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Invasive Weed Optimization Algorithm Optimized Fuzzy Logic Scaling Parameters In Controlling A Lower Limb Exoskeleton

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***Abstract*—This paper describes a new modified versions of invasive weed optimization algorithm with exponential seeds-spread factor. The modified invasive weed optimization algorithm (MIWO) is employed to optimize the fuzzy input-output scaling factors of lower limb exoskeleton. A fuzzy logic control (FLC) system with the (MIWO) are evolved for reference tracking control. The exoskeleton is developed to enhance and upgrade the lower limb capability and augment the torque of knee and hip of elderly people during the walking cycle. Invasive weed optimization is a bio-inspired search algorithm that mimics how weeds colonize a certain area in nature. The algorithm is modified by applying local knowledge during distribution of seeds that depends on their cost function value in each generation to narrow the accuracy and improve the local search ability. The obtained results from the modified invasive weed optimization algorithm are compared with heuristic gain values to improve the performance of the exoskeleton system. The Visual Nastran 4D software is used to develop a simulation model of the humanoid and an exoskeleton for testing and verification of the developed control mechanism. Simulation results demonstrating the performance of the adopted approach are presented and discussed.**

I. INTRODUCTION

Recently, considerable attention has been paid for bio-inspired optimization techniques. The invasive weed optimization (IWO) algorithm is one of the bio-inspired algorithms, initially proposed by Mehrabian and Lucas in [1]. The IWO algorithm is currently used to solve various challenging problems and is constantly evolving. Despite this, the development of more effective ways to arrive at global solution is highly relevant. Thereby, the aim of this work is to develop an improve version of the IWO with the ability to achieve accurate solutions. Moreover, optimisation techniques will enable to achieve the desired characteristics for a control process. A discussion of current work on modification of IWO algorithm for control of flexible systems is presented in this paper. One of the ways to improve the IWO is by changing the standard deviation (SD) mechanism of seeds distribution. Several attempts to improve the SD mechanism have been proposed by researchers such as using chaotic mechanism [2] and modified adaptive SD [3]–[6]. A modified approach to SD measurement of seeds distribution in each generation is developed to improve performance of the original algorithm.

The control methodology is key technology in the exoskeleton area. Literatures shows that many types of controllers have been used such as EMG, PID and intelligent algorithms [7]. PID control is the widely used for its reliability and simplicity. However PID control may not be very efficient for exoskeleton systems because of the system is complex and nonlinear [8]. Fuzzy logic is an example of intelligent algorithms, which has good adaptabilities to the exoskeleton system with uncertain parameters. The work presented in this paper builds on previous work of the authors [9], which was based on conventional PID control. The current work develops a fuzzy control mechanism with IWO algorithm for tracking and control human movement with exoskeleton. Specifically, achieving the fuzzy rules require expert to transfer the involved knowledge into linguistic variable. It does not need precise mathematical equations, instead relay on knowledge based rule of the systems requirement.

Many optimisation algorithms are used to optimize the parameters of fuzzy controller. These can be classified into genetic algorithm, (GA) [10], [11], particle swarm optimisation, (PSO) [12]. The use of IWO in optimizing fuzzy controller parameters has not been reported.

In this work, a methodology based on optimising the fuzzy logic parameters using The invasive weed optimization (IWO) algorithm is presented. The optimised fuzzy control is implemented to the lower limb exoskeleton for walking task and the performance is compared between the optimized IWO and the heuristic technique. The paper is organized as follows: section 2 describes The invasive weed optimization (IWO) algorithm, section 3 and 4 describe the humanoid model and the designed exoskeleton with the control structure investigated, and section 5 presents the simulation results and the paper is concluded in section 6.

