Comparison of Traditional and Evolutionary Tuning Techniques for a Didactic Magnetic Levitation System

Shradha Kishore, D.K. Chaturvedi

Abstract— This paper presents a comparative analysis of the traditional Pole Placement (PP) Technique and the evolutionary Genetic Algorithm (GA) Technique for minimization of the error to be used as a teaching aid for undergraduate studies to demonstrate the differences in both the methodologies. Pole placement technique incorporates system model which helps in obtaining system specific closed loop response. Whereas Genetic Algorithm is a stochastic method which helps in exploring the search area for the best combination of the proportional, integral and derivative (PID) settings required to minimize integral of the absolute error. Magnetic Levitation System is a very interesting phenomenon due to which an object can be suspended in the air without any physical support purely on the basis of force balance condition. It is difficult to obtain exact force balance condition in this sensitive and nonlinear system and precise choice of the controller parameters is necessary. The controller settings have been tested for comparative reduction in error by both the methods in simulated as well as real-time environments.

Index Terms— Absolute Error, Genetic Algorithm, Levitation, Modeling, Pole Placement, Stochastic, Tuning

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1 INTRODUCTION

A PID controller plays a pivotal role in obtaining a desired response which requires evaluation of its proportional, integral and derivative parameters. Often it is difficult to choose the correct tuning technique required for evaluation of these parameters as well as to understand the method by which these techniques operate. Pole Placement is a traditional technique of pole assignment and evaluation of tuning parameters which directly uses the transfer function of the system model. Genetic algorithm is a stochastic optimization technique which can be used for evaluation of optimum value of controller parameters for any system. The techniques mentioned in theoretical textbooks have been applied on a didactic magnetic levitation system for practical demonstration and comparative analysis of both the methodologies.

Magnetic Levitation is a contactless technology in which an object can be suspended in air purely on force balance condition without any external support. The gravitational pull in the downward direction is balanced by an equal and opposite electromagnetic force in the upward direction. It requires high precision and sustained equilibrium force balancing at all times, otherwise the object might fall or get attracted to the electromagnet. Earnshaw's theorem states that it is impossible to levitate an object by fixed electrostatic forces. Levitation of an object is possible by an electromagnetic field of varying strength, polarity or by a moving ferromagnet. It is applicable to inverse square law forces [1]. As the object does not encounter any friction, the phenomenon is highly efficient and finds application in a variety of fields including transportation, launching of space vehicles, turbines, bearing and biomedical realm.

The concept of levitation has been aptly implemented in laboratory setup by Wong, Hajaji and others [2-5]. Traditional Pole placement technique has been found to be aptly suitable tuning strategy as it takes the system dynamics into account [6]. In 1995, Valasek et al proposed an efficient pole placement technique based on eigenvalues of desired system for feedback stabilization of the linear systems [7]. Hwang et al developed an algorithm to derive controller parameters based on the dominant pole placement to minimize IAE errors [8]. Tan et al proposed a criterion based on the system robustness and disturbance rejection to make comparative evaluation of the performance of different tuning algorithms [9]. Sujitjorn applied pole placement with state PID feedback on various applications including magnetic ball suspension [10]. Gao et al applied pole placement to evaluate the parameters of PID controller to achieve matched dynamics and stability [11]. Nicolau designed a PID controller by combining pole placement and symmetrical optimum criterion in 2013 [12]. In 2008, Wang et al proposed two simple methods based on root locus and Nyquist plot to ensure guaranteed dominance of the two poles of a PID controller [13]. Ghosh et al applied pole placement technique to calculate controller parameters [14].

Optimization methods and its application in engineering field [15] were elaborated in a 2014 editorial article by Tsai et al [16]. For better tuning, nontraditional nature inspired stochastic technique has been chosen as they have the ability to make parallel search for any random combination of the controller parameters to attain minimization of the error. Kristinsson applied Genetic algorithm in 1992 for identification of system

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- *Dr. Shradha Kishore is working as AP in EEE Dept. of BIT Mesra Patna Campus, India, E-mail: skishore@bitmesra.ac.in*
- *Dr. D.K. Chaturvedi is working as Professor in EEE Dept. at DEI Agra, India. E-mail: dkc.foe@gmail.com*

in both continuous and discrete time [17]. Hassanzadeh et al applied GA to design an optimum controller for Maglev system with IAE and other parameters as objective function and a random range of lower and upper bounds for controller parameters [18]. In order to minimize vibrations caused due to error, the performance index, IAE has been chosen as the objective function to be minimized. Lopez et al developed quality performance indices in 1976 [19]. Real-time experiment based verification of tuning algorithms have also been done [20].

