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THE ADVENT OF THE PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER: A REVIEW

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Abstract. Engineers have long sought to minimize human involvement in engineering processes by automating them, which reduces the likelihood of human error and imperfection. This not only lowers production costs but also minimizes the risk of life-endangering operations for humans. The control of engineering processes is critical to protecting devices from operating beyond their designed capabilities. This study investigates and presents a thorough review of the adventure of the Proportional-Integral-Derivative (PID) controller and its types. This entails the informative evolution of the controller's birth and how it has become an essential tool for those working in the field of control systems, revolutionizing the way feedback control is used in a variety of engineering applications. This paper examines the efforts of eminent researchers and engineers who have made significant contributions to the development of this theory and actual use of this control approach. Apart from conceptualizing seven categories of control systems, this work addresses the benefits and drawbacks of the PID controller while highlighting its adaptability, clarity, and durability. For researchers, practitioners, and students looking for a deeper understanding of this crucial control technique and its effects on various industries, the mathematical formulation and transfer function representation of the PID controller are presented and recommended, along with a comprehensive tabular review that serves as hands-on for any researcher in this area.

Keywords: Proportional-Integral-Derivative (PID), Control Systems, Machine Learning, Artificial Intelligence, and Transfer Function.

Engineers have frequently thought about automating most engineering procedures to reduce human involvement. By doing this, human errors and flaws are almost eliminated in such processes [1-3]. This lowers the cost of manufacturing and restricts the exposure of people to tasks and procedures that endanger their lives. Engineering processes and operations must be controlled since doing so usually prevents equipment from operating past the limits of its intended functionality [4-5]. A very good example is a thermostat in a pressing iron and refrigerator which automatically controls the temperature of the devices from rising beyond its designed range, if not, such a device develops a fault or even spoils beyond repairs. For these devices, once the temperature rises above its apex range, it automatically dis-contacts and disconnects from the mains and once it cools below its lowest design range, it automatically makes contact and connects to the source for an increase in temperature. These same principles are being utilized as yardsticks in developing sophisticated and automatic controllers to date. These controllers are used industrially to control very high-temperature operations, pressure control, voltage and current controllers, tank or water level controllers, flow controllers and particularly the PID controller, which is the basis of this research work [6-8]. This PID is different from other controllers as it has a comprehensive algorithm for generating its output from the supplied input. Systems and control engineering is a very vital engineering discipline that has drastically taken the aspect of systems automation to a great level [2], [7-10].

Fig. 1. Control system components

Categories of Control Systems Engineering

Control engineering architecture has three main parts, which are the inputs or stimulus, the controller, and, of course, the expected output or response, as depicted in figure 1 below:

Control engineering is a field of engineering that deals with the design, analysis, and implementation of control systems. Control systems are used to regulate or manipulate the behaviour of dynamic systems to achieve desired goals [11-15]. Control engineering can be divided into seven categories which are depicted in figure 2 below:

