Genetic Algorithm Tuned IMC-PI Controller for Coupled Tank Based Systems

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***Abstract*— The proportional Integral and Derivative (PID) Controllers remains one the most versatile and widely adopted controller for industrial as well as educational applications. However, the efficacy of this controller lies in the ability to know how to tune them effectively and efficiently to suit operational needs. There exist numerous approaches to tuning the gains of the controller with varying degrees of complexity. Of all the existing approaches, the internal model control (IMC) stands out because it requires only the filter gain to determine the corresponding PID parameters. However, the ability to determine the appropriate filter gain is also a challenge as it is often than not selected arbitrarily using a trial by error approach. To this end, in this work, a genetic algorithm (GA) technique has been adopted in tuning this filter parameter to eliminate the associated problems of the trial by error approach. The results of the implementation on the double couple tank problem show the performance of the GA tuned IMC outweighing that of the conventional GA tuned PI controller approach.**

Keywords*— *Coupled-Tank System, Genetic Algorithm (GA), Integral Absolute Error (IAE), Internal Model Control (IMC), PI controller.

I. Introduction

The couple tank (CT) remains one of the indispensable systems when it comes to controlling processes in the industry[1-4]. These couple tanks remain some of the most fundamental systems and their applications cannot be overemphasized [2-5]. The CT system also finds application as one of the basic kits in the teaching of control systems as it relates to controller design[3, 6].

In the quest to achieve a suitable control of the CTs, numerous types of control schemes have been developed and applied in the past[3-5, 7, 8]. These schemes include but are not limited to the Proportional Integral Derivative (PID) Controller [4, 5, 7, 8], the Linear quadratic regulator (LQR)[4], Internal Model Controller (IMC)[9], Fuzzy Logic Controller [10-13], Sliding Mode controllers[14, 15], and Model predictive controller [7, 8].

The PID Controller remains one of the most widely adopted controllers both for industrial and theoretical applications[4, 8]. This is due to their capability in providing adequate control measures and improved performance for most CT and other process control applications coupled with the inherent simple structure and ease of tuning[5, 7, 16, 17].

However, the efficacy of the PID Controllers lies in the capability of the tuning algorithm used in determining its parameters[18, 19]. There exist a couple of tuning algorithms and methods, which ranges from classical to Artificial Intelligence (AI) inspired methods. These classical methods includes: Ziegler-Nichols [20],Cohen-coon[3], Pole-placement [5, 7, 9], IMC[1, 3, 5, 9, 17, 21], and Model Reference Adaptive Control (MRAC) [22]. These approaches are sometimes characterized by inadequate or improper settings which results in unsatisfactory performance such as sluggish or oscillatory loop response or even safety problems [9, 23, 24]. Hence to address these challenges, the AI-inspired tuning approaches are born out of the complexity and difficulty of the classical approach in obtaining optimal tuning parameters for the PID using AI based optimization techniques [4, 25-28].

Contrary to the AI-based techniques, the IMC based approach of tuning the PID controllers has proven to be a well-accepted technique in determining the PID parameters [3, 5, 11, 12, 21, 26, 27]. This is due to the simplicity and singular factor (Filter gain (λ_f)) required for the tuning purpose [26, 27]. The IMC is also characterized by good transient, improved steady-state and good stability [5, 26, 27]. However, the performance of the IMC in determining the optimal PID parameters is also subject to selecting suitable λ_f parameter [5, 11, 12, 26, 27]. The λ_f parameter plays a crucial role in determining the steady state as well as transient responses of the system[11, 12, 26, 27]. Thus, in this paper the use of GA

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in determining the optimal λ_f parameter in tuning the PID parameters using the IMC approach is proposed and investigated.

II. THE SYSTEM DESCRIPTION

The CT system adopted is as depicted in Figure 1 and it is a double-column CT [5]. The outlet of the primary tank serves as the inlet to the secondary. The primary tank is supplied through a pump whose rate of discharge is proportional to the applied voltage Vp. The CT requirement stipulates that the level in the tanks are maintained as specified in Table I [5]. The goal is to ensure that the level in the primary tank does not exceed the defined specified point.