The main contribution of the present work is to present a comparison of traditional and evolutionary tuning techniques for Maglev system to obtain successful levitation of a steel ball with minimum vibrations do help undergraduate students in understanding the techniques and their implications on practical models.

The paper has been organized such that the model under present consideration has been dealt in Section 2. The traditional Pole Placement technique has been discussed in Section 3. Controller tuning by Genetic Algorithm has been discussed in Section 4. The comparison of results by both the methods has been done in Section 5. The inferences that can be drawn from the experimental evaluations have been discussed in Section 6.

In order to analyze any system it is imperative to understand the science and working of the system. In this work a systematic approach was taken which is as follows:

- System Description
- Application of traditional Pole Placement technique.
- Application of Genetic Algorithm in a specific search range.
- Analyzing the response in a simulated environment and real-time set up.
- Comparison of both the methodologies.

2 MAGLEV SYSTEM

2.1 Model Description

The model chosen for present case study is an experimental set up for magnetic levitation of a steel ball developed by Feedback Instruments, UK. The objective is to evaluate the parameters of the controller required for successful levitation the ball at an equilibrium position where the downward gravitational pull is exactly equal and opposite to the upward magnetic attractive forces [2]. The setup as shown in Fig. 1 consists of an electromagnetic coil, a steel ball, an infrared light sensor, a computer based controller board and an analog and digital interface unit.

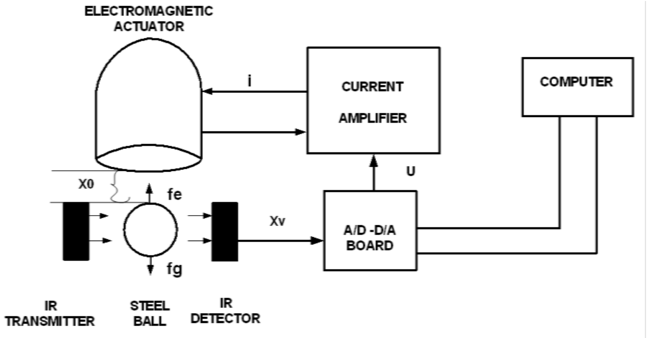

Fig. 1 Setup of the Maglev system

The setup consists of an electromagnet with one pole exposed downwards, an infrared sensor – transmitter pair in the middle portion which senses the vertical position of the ball and a signal conditioning circuitry at the bottom. An interface unit is required for communication between hardware and software unit as shown in Fig 2.

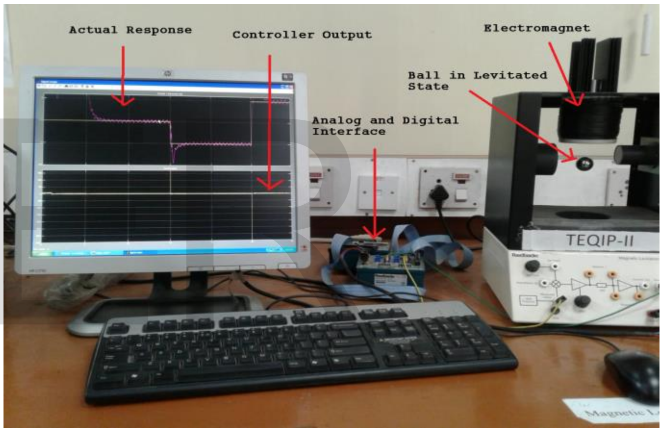

Fig. 2 Actual Layout of the Maglev System

The current in the electromagnet is controlled on the basis of inverse square law which causes the magnetic force to decrease if the ball moves closer to the magnet and to increase if it moves far away. The position of ball determines the amount of current required in the electromagnetic coil. The input signal is voltage and the output is the position of the ball. This regulation of the current is done by the controller for which the evaluations of the parameters are required by suitable tuning techniques.