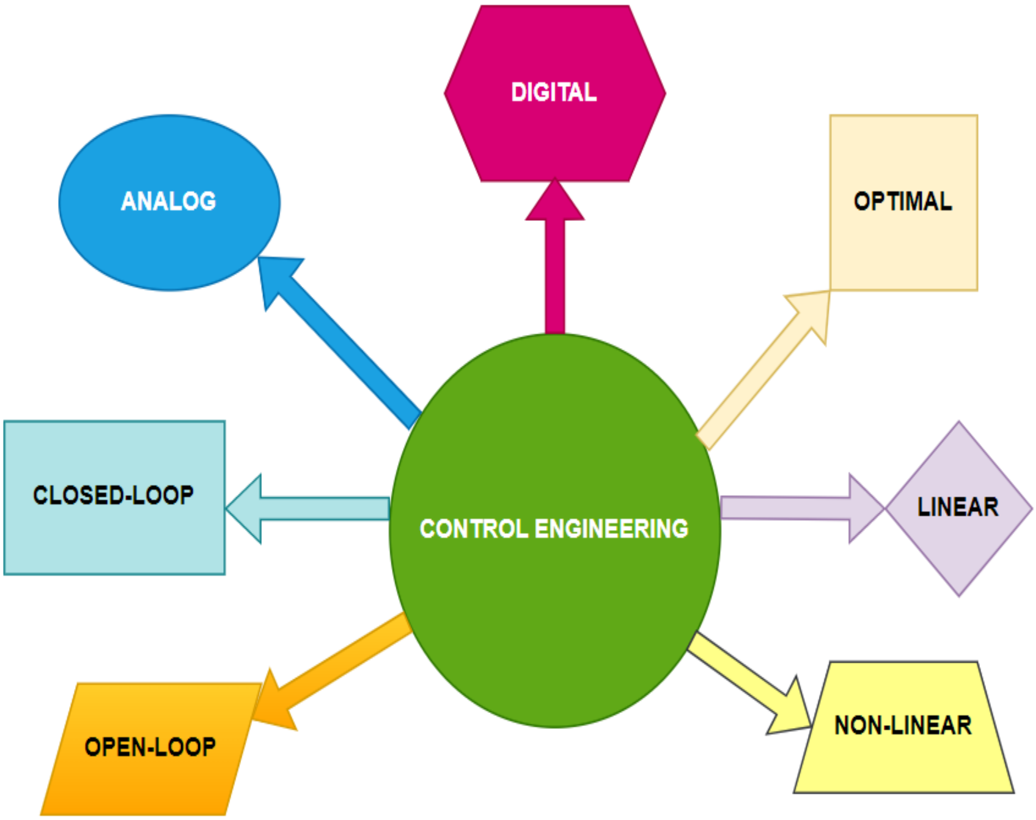

Fig. 2. Control engineering categorization

Open-loop control: Open-loop control is a type of control system where the control action is determined by a set of predefined rules or a fixed input. The output of the system is not compared to the desired output, so it cannot correct any errors that may occur [16].

Closed-loop control: Closed-loop control is a type of control system where the output of the system is compared to the desired output, and any errors are corrected by adjusting the input [17].

Linear control: Linear control is a type of control system where the system can be modeled using linear differential equations. Linear control systems are widely used in industry and are relatively easy to design and analyze [18].

Nonlinear control: Nonlinear control is a type of control system where the system cannot be modeled using linear differential equations. Nonlinear control systems are more difficult to design and analyze than linear control systems but are required for many real-world applications [19].

Analog control: Analog control is a type of control system where the control signal is a continuous voltage or current. Analog control systems are still widely used in industrial applications, but digital control systems are becoming more popular due to their superior performance and flexibility [20].

Digital control: Digital control is a type of control system where the control signal is a series of discrete values. Digital control systems can be programmed to perform complex operations and are more precise and flexible than analog control systems [21].

Optimal control: Optimal control is a type of control system that seeks to minimize a cost function while achieving a desired performance level. Optimal control systems are used in many real-world applications, including aerospace, robotics, and manufacturing [2], [22].

The advent of the pid controller

The inaugural edition of the PID controller was first constructed by an American engineer, Elmer Ambrose Sperry in 1911 [3], famously tagged the father of modern navigation technology [22]. Although, the first proportional controller (pneumatic controller), with the functionality of being tuneable, was only introduced by the then-Taylor Instrumental Company (TIC) in 1933. However, this was not a perfect proportional controller until after some years control engineers resolved its steady state error by resetting the point to some artificial values so far error was not rounded to zero. This resetting integrated the error and as such, gives rise to the emergence of a proportional-integral controller. By 1940, the TIC organization constructed the first ever pneumatic proportional integral controller with a derivative functionality, which resulted in reduced overshooting challenges experienced before. Thanks to engineers Ziegler and Nichols whose tuning techniques made it easy for other engineers to find and set the befitting parameters of PID controllers two years later. And by late 1950, smart PID controllers were famously adopted for massive industrial use [3].

