the upper point, centre point, and lower point of each triangular-shaped upper and lower MFs inside the randomly generated ranges of each fuzzy variable.

The three numbers of upper MFs of each variable are distributed by using the following equation:

$$mf_{ij_{upper}} = x_{\min} + (i + j - 3)\left(\frac{x_{\max} - x_{\min}}{i_{\max} - 1}\right) \quad (15)$$

Where x is ranges of membership variables (e, ce, k_p, k_i, k_d), $i = 1 \ldots 3, j = 1 \ldots 7$.

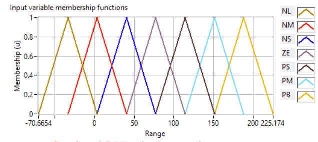
Step 4: Optimizing upper and lower membership functions The FIS created above is optimised using the CTO algorithm considering the ranges of each fuzzy variables as the searching variables.



a. Optimal MF of error

MFs	Lower Point	Central Point	Upper Point
NL	-215.129	-146.76	-78.3914
NM	-146.76	-78.3914	-10.0224
NS	-78.3914	-10.0224	58.3466
ZE	-10.0224	58.3466	126.716
PS	58.3466	126.716	195.085
PM	126.716	195.085	263.454
PB	195.085	263.454	331.823

b. Optimal points of MF of error

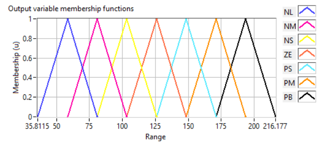


c. Optimal MF of change in error

MFs	Lower Point	Central Point	Upper Point
NL	-70.6654	-33.6855	3.29442
NM	-33.6855	3.29442	40.2743
NS	3.29442	40.2743	77.2543
ZE	40.2743	77.2543	114.234
PS	77.2543	114.234	151.214
PM	114.234	151.214	188.194
PB	151.214	188.194	225.174

d. Optimal points of MF of change in error

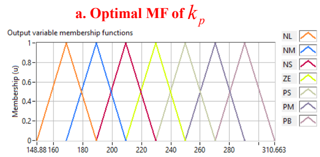
Fig. 4: Optimal MFs for fuzzy inputs variables.



a. Optimal MF of k_p

MFs	Lower Point	Central Point	Upper Point
NL	35.8115	58.3572	80.9029
NM	58.3572	80.9029	103.449
NS	80.9029	103.449	125.994
ZE	103.449	125.994	148.54
PS	125.994	148.54	171.086
PM	148.54	171.086	193.631
PB	171.086	193.631	216.177

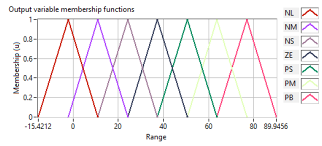
b. Optimal points of MF of k_p



c. Optimal MF of k_i

MFs	Lower Point	Central Point	Upper Point
NL	148.88	169.103	189.325
NM	169.103	189.325	209.548
NS	189.325	209.548	229.771
ZE	209.548	229.771	249.994
PS	229.771	249.994	270.217
PM	249.994	270.217	290.44
PB	270.217	290.44	310.663

d. Optimal points of MF of k_i



c. Optimal MF of k_d

MFs	Lower Point	Central Point	Upper Point
NL	-15.4212	-2.25033	10.9205
NM	-2.25033	10.9205	24.0914
NS	10.9205	24.0914	37.2622
ZE	24.0914	37.2622	50.4331
PS	37.2622	50.4331	63.6039
PM	50.4331	63.6039	76.7748
PB	63.6039	76.7748	89.9456

d. Optimal points of MF of k_d

Fig. 5: Optimal MFs for fuzzy output variables.

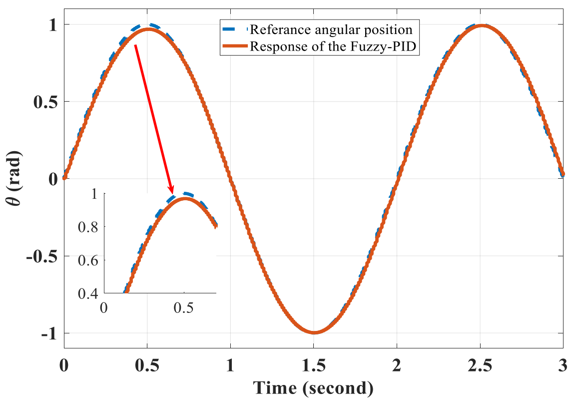


Fig. 6: Response of the proposed controller.