2.2 Transfer Function of the Model

Dynamics of the free body diagram of the ball shows that it experiences an upward electromagnetic force and a gravitational force in the downward direction [3]. The attractive force, f_e, due to electromagnetic attraction is directly proportional to the square of current, i and inversely proportional to the square of distance, x and follows inverse square law.

$$f_e = k\, i^2 / x^2 \quad (1)$$

Gravitational force, f_g due to weight of the ball in the downward direction is given by,

$f_g = mg$ (2)

According to Newton’s law, at equilibrium position both these forces must be equal and opposite and at that position the ball levitates as shown in Fig. 1. The transfer function of the Plant dynamic setup can be represented as [detailed derivation in 4],

$$G_P(s) = \frac{-3653.3575}{S^2 - 2180} \quad (3)$$

It can be inferred from the transfer function of the Maglev system that the system has two poles at ± 46.69 and it is unstable due to one of the poles lying in right half of the s plane. The parameters used for the model have been shown in the Table I below [5]:

TABLE 1
PHYSICAL PARAMETERS OF MAGLEV SYSTEM

Parameter	Value
1. Mass of the ball (m)	0.02 kg
2. Acceleration due to gravity (g)	$9.81 m/s^2$
3. Current at equilibrium (i_0)	0.8A
4. Equilibrium Position (x_0)	0.009m
5. Control voltage to coil current gain (K_1)	1.05A/V
6. IR sensor gain (K_2)	143.48V/m
7. Offset voltage (η)	-2.8V
8. Control input voltage level (u)	±5V
9. Sensor output voltage level (X_V)	+1.25V to – 3.75V

3 POLE PLACEMENT TECHNIQUE

It is possible to design a controller such that dominant closed loop poles have a desired damping ratio and undamped natural frequency by placing them at a desired location [6-7]. Pole placement is a technique that allows any pole to be placed arbitrarily at any desired location. Pole placement technique ensures satisfactory response for both transient state and steady state. In the time domain approach the dominant poles are first calculated for desired damping and settling time. Insignificant poles are placed far off in the left hand side of s plane so that their response is much faster than the dominant poles. There is a limit to the distance at which the poles can be placed. It is assumed that the effects of the insignificant closed loop poles are negligible [8-10]. Direct substitution method of this technique is very useful and gives good response characteristics for systems ≤ 3rd order. In the direct substitution method the actual closed loop response of controller and plant is compared to the desired response and the similar coefficients s on both sides are equated [11-12].

3.1 Evaluation of Controller Parameters by Pole Placement (PP)

The transfer function of a simple PID controller can be written as,

$$G_c(s) = K_P + sK_D + K_I/s \quad (4)$$

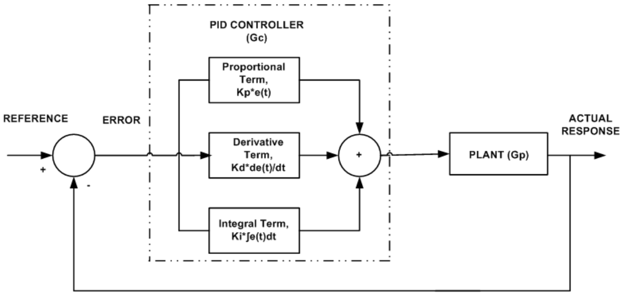

Fig. 3 Controller Parameters

The closed loop transfer function of the actual plant $G_P(s)$ with PID controller $G_c(s)$ as shown in Fig. 3 is given by,

$$T(s) = G_P(s)\, G_C(s)/1 + G_P(s)\, G_C(s) \quad (5)$$

The damping ratio, ξ has been taken as 0.8 and the tolerance band as 2%.

Let $\xi = 0.8$ and $t_s = 2$sec then $\omega_n = 4/\ \xi t_s = 2.5$

Using these parameters the desired response may be evaluated as,

$$D(s) = 6.25/\ (s^2+4s+6.25) \quad (6)$$

The dominant poles are evaluated as -2 ± j 1.5 which gives $\xi\omega_n$ as -2 [13],

Comparing the desired characteristic equation of closed loop transfer function to that of the characteristic equation of actual response with plant and PID controller at a pole assignment of -750 $\xi\omega_n$ we get [14],

$$(s + 1500)\,(s^2 + 4s + 6.25) = s\,(s^2 - 2180) + (sK_P + K_D s^2 + K_I)\,(-3653.3575) \quad (7)$$

This relation has been used to calculate the parameters of PID controller (K_P, K_I, K_D) which are evaluated as shown in Table 2.