Types of PID Controllers

The PID controller is simply a device majorly applied in industries to control and regulate flow, pressure, speed, temperature, and other process parameters. They contain a control loop feedback technique to regulate process parameters due to their high level of accuracy and stability [3], [23-24]. The three types of PID controllers that exist are on-off, proportional, and standard PID.

(a) On-off (b) Proportional (c) Standard PID

Fig. 3. Types of PID controllers [2]

The mathematical formulation of the PID Controller

The PID control systems have controllers and controlled devices. Desired output is achieved by varying control parameters such as proportional coefficient K_P, integral coefficient K_I, and differential coefficient K_D. As discussed in the previous section, the fundamental of the PID control technique, the integral control eradicates the steady-state errors but may cause over-adjustment, and the differential control elevates the response time but equally increases the over-adjustment [25-26]. The error e(t) of the controller is computed as:

$$e(t) = r(t) - y(t) \qquad (1)$$

Where r(t) and y(t) are the desired output or set point and measured output/process respectively.

The controlled magnitude is also computed as:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{d\, e(t)}{dt} \qquad (2)$$

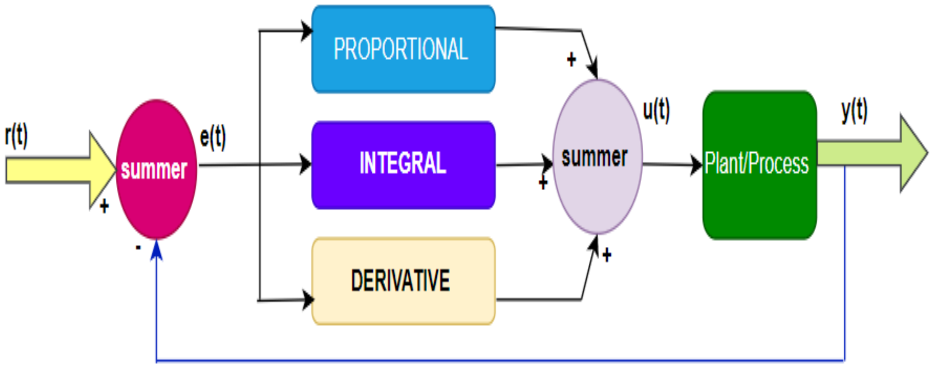

Fig. 4. Conventional PID control system

Review of related works on pid controllers

Herein, numerous past works by researchers on PID controllers are concisely presented, stating their research methodologies and the significance of the results obtained.

General Related Works Review

According to N'Doye et al in [26], research on intelligent PID (iPID) control-based functions of modulating for pointing laser beam and stabilization was carried out. They designed a PID controller system, implemented it, and equally tested it to stabilize a beam of the laser so that the fast-steering beam's (FSB) incident laser beam was reflected to the position sensor's center despite having uncertainties and active disturbance. The iPID controller's performance was examined in a closed-loop and was matched to the traditional PID and the robust PID (RPID) controllers. It was gotten from the real-time experiment that the iPID controller achieved better results, emphasizing the positivity of the proposed controllers in form of robustness. More so, modelling deviations, system probabilities, and disturbances which are described by the real-time approximation issue of the hidden function using modulating function-based method (MFBM) were examined. N'Doye concluded that the MFBM techniques joined with the model-free-based control were easy to implement since they did not need a perfect model of the control system and that they possessed excellent robustness performance with good location tracking precision.

