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Design an Optimal Fractional Order PI Controller for Congestion Avoidance in Internet Routers

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ABSTRACT

The main problem that degrade data transition in communication networks is the congestion, to achieve stable TCP network, an active queue management (AQM) is used for controlling congestion and saving regular queue length .In this paper, a robust Fractional Order PI (FOPI) controller is suggested to control the AQM system, Gray Wolf Optimization Algorithm (GWO) is used for tuning of the controller gains and the Integral Time Absolute Error (ITAE) is adopted as a fitness function for monitoring system response by minimizing its error value until reach an efficient and robust response. The transient analysis is used for comparing the suggested controller with two conventional controllers (PI & PID) to show the efficient behavior of suggested controller, then a robustness analysis is applied by adding disturbances positive and negative signals with value 150 packets at different time(15 sec, 30 sec) to the system also varying the queue size after each 40 sec to see the system response , the controller overcomes the disturbances signals with less than 3.5 sec and faces the queue size varying values and returning the system response to its desired value efficiently.

1. INTRODUCTION

Due to the great evolution in the communication systems, congestion might occur if the capacity of these systems could not be fitted with the large amount of incoming data delivered from unpredictable number of users. As a result, more attention has been attracted to control such congestion as it may causes high rates of losing data [1-3]. Congestion is the process of overflowing and overused of buffer resources in the router once the number of packets in the queue increases over a certain time. It leads to delay in the system resources and eventually, degradation in system performance [4].

Transmission Control Protocol (TCP) has crucial roles in the performance of wireless mobile systems [5]. TCP is combined with the internet protocol (IP) to work as one protocol named TCP/IP. TCP roles as error checking delivery of bytes between applications working on hosts communicating through an IP network [6]. Despite TCP is powerful congestion control tool, it could not provide good performance with the increasing amount of data and that, on its role, may causes drawback in the quality of service (QoS) [7, 8]. Hence, to protect systems from congestion downfall, especially in case of fully-loaded network, finite memories, work as buffers, could be used in any network to perform three main processes; queuing, marking, and dropping. Based on first-in-first-out (FIFO) algorithm, the system drains the memory contents, whenever the rate of received data higher than the specified link capacity, the data in memory will increase and make a buffer overflow and the congestion will happen. To handle this problem, the active queue management (AQM) [9, 10] algorithms have the function of either marking or dropping the packet before the queue full [9]. As FIFO algorithm is easy to implement, but it does not work properly when the system is heavy loaded resulting throughput decreasing and high rate of data loss [11].

Recently, many researchers have focused their works in proposing a variety of techniques used in demonstrating the core role of ACM in congestion control. An improvement for [1] AQM stability is specified to work with dynamic environments called stable active queue management SAQM where certain parameters like number of TCP connections, network bandwidth, round trip time (RTT) besides the target queue length are all suggested to be changed with time. In 2019, a new performance function [12] called finite-time performance function (FTPF) is introduced to manage the finite-time control issue in (TCP/AQM) networks. A multiclass network traffic with different packet [13], bandwidth share and queue size for each class is presented as a control theory-based approach intended to solve the problem of multiclass AQM in TCP/IP routers. Hotchi et al. [14] have utilized disturbance observer (DOB) and Smith predictor (SP) in form of a novel TCP/IP congestion control to deal with modeling error and network time delay concurrently. In another work [6] proportional-integral (PI) controller with a genetic algorithm (GA) as a combined AQM/TCP congestion control approach is designed to overcome network problems such as packets loss, delay in packets delivery and saturated buffer capacity for the middle routers. Berbek and Oglah [15, 16], have designed a hybrid congestion control technique using intelligent (PID) with type1 fuzzy logic controller. social spider optimization (SSO) is utilized in this study for reducing queue size error. The same researcher Oglah, in 2021, together with Kadhim and Oglah [17] have used fuzzy-PID controller as a control system for nonlinear TCP/AQM model.

In this paper a Fractional order PI controller is suggested, Fractional order controller disseminates the relations of differentiation and integration to non-integer orders. In this controller, it is flexible to truncate the minimum and maximum peaks of the response, because two extra tuning parameters in addition to three gains as usual are available. FC regarded as a significant tool for the field of dynamical systems. Linear, nonlinear, and complex dynamical systems have attracted researchers in systems modeling and control to apply it in different real-world problems.