TABLE 2
CONTROLLER PARAMETERS OBTAINED BY PP

Value of IAE	K_P	K_I	K_D
3.81 e+187	-2.24	-2.56	-0.40

3.2 Responses Obtained

The simulated response for these controller settings have been shown in Fig.4 below.

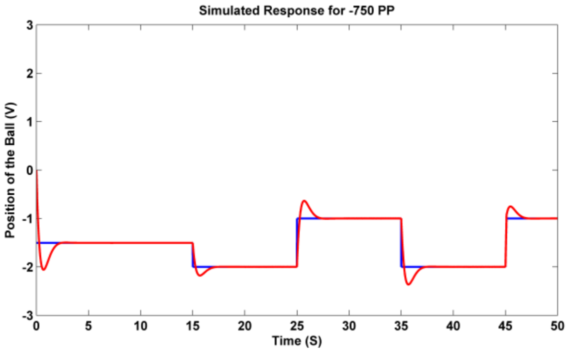

Fig. 4 Simulated Response for -750 $\xi\omega_n$

The real-time response for controller parameters at a pole assignment -750 $\xi\omega_n$ has been shown in Fig. 5 below.

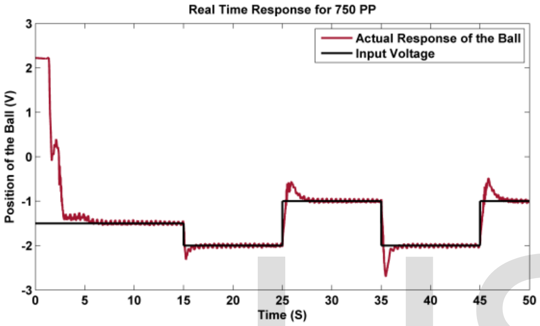

Fig. 5 Real-Time Response for -750 $\xi\omega_n$

The ball levitated for the full duration of 50 seconds at this pole assignment with visible fluctuations. The maximum control voltage is around ± 410V which is just sufficient to levitate the ball for full 50 seconds duration as shown in Fig.6.

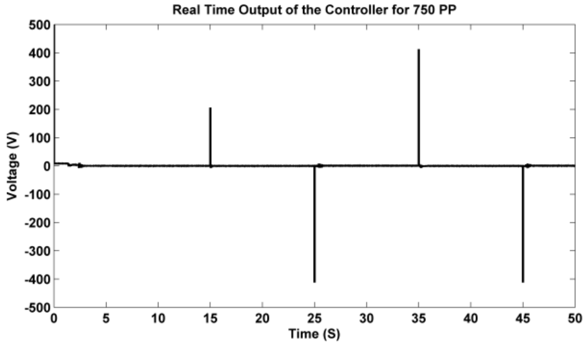

Fig. 6 Real-Time Output of the Controller at -750 $\xi\omega_n$

The control signal shows no deviation from real axis. It is the vicinity of this region which needs to be explored further to find a better setting of controller parameters which is done by application of stochastic evolutionary technique.

4 GENETIC ALGORITHM (GA) TECHNIQUE

This evolutionary optimization technique inspired by the evolution of species was a pioneering work in nontraditional optimization field by John Holland in 1960 [15-16]. In this algorithm the candidate solutions combine randomly by selection, crossover and mutation processes to give a new candidate solution and its fitness is evaluated. Better candidates subsequently lead to optimum solutions mimicking Darwin's theory of survival for the fittest. The central theme of this algorithm is robustness or survival in a new environment where parameters change or are subjected to external variations. Numerically, the candidate solution is a binary coded string in a set of array/population which after initialization, combines with another fitter candidate/ string to produce an offspring/new candidate solution in a number of iterative stages [17]. They work well in scheduling or routing problems but do not give satisfactory results in complex problems. In some applications, this pioneering evolutionary algorithm also tends to converge towards local optimum values and has a slower rate of convergence as compared to other modern algorithms.