VI. Simulation and Result Analysis

In this section, the optimum MF based Fuzzy-PID controller is simulated and analysed for position control of the knee exoskeleton system. In order to accomplish this, the recommended control framework, CTO algorithm, and the

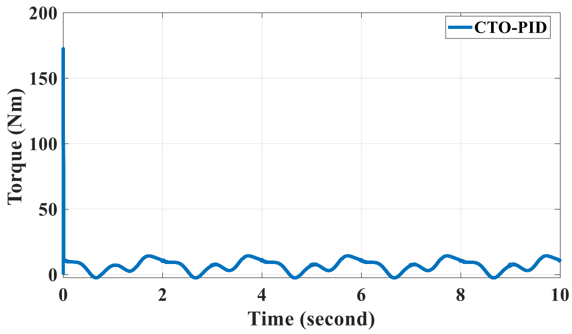


Fig. 7: Control signal generated by the proposed controller.

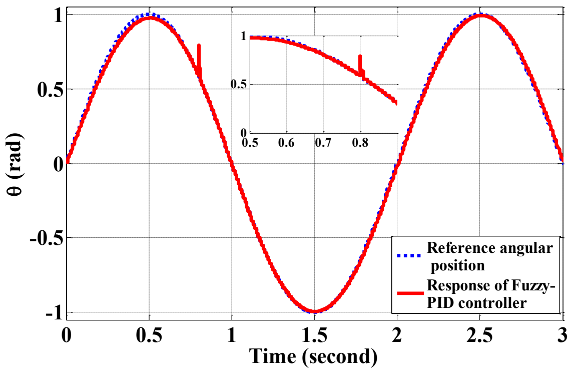


Fig. 8: Controller response under a disturbance of angular position in the knee exoskeleton system.

exoskeleton system's transfer-function model are used in LabVIEW©2015 platform. For a desired position of the knee system, a sine signal with amplitude 1, frequency 0.5 is considered. The initial ranges of the membership function of the fuzzy controller parameter for the knee system are set randomly within a desired range.

For this reference knee position, we have optimised the controller parameters with the CTO algorithm. The parameters of the CTO are presented in Table II. The CTO algorithm is made to run for 500 times with the simulation time of 10sec for each iteration. The optimal MFs as obtained by the CTO algorithm are presented in Figures 4 and 5. With the optimized FIS, the fuzzy controller will set the gains of PID controller for the knee exoskeleton system. The PID parameters are found as follows: k_p is 189.41, k_i is 286.654, and k_d is 74.309. The response of the proposed control scheme is shown in Figure 6. It is observed that the position of the knee exoskeleton system is exactly tracking the desired position. The control torque generated by the fuzzy-PID controller is presented in Figure 7. The average and RMS value of tracking error by the proposed controller are approximately -0.014728059 and 0.0223449 respectively, in the absence of external disturbance. For the same system, the RMS value of tracking error is 0.1776 with NDO RTSMC [13], 0.0305 SMC [14] and 0.0693 SMC [9].

To check the disturbance handling capability of the proposed controller, a disturbance of angular position of 0.2 rad at time 0.8 second is introduced in the knee exoskeleton system. The performance of the proposed controller under this scenario is observed and presented in Figure 8. It is found that the proposed controller can overcome the external disturbance to bring the angular knee position in desired one.

e\ce	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NL	NL	NL	NL	NM	NS	NS	ZE
NM	NL	NL	NM	NS	NS	ZE	PS
NS	NL	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	M	B	PS	PM	PM	PB	PB

TABLE I: Rule for $K_p, K_i, and K_d$

TABLE II: Range and value of parameters and constants to implement CTO

Parameter	**Range/Value**
Section Size	3
Total Population Size	90
Iteration number	100
K_p	1.4 to 2
K_i	130 to 150
K_d	0.004 to 0.006
Whf_{max}	0.9
Whf_{min}	0.4
C	1.4

Remark 1: During simulation, a set of ranges of different fuzzy input-output variables are selected on the basis of trial and error for the knee exoskeleton system in presence of proposed controller. The optimal ranges of error and change in error may vary in real application. According to that, the optimal ranges of all fuzzy variables will be set by the CTO algorithm. Once the fuzzy variables are optimally set, it can adjust the PID controller for the knee system.

VII. Conclusion and Future Work

From this work, the in-depth information on the knee exoskeleton system was studied. Various factors like design, mechanical structure, modelling of knee exoskeleton system are also studied. State of art devices like PID and optimal fuzzy controller and their working based on the knee system are also reviewed. For a simple knee exoskeleton system, an optimal Fuzzy-PID controller has been designed for a reference sine signal. The purpose of this study is to model a knee exoskeleton system operated by an optimal Fuzzy-PID controller. During any adjustments to the Knee system, the PID controller settings are automatically tuned by the best fuzzy controller in this process. For real implementation, a detail performance analysis of the proposed controller for the system can be made with available work [2]. In the present work, a simple Knee exoskeleton system is verified with the proposed control scheme. One can extend the work for a higher-order system. Moreover, the rule base system of fuzzy controller can also be optimized to establish optimal coordination between fuzzy input-output variables.

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