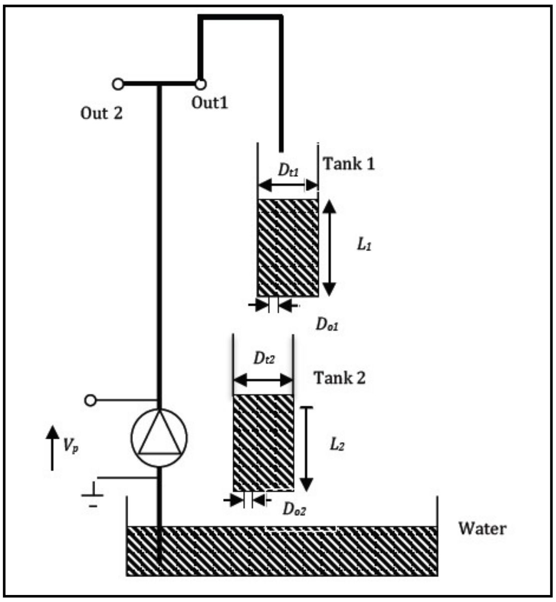

Figure 1: The Coupled Tank System.

TABLE I. CT OPERATING PARAMETERS VALUES[5]

Parameter	Description	Value
K_p	Constant related to the flow rate into the tank	$3.3\ cm^3/(s.V)$
a_1/a_2	The cross-sectional area of tank one and tank two outlet hole	$0.1781\ cm^2$
g	Gravity constant	981 cm/s^2
A_1	The cross-sectional area of tank one	$15.5179\ cm^2$
A_2	The cross-sectional area of tank two	$15.5179\ cm^2$
L_{10}, L_{20}	The operating points for the water levels in tank one & tank two	15 cm

The linearized mathematical model in the transfer function of the CT system putting into consideration the level and rate of flow into the primary tank as developed in [5] is adopted and presented as ;

$$\frac{L_{11}(S)}{V_{ps}(S)} = \frac{\frac{K_p\sqrt{2gL_{10}}}{ga_1}}{\frac{A_1\sqrt{2gL_{10}}}{ga_1}s+1} = \frac{K_{dc1}}{\tau_1 s+1} \quad (1)$$

The mathematical model is approximated to a first-order system without dead time as shown in (1) and upon substituting all the variables therein the model equation is given as;

$$\frac{L_{11}(S)}{V_{ps}(S)} = \frac{3.240}{15.237s+\ 1} \quad (2)$$

The system requirement is such that the performance of the controller is subject to the design requirement as stated:

1) The operating point L_1 = 15 cm
2) The per cent overshoot less than 10%, thus;
   $PO_1 \leq$ 10.0 ["%"]
3) The settling time less than 20 sec, thus;
   $T_{s1} \leq$ 20.0 [s]
4) The response has no steady-state error, thus e_{ss} = 0

III. CONTROLLER DESIGN

In the first part of the controller design, the concept and design of the IMC for tuning the PI parameters is presented, while the second part focuses on the development of the Genetic Algorithm for tuning the filter gain

A. Internal Model Control PI Design

The IMC Controller has proven to be an effective measure of tuning the parameters of the PID Controller, as it requires very limited computations [29-31]. The structure of the IMC controller is as depicted in Figure 2. Where $G_p(s)$ is the system model, $G_m(s)$ is the process model which is used in the controller design and $G_q(s)$ is the IMC controller.

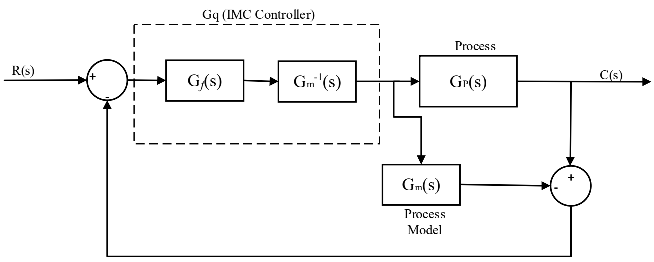

Figure 2: IMC Controller

The IMC uses the process model $G_m(s)$ and inverts parts of the model for use as a controller for the process. However, some parts of some models are not invertible such as the delay and right half-plane [29]. In such situations, linear filters are added to make the model invertible and the tuning of these filter parameters determines the performance of the

IMC controller. The steps and processes of tuning the PID Controller using the IMC approach are as follows:

1) Obtaining the Invertible and non-invertible Parts

The controller $G_q(s)$ is obtained by factorizing the model process $G_m(s)$ into invertible $G_m^-(s)$ and non-invertible $G_m^+(s)$ parts:

$$G_m(s) = G_m^+(s) * G_m^-(s) \quad (3)$$

The non-invertible part $G_m^+(s)$ is eliminated if the system is a first-order without delay such as the adopted model, as it often brings about instability if not discarded. Put into consideration the invertible part $G_m^-(s)$ which is stable and causal [32] the Controller is obtained in step 2.