The use of mathematical features of the fractional order controllers will adjust the system performance with adapting an efficient tuning algorithm (GWO) to tune all the gains of the suggested controller to ensure robustness and achieve a stable response and eliminate any undesired values when data flow through AQM system.

This paper is organized as follows: Section 2, describes AQM system model. Section 3 presents the suggested controller used in this paper. Section 4, presents GWO algorithm, Section 5 demonstrates the simulation results and finally Section 6 explains the conclusions of this study.

2. AQM SYSTEM MODELING

According [18, 19] to a dynamic TCP model was suggested depending on fluid-flow analysis [20] and ignoring the timeout TCP mechanism. Its differential equation will be as indicated below:

$$\dot{w}(t)=\frac{1}{R(t)}-\frac{w(t)w(t-R(t))}{2R(t-R(t))}P(t-R(t)) \quad (1)$$

$$\dot{q}(t)=\frac{w(t)}{R(t)}N(t)-C \quad (2)$$

where, *w(t)* denotes the predicted TCP dispatching window size (packets); *C(t)* is the real network capacity (packets/seconds), *q(t)* is the expected number of packets in queue (packets); *R(t)* denotes the time of full-trip transmission (seconds), while *P(t)* is the probability of packet marking/dropping; and *N(t)* is the number of TCP sessions.

The nonlinear differential equations of the system were linearized as explained [21] which represent an operating point for generating the following linearized model.

The linearized equation model was generated based on linearizing the nonlinear equation appeared in Eq. (1) and Eq. (2) around (w_o, q_o, P_o) which are repressing the operating point for these parameters, then the linearized model transfer function will be:

$$G(S)=\frac{w(s)}{P(S)}=\frac{\frac{c^2}{2N}e^{-sR_o}}{(s+\frac{2N}{R_o^2C})(s+\frac{1}{R_o})} \quad (3)$$

3. FRACTIONAL ORDER PI CONTROLLER

PID controllers are regarded as an easy and traditional controller for enhancing the system performance. Recently, scholars made different enhancements for conventional PID controller like using intelligent techniques such as neural network [22] or change its structures depending on system response [23] or use of the fractional analysis that is powering either the integral or the differential operators or together by fraction number, this type of enchantment is a particular case controller and become an enhanced form of the conventional PID [24, 25]. The powering values are (μ for derivative part and λ for the integral part) then controller parameter will be five instead of three, the powering parameters will enhance system robustness improve its response.

The idea of FOPI depends mainly on the classical PI, a field of mathematics called Fractional calculus (FC) that assigns an arbitrary fractional order to derivatives and integrals terms. These fractional order systems can be described by a Linear Time Invariant (LTI) fractional-order differential equation [26]. The traditional fractional order transfer function is given in Eq. (4). This controller is suggested to control the congestion problem.

$$G_{FOPI}=K_P+K_I\frac{1}{s^{\lambda}} \quad (4)$$

According to Eq. (4) tuning parameters will be (K_P, K_I, λ) and the fractional λ be real or integer and FOPI controller block diagram will be as shown in Figure 1 [27].

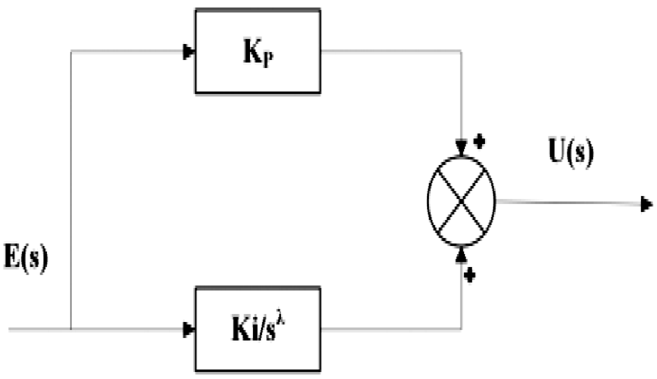

Figure 1. FOPI controller block diagram

4. THE GREY WOLF OPTIMIZATION

Grey Wolf Optimization (GWO) is one of the smart population-based swarm methods, this optimization technique is adopted by S. MirJalili in 2014, it translates the way of hunting in grey wolves. The population in this method is divided into four groups as indicated in Figure 2 based on priorities in giving decisions, the first one in hierarchy is named Alpha (α) which is responsible for giving solution optimally and it is considered as a leader, second one is named Beta (β) is responsible of the population when the leader is absent in its way for hunting, while the third one named Delta (δ) and is regarded as the support team, its different from all other types mentioned in its duty because its responsibility in saving all the population also its absolute loyalty for first and second one in their decisions in hunting and final one is Omega (ω) which is have the last priority in taking any solution [28, 29].