In order to search for the optimum parameter values which results in least integral of the absolute error (IAE) in the successful zone of levitation, Genetic Algorithm is applied [18]. Therefore, the objective function is the minimization of the absolute error. As the model under consideration is unstable, it is desirable to eliminate all the overshoots and undershoots for the whole chosen duration of levitation [19].
The integral of the absolute error (IAE) may be represented as,

$$IAE=\int_0^\infty |e(t)|\, dt \qquad (8)$$

The upper and lower bounds for the controller parameters have been taken as -1.91 ≤ K_P ≤ -3.22, -0.33 ≤ K_D ≤ -0.65 and -2.05 ≤ K_I ≤ -4.10.

4.1 Evaluation of Controller Parameters by Genetic Algorithm (GA)

As GA is stochastic in nature, each iterative run might not yield optimum value so the algorithm is run around 25 times and the controller parameters corresponding to the least IAE has been taken.

The parameters chosen for this algorithm are:
Population size = 50,
Crossover probability rate = 0.8,
Mutation rate = 0.05 and
Maximum generation = 100.

The parameters corresponding to the lowest value of IAE have been shown in Table 3.

TABLE 3
CONTROLLER PARAMETERS OBTAINED BY GA

Value of IAE	K_P	K_I	K_D
4.47 e+160	-2.48	-2.98	-0.42

4.2 Responses Obtained

The chosen parameters are then set in simulated model as well as real-time execution [20]. The simulated response and the real time responses are shown in Fig. 7 and Fig 8 respectively.

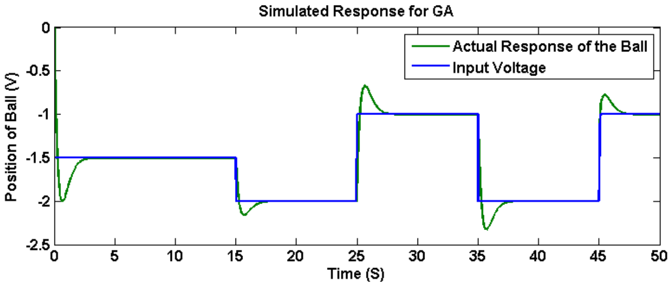

Fig. 7 Simulated Response for GA

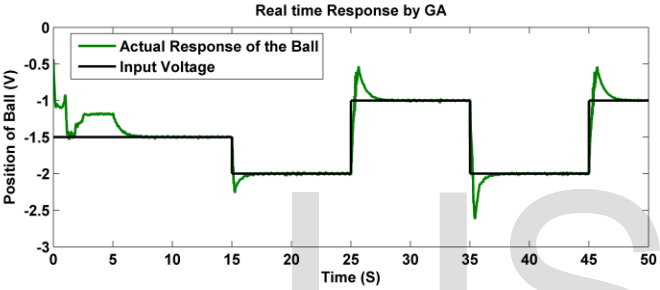

Fig. 8 Real-Time Response for GA

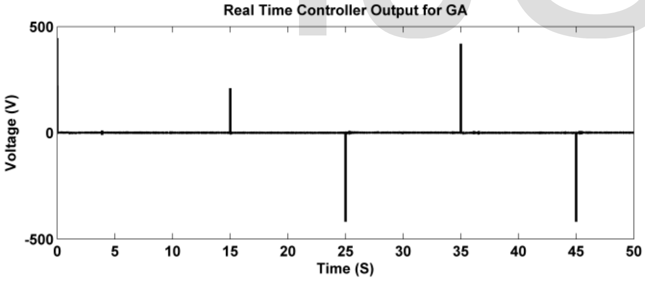

Fig. 9 Real-Time Controller Response for GA

The output response of the controller in Fig. 9 shows a smooth signal which does not deviate from the real axis and has a voltage level of ± 420 V.

5 COMPARATIVE RESULT ANALYSIS

Application of any suitable optimization technique helps in searching the best combination of controller parameters which can minimize the absolute error. Fig. 10 shows the comparative responses for pole assignment at -750 $\xi\omega_n$ by PP and that by application of GA.