2) Obtaining the Controller

The inverse of the invertible part is to be equal to the controller.

$$G_C(s) = [G_m^-(s)]^{-1} \quad (4)$$

3) Addition of filter

To ensure increased system performance and stability at all times, a tunable filter $G_f(s)$ with parameter λ_f is multiplied to the controller $G_C(s)$ to give rise to the IMC controller $G_q(s)$. The n is the order of the filter and it corresponds to the order of the system model.

$$G_f(s) = \frac{1}{[\lambda_f s + 1]^n} \quad (5)$$

$$G_q(s) = G_C(s) * G_f(s) \quad (6)$$

4) Obtaining the IMC -PI

At this stage the tuning rules for a first of system is applied to obtain the values of the parameters for the Proportional and Integral gain without delay is defined as [33] :

$$Proportional\ Gain\ (K_P) = \frac{\tau_1}{\lambda_f K_{dc1}} \quad (7)$$

$$Integral\ \ Gain\ (K_I) = \frac{1}{\lambda_f K_{dc1}} \quad (8)$$

Based on the ongoing, it is evident that values of the K_P and K_I are solely dependent on λ_f, thus making it the only parameter required to be tuned to achieve a satisfactory IMC-PI controller. Hence, the need to select an appropriate value for this. Smaller λ_f value can provide an improved transient response while a larger value reduces the overshoot. Thus, there is a need to strike a balance in obtaining this value putting into consideration the system requirement. The value is often selected by a trial by error approach using a continuous process as described in Figure 3, which sometimes becomes difficult to obtain, hence the basis for using the GA to optimally select this parameter.

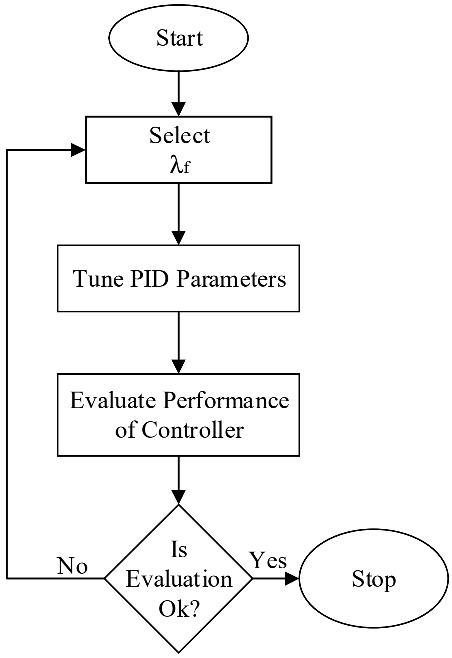

Figure 3: Tuning Process using the Manual Approach.

B. Genetic Algorithm Implementation

Genetic Algorithms (GA) are adaptive heuristic search techniques a subclass of the Evolutionary Algorithms. They are based on the evolutionary ideas of natural selection and genetics. The fundamental concept behind the Genetic Algorithm is to model a problem in a natural system way such that Charles Darwin's concept of selection alongside other evolutionary processes can be applied, to produce iterations of solutions for the problem that is better than their predecessor.

The concept of the Genetic Algorithm was first pioneered by John Holland in the '70s and has been studied by numerous researchers for application in problems ranging from Engineering to non-engineering. Over the years, various variants of GA have been applied in control to obtain various optimal values of different parameters such as the PID parameters.

In this paper, GA has been used to obtain the optimal value for the filter gain of the IMC-PI controller in place of the manual trial approach. The structure of the GA adopted for this work is as depicted in Figure 3, while other parameters are as depicted in Table II. The process is initiated with the codification of the chromosomes of the initial population using a binary code approach with a 4-bits used to represent the chromosomes of λ_f such that has a maximum and minimum value of 0 to 15 respectively.

$$\lambda_{fmin} < \lambda_f < \lambda_{fmax} \quad (9)$$

The initial population is created such that it satisfies the constraint of the overshoot, settling time and steady-state as defined;

$$1 < T_S < 20\ sec \quad (10)$$

$$0 < OS < 10 \quad (11)$$

$$e_{SS} = 0 \quad (12)$$

Where, T_S is the settling time, OS is the maximum overshoot and e_{SS} is the steady-state error.