II. IWO OPTIMISATION ALGORTHIM

Invasive weed optimization is a type of ecologically inspired optimization algorithm based on colonizing of weeds, and was

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introduced by Mehrabian and Lucas. The IWO algorithm mimics the natural behaviour of weeds in colonizing and searching suitable place for growth and reproduction. Weeds are vigorously invasive and robust plants able to adapt to changes in the environment, posing as threat to agriculture. The robustness, adaptation and randomness of the algorithm are shown by imitating a natural phenomenon of invasive weeds. In the IWO algorithm, the process simulates the survival of weeds colony, where it begins with initializing the initial plant in the search area. The plant is spread randomly in the search place. Each member is able to produce seeds. However, production of seeds depends on their relative fitness in the population. The worst member produces minimum number of seeds (s_{min}) and the best produces maximum number of seeds (s_{max}) where the weeds production of each member is linearly increased. After that, the seeds are randomly scattered over the search space near to its parent plant. The scattering process uses normally distributed random number with standard deviation (SD) as

$$\sigma_{iter} = [\frac{(iter_{max} - iter)}{iter_{max}}]^n(\sigma_{max} - \sigma_{min}) + \sigma_{min} \quad (1)$$

where $iter_{max}$ is maximum iterations,iter is current iteration, n is the nonlinear modulation index, σ_{max} is usually initial SD and σ_{min} is the final SD in the optimization process. The seeds with their respective parent plants are considered as potential solution for subsequent generations. In order to maintain the size of population in the search area, the algorithm conducts a competitive exclusion, where an elimination mechanism is employed; if the population exceeds its maximum size only the plants with better fitness can survive. Those with better fitness produce more seeds and with high possibility of survival and become reproductive. The process continues until the maximum number of iterations is reached and the plant with best fitness is closest to the optimal solution.

A. *Modified IWO with exponential seeds-spread factor*

Therefore, in order to enhance the search strategy and get desired global minimum a new modification is proposed in this paper. The proposed modification improves the neighbourhood search of weeds depending on their cost function. The new search mechanism will be formulated and verified by optimizing several benchmark functions in comparison with the original IWO method.The modified IWO with exponential seeds-spread factor (MIWO-eSSF) algorithm proposed that is aimed to provide better balance between global and local search as well as achieve in more accurate result during the iteration process. However, variation in the SD are made exponential in the spatial dispersion process. By adding the new factor in the equation (1), the new SD is given as

$$\sigma_{iter} = k[\exp\{\tau[\frac{iter_i}{iter_{max}}]^\delta\}](\sigma_{ini} - \sigma_f) + \sigma_f \quad (2)$$

where the values of σ_{ini},σ_f,and $iter_{max}$ are as described in the initial parameters setting of the algorithm. The values of τ and δ are pre-set to determine the shape of the exponential slope changes of the SD during the iteration process. It is assumed that τ = 2 and δ = 4, which are found as competitive values for MIWO-eSSF. In this work, investigations on adaptive spread factor distribution of SD of the seeds are carried out. To make the computational complexity simpler, exponential distribution was adopted. In order to control changes of SD, the following spread factor relation is used:

$$\sigma_i = \frac{\sigma_{iter} - \sigma_{final}}{\frac{|f_i| - f_{max}}{ef_{min} - f_{max}}} + \sigma_{final} \quad (3)$$

where σ_i is SD for every i weed,f_{min} and f_{max} are minimum and maximum fitness functions in the colony respectively, $|f_i|$ is an absolute fitness value of every weed, σ_{final} is final SD and σ_{iter} is SD for each iteration which is calculated using equation (2). Using the equation (3), the SD will vary in the range [σ_{final} σ_{iter}] at each iteration. In this way, the exploration ability of weeds located closer to the best weed increases and allows searching around the optimal solution. It is worth mentioning that modified SD equation (2) with the adaptive spread factor (3) is necessary to handle the task from a new point of view and an original improvement may be achieved based on the proposed strategy.