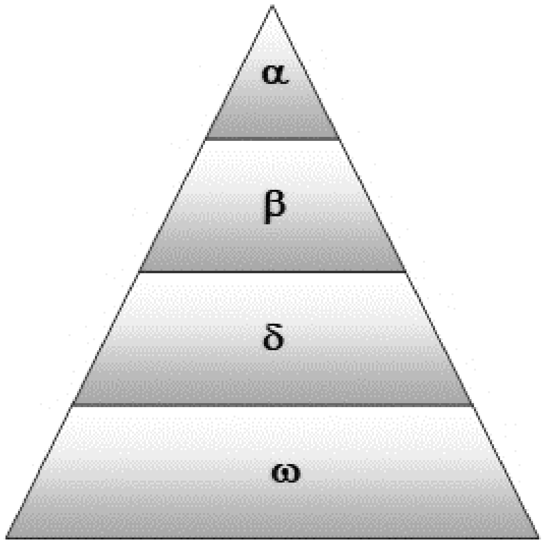

Figure 2. Hierarchies of grey wolves

The activities of the wolves are as shown below:
1- Searching
2- Tracking
3- Encircling
4- Attacking

These activities are translated into mathematical formula as indicated below:

1. Specify initial values of positions for wolves ($\vec{X}$).
2. Evaluate fitness function (tracking).
3. Find prey positions given from (α, β and δ) wolves.
4. Compute $\vec{A}$ and $\vec{C}$ vectors for each place based on based on α, β and δ wolves, where $\vec{A}$ vector is responsible of preserve population from become far from prey while $\vec{C}$ vector preserve discovering activity during search for alliterations.

$$\vec{A} = 2\vec{a}.r_1 - \vec{a} \tag{5}$$

$$\vec{C} = 2r_2 \tag{6}$$

r_1 and r_2 are random values [0,1] and $\vec{a}$ vector decreased from 2 to 0 linearly, it will maintain the reduction of encircling for (α, β and δ) wolf groups.

5. Compute the encircling for the (α, β and δ) wolves as indicated below:

$$\overrightarrow{D_\alpha} = \left|\overrightarrow{C_1}.\overrightarrow{X_\alpha} - \vec{x}(t)\right| \tag{7}$$

$$\overrightarrow{D_\beta} = \left|\overrightarrow{C_2}.\overrightarrow{X_\beta} - \vec{x}(t)\right| \tag{8}$$

$$\overrightarrow{D_\delta} = \left|\overrightarrow{C_3}.\overrightarrow{X_\delta} - \vec{x}(t)\right| \tag{9}$$

$$\overrightarrow{X_1} = \left|\overrightarrow{X_\alpha} - \overrightarrow{A_1}.\overrightarrow{D_\alpha}\right| \tag{10}$$

$$\overrightarrow{X_2} = \left|\overrightarrow{X_\alpha} - \overrightarrow{A_2}.\overrightarrow{D_\beta}\right| \tag{11}$$

$$\overrightarrow{X_3} = \left|\overrightarrow{X_\alpha} - \overrightarrow{A_3}.\overrightarrow{D_\delta}\right| \tag{12}$$

6. Finally update wolves' positions for attack as in Eq. (13):

$$\vec{X}(t+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \tag{13}$$

$\overrightarrow{X_\alpha}$, $\overrightarrow{X_\beta}$ and $\overrightarrow{X_\delta}$ are the (α, β and δ) wolves position vectors. The flowchart of GWO algorithm is shown in Figure 3 [30]. Finally for check system performance one of the performance indices must adopt as indicated in Figure 4 below to enhance system response and ensure stability. In this paper, the Integral Time Absolute Error (ITAE) which is defined as a mathematical relation depends on error value between desired and actual response [31] and the instant time of simulation time of running the algorithm and its parameter is the error and the time.