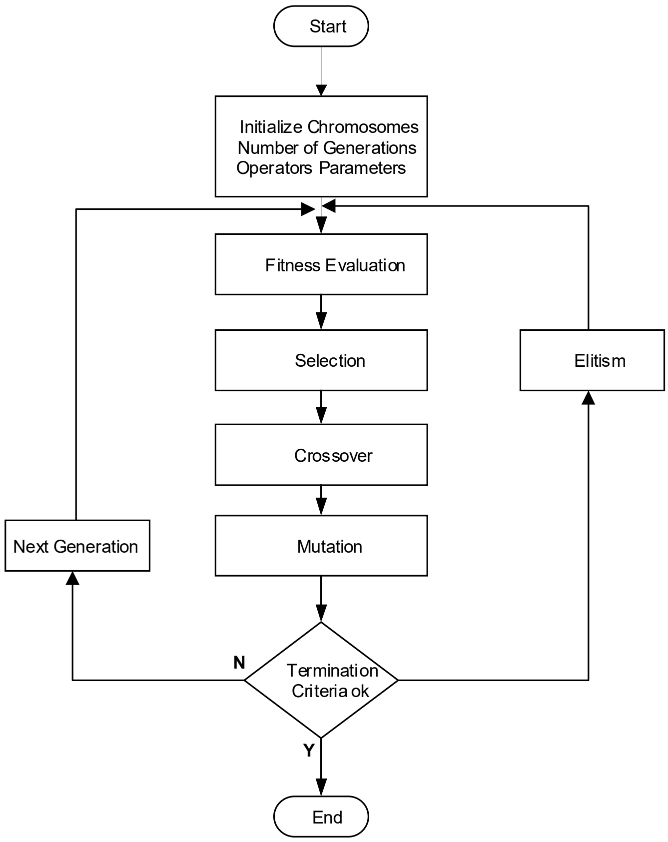

Figure 4: Structure of the Adopted Genetic Algorithm.

In the next stage, the fitness function is evaluated as the inverse of the Integral Absolute Error (IAE). The IAE is obtained by using the obtained λ_f chromosome to determine the PI parameter based on (7) and (8). The roulette wheel selection type and a single point cross over with a rate of 0.4 were adopted. The implemented GA uses a mutation rate of 0.05 and adopts an elite count of 2 to ensure good solutions is always replaced in each of the 100 generations.

TABLE II. PARAMETERS OF THE IMPLEMENTED GA

Parameters	Values
Initial Population	100
Number of Generations	100
Elite Count	2
Mutation rate	0.05
Crossover rate	0.4
Selection Type	Roulette Wheel

IV. RESULTS AND DISCUSSION

In this work, the Matlab/Simulink software version 2015a was adopted for the development and implementation of the Genetic Algorithm (GA), the control scheme and the obtained results are as presented. Figure 5 shows the open-loop response of the system model to a unit step function. From observation, the system is stable with a single point on the negative axis but does not meet the operational requirement with regards to steady-state as it was around 60sec hence, the need for a controller.

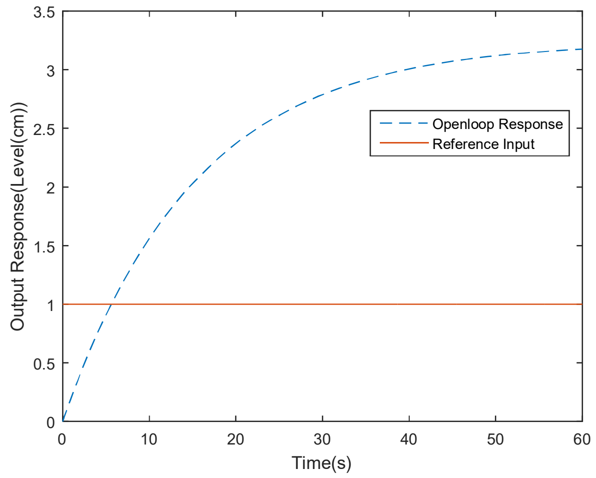

Figure 5: Open Loop Response

On the application of the proposed GA scheme to determine the optimal filter gain λ_f and the consequent tuning of the controller gain using the IMC step as defined earlier. A filter gain (λ_f) of 1.2 was obtained and based on this the PI controller (GAIMCPI) are obtained as depicted in Table III.