III. SYSTEM MODEL

A. *HUMANOID MODEL*

The human model segment parameters were built according to the anthropometric data presented by winter [13]. A humanoid model of 75 kg weight and 1.7m length is used in this work. The humanoid was designed in Solidworks software and exported to Visual Nastran 4D (VN4D). Visual Nastran 4D software is a combined Computer aided design (CAD) which is a virtual environment developed by MSC Software Corporation for the designing of 3D model and assemblies. Due to the complexity in identifying the lower limb musculoskeletal system with traditional mathematical model because of the nonlinearity. The VN4D allows development of simulation models of complex mechanical systems easily [9], [14], [15]. Furthermore, it links with Matlab/Simulink for development and testing of controllers. It is important to mention that simulations were performed with fixed trunk , therefore no contact with the ground is considered at this stage.

In the humanoid model the hip and knee joints follow the reference orientation from Clinical Gate Analysis (CGA) data, which was collected by recording video motion for standard walking cycle.Hip and knee joints are controlled based on these references with the outputs being torque signals (Nm) which are sent to the exoskeleton and humanoid actuators in VN4D. While the ankle motion is defined as:

$$Xankle = L_{th}sin(\theta_h) + L_{sh}sin(\theta_k). \quad (4)$$

$$Yankle = L_{th}cos(\theta_h) + L_{sh}cos(\theta_k). \quad (5)$$

Where θ_h, and θ_k are the hip and knee joint angles respectively. L_{th}, and L_{sh} represent the length or height of thigh, and shank respectively. These where L_{th} = 416.5mm, L_{sh} = 418.2 mm in this work.

B. EXOSKELETON

The PCM, Proyecto Control Montaje, S.L have been designed the exoskeleton model used in this section, as part of the EXO LEGS project [16]. The Solidworks software was used to modify and simplify the CAD model to 16 parts per leg [17]. Later these parts were exported to VN4D and then linked by Matlab Simulation. The thigh and leg represent by length adjustment joints used to adapt the exoskeleton to humanoid dimensions.Two actuated joints are applied to the exoskeleton for hip,and knee joints.The exoskeleton can perform many functions, and its main purpose is assistive mobility for elderly. The second purpose is to provide assistive torque to reduce the torque (effort required) of the humanoid joint during the walking cycle [18], [19]. Light weight and low cost material are the main mechanical design considerations; a glass fibre reinforced polymer (GFRP) is used in this work. It provides back support and consists of waist part, upper leg parts, lower legs parts, soles and hip and knee joint. Sensors are added to get feedback from the system; orientation and torque at hip, knee and ankle joints are monitored. The final design was incorporated into the humanoid model as shown in Fig.1.The exoskeleton in this work is expected to transfer the force directly to the ground therefore sole segment is included.

Figure 1. The Combination of Humanoid with Exoskeleton

IV. FUZZY LOGIC CONTROL

The control methodology takes essential role in controlling the exoskeleton. The exoskeleton is to follow the human movement all the time, which makes the exoskeleton system more complex [8], [20], [21]. It is evident from reviewing the previous work, that the main issue of elderly mobility is body weight, so support should be provided by the exoskeleton system to the user all the time. The fundamental goal of the control method is to provide an assistive torque to enhance the ability of elderly people to walk. Many exoskeleton system designs do not take into consideration self-balancing control; instead, the user will control the exoskeleton balancing. Moreover, the measured real force generated by human muscle varies with different people.

Fuzzy logic control has been well known due to ability in representing and controlling a complex nonlinear system without describing accurate a mathematical model of the system. Lutfi zadeh was firstly introduced the idea of fuzzy set theory in1965. The FLC converts the input value to a continuous value between 0-1 by the concept of logical linguistic. The fuzzy logic is essentially a words computation more than numbers and defines as control sentences rather than equations [22]. Fuzzy logic has successfully engaged in significant applications scope from social to engineering researches due to its capability to construct rule of knowledge. It is one of the most mathematical intelligent approaches which is close to human expression and thinking. furthermore, fuzzy logic is easy to implement in terms of formulate the characteristic of real systems and environments. It is simple to implement in software and hardware architecture [7], [8], [23], [24].