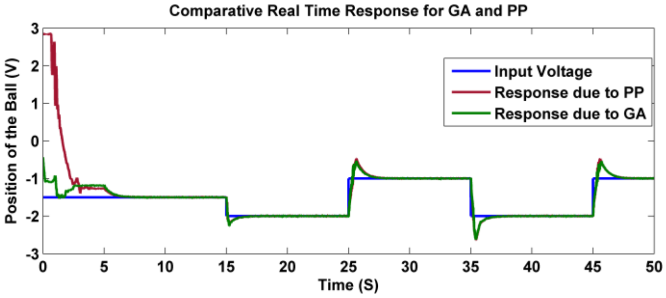

Fig. 10 Comparative Real-Time Response for PP and GA

Zooming in the responses clearly shows reduction in peak overshoot and undershoots values by application of GA in Fig. 11-12 respectively.

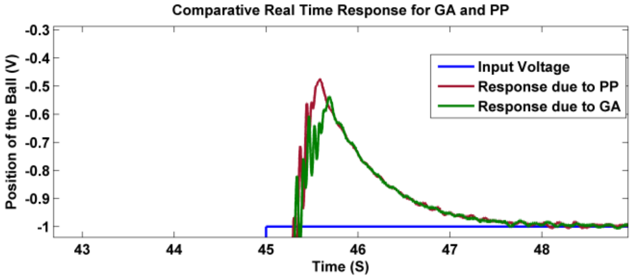

Fig. 11 Zoomed Overshoot Real Time Responses for PP and GA

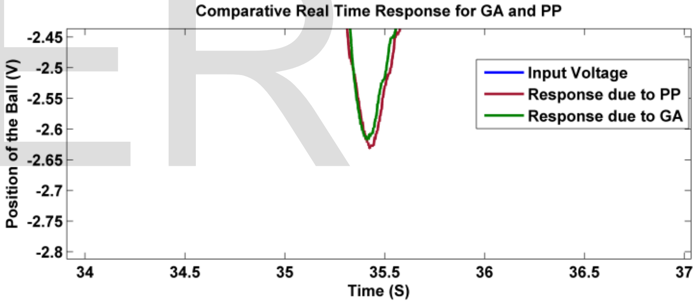

Fig. 12 Zoomed Undershoot Real Time Response for PP and GA

Analyzing the level of controller output voltage values in Table 4 clearly shows the necessity of optimum voltage level requirement for successful levitation and reduction in error values. If it is too low or too high then a lot of fluctuations maybe witnessed even while the ball is in levitated and ultimately might result in falling out of levitation during the full range of input signal supplied.

TABLE 4
Controller Voltage Levels for PP and GA

Type of Technique	Value of IAE	15 Second Instant	25 Second Instant	35 Second Instant	45 Second Instant
PP	3.81 e+187	+ 210 V	-410 V	+ 410 V	- 410 V
GA	4.47 e+160	+ 220 V	- 420 V	+ 420V	- 420 V

It can be seen that even though there is not much difference in values of the controller parameters, GA results in considerable reduction in the value of the absolute error due to a better combination of parameters searched from a wide possible combination. At this stage it can be seen that the difference in methodologies applied for evaluation of controller parameters plays a significant role and may be summarized as follows in Table 5.

TABLE 5
Comparison of PP and GA techniques

Attribute	PP	GA
Repetitions	Pole assignment location can be varied	A number of iterations are required to verify the optimum combination
Nature	Numerical and deterministic Approach	Population based Stochastic method
Values	Same value of Parameters for a particular assignment always	A different set of value may be obtained for repeated iteration
System Model	Values are specific to the system used	Does not require transfer function of the model
Bounds	There are no restrictions on the values of the parameters	It requires a definite range of upper and lower bound to restrict search area and for faster convergence
Objective Function	No objective function is required, only closed loop characteristic function of actual and desired response are compared	It is an optimization process so it requires a definite objective function which is to be maximized or minimized.

6 CONCLUSION

This paper successfully demonstrates the application of PP and GA techniques for the chosen system. As this system is very sensitive it is necessary to choose the controller parameters which would result in successful levitation. Evolutionary Genetic Algorithm technique exploits all possible combination of controller parameters by stochastic search methods resulting in considerable reduction of absolute error which is quite cumbersome by traditional Pole Placement technique as pole assignments have to be varied depending on intuitive guess. It can be concluded that evolutionary optimization technique gives a better response and results in reduction of absolute error as compared to traditional Pole Placement technique within the chosen bounds.

ACKNOWLEDGMENT

The authors are thankful to the management of BIT Mesra and DEI Agra for providing a research friendly atmosphere.
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