Fitness function [32] is used to test the efficiency. Optimum gain values of suggested controller are tuned using GWO algorithm and are chose based on minimizing this fitness function by tracking the error value.

$$ITAE = \int_0^\infty t\,|e|\,dt \tag{14}$$

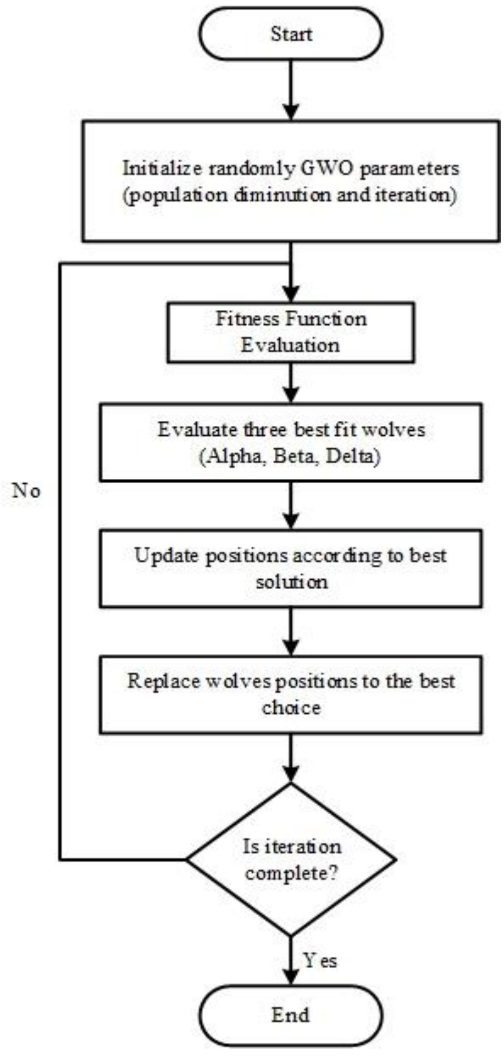

Figure 3. Flowchart of GWO algorithm

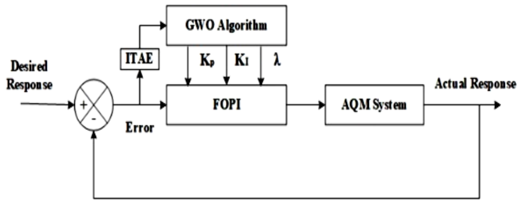

Figure 4. AQM system with GWO-based FOPI controller

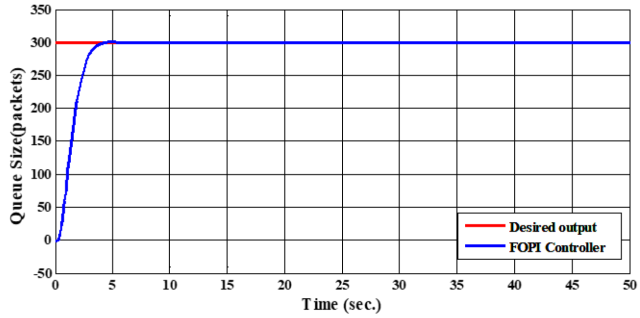

Figure 5. AQM system responses based on GWO algorithm

5. SIMULATION RESULTS

The simulation analysis for controlling AQM system using FOPI controller is simulated using MATLAB based on GWO algorithm and the initial parameter used is shown in Table 1.

Table 1. GWO parameter

Description	Value
No. of population	50
Maximum number of iteration	30
Dimension	3

The response of optimal AQM system with network parameters (N=60, C=3750 packet/sec and R_o =0.253) based on GWO is shown in Figure 5 and the optimal controller parameter are listed in Table 2.

Table 2. The optimal controller parameters tuned by GWO algorithm

Controller parameter	K_P	K_I	λ
Value	0.0000164	0.0000129	0.7233

For test the performance of the optimal FOPI controller a comparison with PI & PID controllers which is tuned also based on GWO algorithm indicated in Figure 6 and their optimal gains are listed on Table 3. To analyze system response for all controllers a step response analysis is calculated and indicated in Table 4.