PD-like fuzzy logic controllers (FLCs) are developed in this work. Mamdani type Fuzzy logic represented by five Gaussian membership function: Positive Big (PB), Positive Small (PS), Zero (Z), Negative Big (NB), and Negative Small (NS) for input and output are used, which lead to 25 rules as shown in Fig.2. Normalized universe of discourse value was used for input and output within range [-1, 1]. Four PD- like fuzzy closed loop controllers were used for controlling the hip and knee joints of each leg as shown in Fig.3. Same fuzzy rule base is used for each module; FLC1, FLC2, FLC3, and FLC4, the fuzzy rules are shown in Table I.

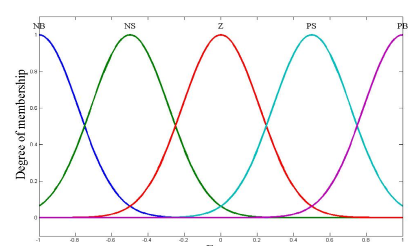

Figure 2. Membership functions for inputs and output

In this work, the inputs and outputs of all controllers are normalized between [-1, 1].Two input for each controller the error (the difference between the reference trajectory and the actual trajectory measured from Visual Nastran 4D simulation output), and the change of error. The output of the controller is the torque. The objective of fitness function of IWO is to minimise the orientation error for hip and knee joints while the exoskeleton system performs walking task. The performance index is the root mean square error (MSE) as follows:

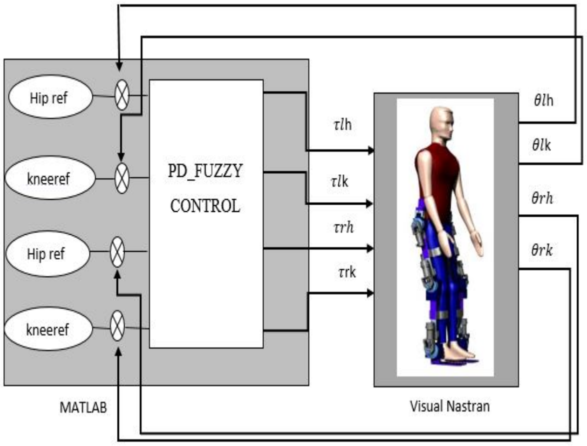

Figure 3. Simulink block diagram of the control system

Table I
THE FUZZY RULE BASE

Error e	Change of Error Δe				
	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

$$MSE = \sqrt{(\frac{1}{N})\sum_{=1}^{N}(e^2)...} \quad (6)$$

The cost function of the system is represented as the summation of MSE function of the four joints. The formulation is given in to take the summation weight of these four. The cost function is as follows:

$$\begin{aligned} Costfunction = w_1 MSE_1 + w_2 MSE_2 \\ + w_3 MSE_3 + w_4 MSE_4 \end{aligned} \quad (7)$$

The vector of weight is selected as $[w_1 w_2 w_3 w_4]$ =[0.25 0.25 0.25 0.25] to give equal emphasis on both of them. TheMSE_1,MSE_2,MSE_3, and MSE_4 are the mean square error for left hip, left knee, right hip , and right knee angle respectively. Population of 5 searching points for 100 iterations. It noticed that minimum cost function for the system is 0.8356 as shown in Fig.4.

Figure 5 shows the fuzzy scaling factors, which were chosen by trial and error technique to get satisfied performance.

V. SIMULATION AND RESULT

The PD like fuzzy parameters were tuned on line using the IWO optimization algorithm based on minimising the mean square of the error between the reference and actual joint trajectories for the hip and knee.

The simulation was performed for 2 gait cycles, the results were collected from the right and left leg of the humanoid and the exoskeleton. The angle trajectories of the hip and knee joints measured by angle sensor attached to the exoskeleton in visual Nastran 4D software. The reference tracking performances of the control system for hip and knee joints are shown in Figs 6-9. Both IWO and heuristic approaches produced similar torque.

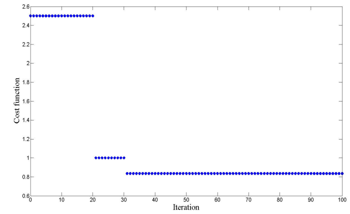

Figure 4. IWO fitness cost function.