The performance of the system model to the obtained Kp of 3.917 and Ki of 0.257 is as shown in Figure 6. Observe that the performance shows a zero overshoot, this is owing to the inherent characteristics and advantage of the IMC controller. Furthermore, the GAIMCPI has a better transient and steady-state response with a rise time of 1.2sec, settling time of 6 secs and a zero steady-state error as compared to that open-loop response. This shows the developed GAIMCPI controller meets the operational specification of the system as specified earlier.

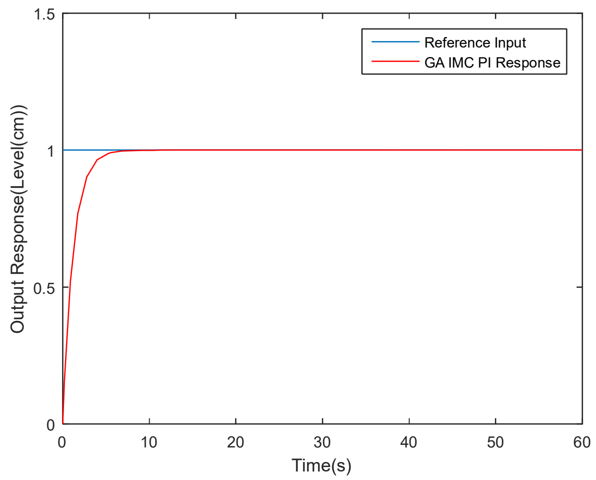

Figure 6: Output response of the GA IMC PI Controller

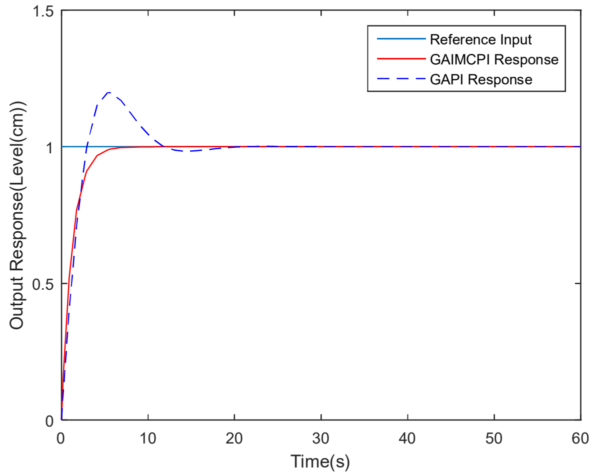

Figure 7: Output response of GAIMCPI Vs PI Controller

In addition, for comparison, a GA based PI (GAPI) controller was developed using the same algorithm parameters as defined in Table II, to obtain the PI parameters for the system. The obtained controller gains for the GAPI are as shown in Table III and the system performance depicted in Figure 7. Observation shows the GAPI exhibits a maximum overshoot of about 1.2 corresponding to 20% of the input with a settling time of about 16sec. The GAPI has a slightly higher rise time of 1.5 sec and also enjoys a zero steady-state error as compared with the GAIMCPI. This depicts the GAPI of meeting the system specification in terms of the steady-state error and that of the settling time. However, it has a slightly higher overshoot than the requirement. A further comparison of the GAPI and GAIMCPI shows that the latter has a reduced IAE of 1.201 as compared with the former that has 2.302, thus making the GAIMCPI have a better error approximation as compared with the GAPI. Thus, this makes the GAIMCPI a better controller as compared to that of the GAPI in controlling the CT system.

TABLE III. SYSTEM PERFORMANCE COMPARISON

	GA-IMC-PI	**GA-PI**
Kp	3.917	2.31
Ki	0.257	0.942
Rise Time(sec) Tr	1.2	1.5
Settling Time(sec) Ts	6	16
Over Shoot (%)	0	20
Steady Error ess	0	0
IAE	1.201	2.302

V. CONCLUSION

In this work, a GA based IMC PI controller has been developed for a first-order couple tank system, this is with the view of tuning the filter gain (λ_f) intelligently as compared with the manual or trial by error approach obtainable in practice. The results obtained show the capability of GA to obtain suitable filter gain for the IMCPI controller to control the system model. Furthermore, the results obtained from the GAIMCPI controller when compared to that of the GA tuned PI controller without the IMC scheme shows an improvement of the system performance in terms of the transient and steady-state response as well as the error approximation.

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