Table 3. Gains of all controllers based on GWO algorithm

Controller	K_p	K_I	K_D	λ
PI	0.000021	0.000016	-	-
PID	0.0000165	0.00001	0.0000018	-
FOPI	0.0000164	0.0000133	-	0.723

Table 4. Optimal controller step responses

Controller	Peak time(sec.)	Rise Time(s)	Settling Tim(s)	M_p (%)	Error (ess.)
PI	3.2	2.35	2.23	7.7	0
PID	6.25	2.75	4.2	3.1	0
FOPI	4.5	2.015	3.43	0.13	0

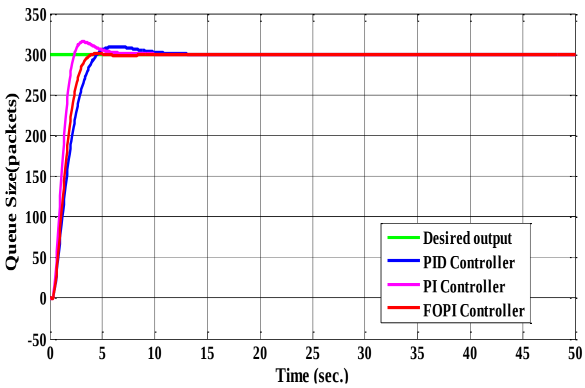

Figure 6. AQM system responses for three optimal controllers

It can be seen in Table 4 the PI controller suffer from high overshoot value (7.7%) with respect to other controllers and the FOPI controller suffers from small value (0.13%), this limited value reflect the robust behavior of the FOPI controller due to the fraction part in its structure and to the optimal values of its gain values calculated using the smart GWO algorithm, these two reasons effect appeared also in the fast and stable response in tracking the desired value without any fluctuations in its response, this results give the FOPI the superiority and the efficiency upon PI and PID controllers.

Now to test the robustness of the proposed controller in tracking the desired system response two tests is done to achieve this, the first one is changing the queue size value each 40 sec, the controller gives the same response in spite of this change as indicated in Figure 7. The second test is done by adding signals that are considered as disturbance signals at t=15 sec with a value 150 packets and at t=30 sec with value -150 packets, as shown in Figure 8 the system response is changed and the controller is faced this disturbance within 3.5 sec for each signal add and return the system response to its desired value, this controller behavior reflects its robustness to solve and face any matter may occur.

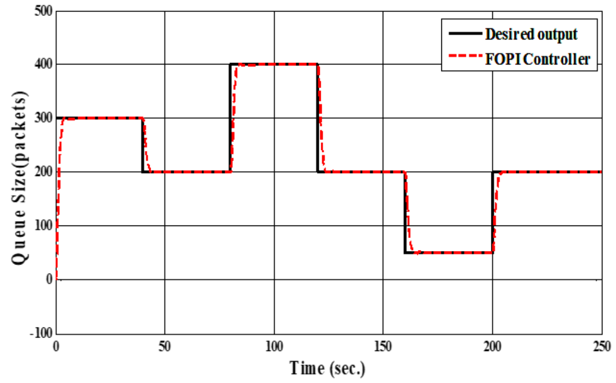

Figure 7. System response when applied different values of queue size

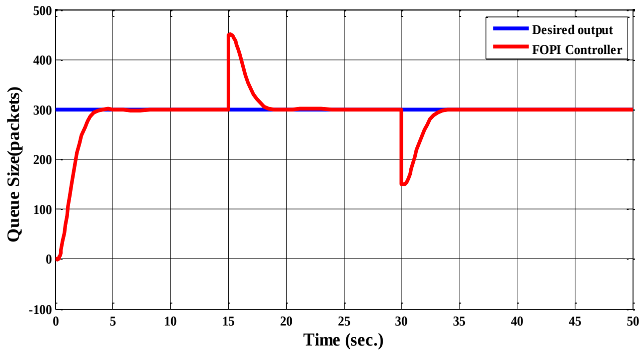

Figure 8. System response when adding disturbances signals

6. CONCLUSIONS

In this paper, a robust FOPI controller is suggested to control the AQM system based on an efficient tuning GWO algorithm to enhance the desired response by minimizing error value. The proposed controller behavior is compared with two conventional controllers (PI & PID) to test its efficiency in terms of settling time, peak time, rising time, and overshoot. The simulation results showed that the suggested controller is superior in its output to the other conventional controllers, robustness analysis is applied to see the suggested controller robustness in solving different types of problems and disturbances may controller face; the suggested controller solves and maintains these changes and signals applied to it fast and returns the system to its stable response.

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