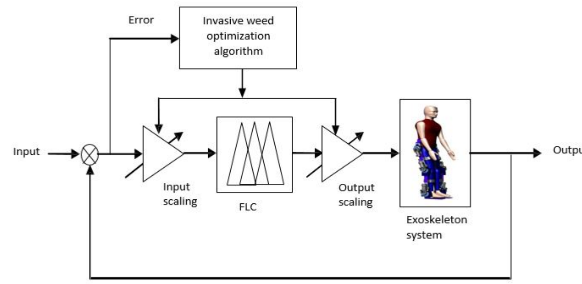

Figure 5. Input output of fuzzy scaling factor

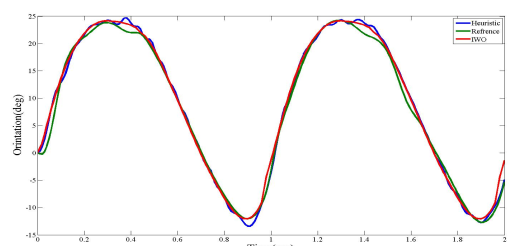

Figure 6. Hip joints reference and actual for left leg

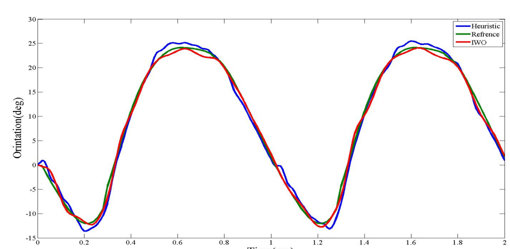

Figure 7. Hip joints reference and actual for right leg

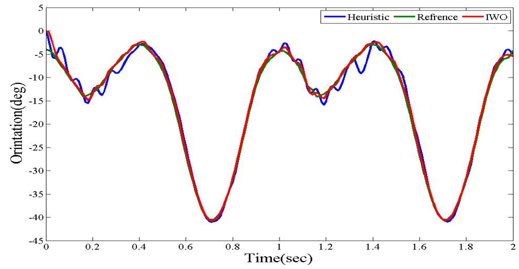

Figure 8. Knee joints reference and actual for left leg

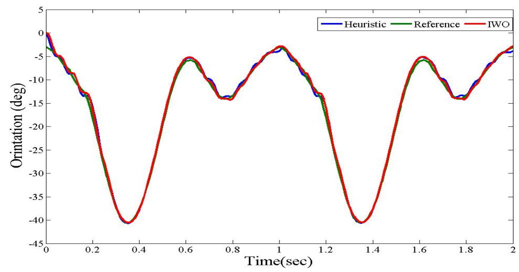

Figure 9. Knee joints reference and actual for right leg

The torque of humanoid for hip and knee joints measured during the walking cycle is illustrated in Figs 10-13. It is noted that the maximum torque for the hip joint of the humanoid for left and right leg , which was below 160 N.m through the walking cycle as shown in Fig.10 .Fig.11 shows the maximum torque measured at the knee joint of the humanoid for left and right leg, was below 80 N.m through the walking cycle.

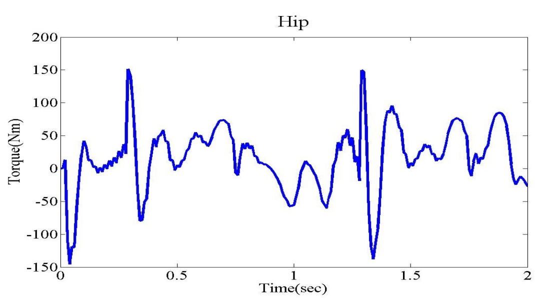

Figure 10. Hip torque profiles of humanoid during walking

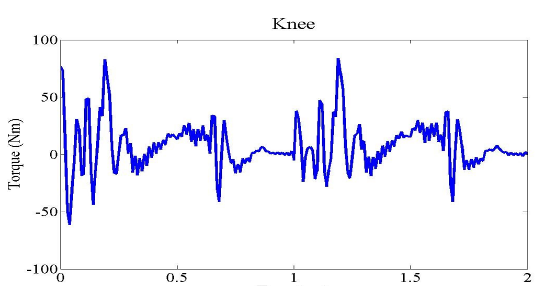

Figure 11. Knee torque profiles of humanoid during walking

Figs.12,13 show the torque profiles of the hip and knee joints, for the humanoid and exoskeleton. It is noted that the exoskeleton has provided the necessary augmentation to the humanoid joints during the walking cycle by supplying 25 Nm to the knee joint a 60 Nm to the hip joint. All of them are acceptable according to Low [25], who presents that the maximum assistive torque to enhance the hip joint should be lower than 120 N.m , and for knee joint should be lower than 60 N.m.The values obtained from the IWO optimization and the trail and error are compared in Table II, which shows the controller parameters for the hip and knee joints with optimal cost function values.

Table II shows the scaling parameters of the fourth PD-fuzzy controllers. where the first two gains are the input scaling factor whereas the last one is the scaling factor for the output.

Table II
OPTIMISED CONTROL PARAMETERS

Controllers	Gain Parameters	Heuristic	IWO
FLC1	K1	0.5	0.3571
	K2	0.052	0.010
	K3	30	80
FLC2	K4	0.166	0.6599
	K5	0.63	0.009
	K6	100	71.429
FLC3	K7	0.55	0.3081
	K8	0.06	0.3081
	K9	75	34.0528
FLC4	K10	0.43	0.3104
	K11	0.07	0.009
	K12	50	37.9268

The results prove the IWO has significantly decreased the error as compared to the heuristic one,as well the performance of the system has improved.The IWO algorithm with Fuzzy logic provide better reference tracking.

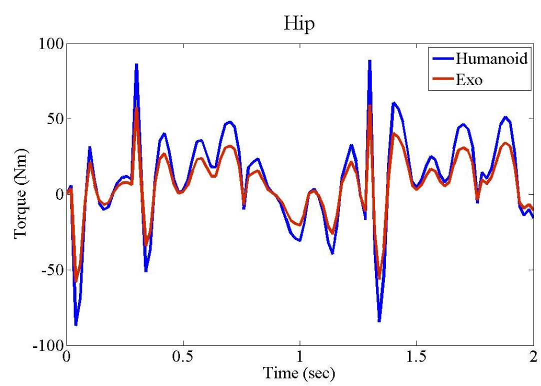

Figure 12. Hip torque profiles of humanoid and exoskeleton during walking

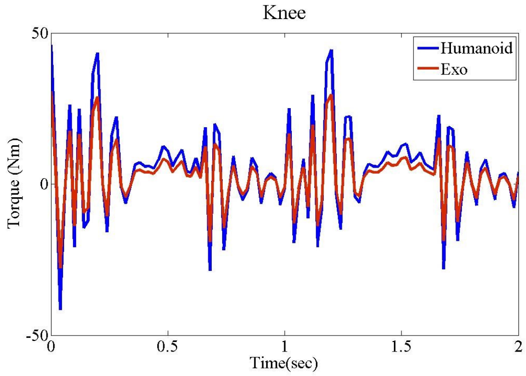

Figure 13. Knee torque profiles of humanoid and exoskeleton during walking

VI. Conclusion

A new modified SD mechanism has been introduced to improve the SD in IWO. Humanoid model and lower extremity exoskeleton device have been developed. The exoskeleton main function is to support the elderly mobility. An assistive torque 40% of the total torque required for the walking cycle is provided by the exoskeleton. This has been achieved for a PD Fuzzy controller with a modified invasive weed optimization algorithm for the knee and hip joints. The proposed modification of IWO is developed in this way to improve the search area and avoid local optima points. Torque was always below the admissible limits for a human. Future work will investigate sophisticated fuzzy logic, fuzzy/PID with control paradigms with bio-inspired optimisation algorithms.

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