Er and Sun in [27], worked on hybrid fuzzy proportional-integral with traditional derivative control of nonlinear and linear systems. They introduced a new idea of using genetic algorithms (GAs) for the perfect design of their hybrid-PID controller (PHC) model. A fuzzy logic controller (FLC) was normalized using GA for the building of the fuzzy region to be easier and more analytical. The evaluation of the reliability of the desired hybrid-PID controller was achieved through MATLAB on a linear temperature control system (TCS) and a missile model (MM) that is strictly nonlinear. The TCS demonstrated by the simulation results showed that the presented controller model outshone traditional PID controllers and many other fuzzy PID systems based on overall performance grades. It was concluded that the proposed controller for the MM further demonstrated the correctness and capability in organizational applications of the PHC. In [28], Huang et al analyzed normal stay time (ADT) based smooth exchanging (SS) direct boundary differing (LPV) PID control for a F-16 airplanes. A SS gain plan PID control strategies for LPV frameworks was introduced. They planned the regulator to have the SS ability in the change subspaces between adjacent LPV subsystems. With an ADT changing sign to guaranteeing gauged L2-gain (space of square-incorporate capable capabilities) result and soundness, the circumstances for different boundary subordinate Lyapunov capabilities were shown up at for the shut circle framework. The amalgamation limitation was inferred as a streamlining issue being exposed to straight network imbalance (LMI) conditions considering these circumstances and the utilization of Finsler's lemma. The proposed strategy control method accomplished progress execution and smooth control orders by contrasting it and the typical ADT exchanging. They expected that the framework boundaries were precise and suggested more intricate situations for additional investigations [28].

Salem et al investigated tuning PID controllers using AI techniques as applied to direct-current (DC) motor and automatic voltage regulator (AVR) systems in [29]. They concluded that in comparison to traditional tuning techniques, the PID controllers tuned with GA and Particle Swarm Optimization (PS0) displayed improved performance indices and steady-state response. The optimization's computation takes only a small amount of time to complete. The controller with the best performance was the one tweaked with PSO algorithms (very little rise time, no overshoot, and steady-state error was equally zero). Simulations of PSO-tuned PID controllers demonstrated that they produced solutions of greater quality and greater computational effectiveness. In comparison to the GA technique, the proposed PS0 method proved more effective at addressing the PID control tuning issue [29].

Chengwei and Qian in [30], explored enhanced PID control strategies with recreation for lower appendage utilitarian electrical feeling. The recommendation of a nonlinear autoregressive organization with exogenous sources of info (NARX) model with a backpropagation PID (BP-PID) control calculation was introduced. From the reproduction, it was demonstrated the way that the point of the knee could be moved by the regulator successfully and impeccably. Chengwei had the option to accomplish underneath 5% relative error, getting the framework to a steady state soon after the course of change. Despite the advantages, it was noted that the model never represented all gotten parameters of the muscle like time-dependent actions. They recommended that neural networks should be considered and analysed in future works. In [31], Cheng et al researched the radiofrequency removal (RFA) temperature control framework utilizing fluffy PID control. In the RFA temperature framework, their work proposed a self-boundary Fluffy PID regulator. The PID regulator was planned and reproduced utilizing the MATLAB Simulink stage, with recreation examination using the unadulterated fluffy control technique and regular PID control. Various regulators' reproduction and error investigation discoveries were assembled. Oneself tuning Fluffy PID regulator beats PID control and unadulterated fluffy control as far as framework security and blunder control capacities. The powerful highlights of the framework were additionally further developed by oneself tuning Fluffy PID regulator's boundaries. Fluffy PID regulators are the best. A controlled environment, such as a test tube or petri dish, is used for an in-vitro study, which includes diagnostic procedures, scientific testing, and experiments carried out by researchers apart from a living thing [7]. The goal of this stage was to determine whether the Fuzzy-PID controller could successfully control temperature. To obtain the effect of intelligent temperature regulation, Cheng proposed that more research on the use of fuzzy-PID program code should be carried out. Demetriou led the solitary examination concerning the spatial PID punishment of appropriated agreement channels for topographically dispersed frameworks in [32]. For a class of pairwise gauges contrasts, it was recommended to punish the spatial slope of pairwise conflict of conveyed channels (PDEs). The system that punished the spatial gradient and perhaps the spatial averages of PDE in addition to pairwise disagreement was examined. A spatial PID consensus controller's implementation was shown. It constituted a paradigm leap in the understanding of unanimity filtering for spatially distributed networks. t.

As per Youssef et al in [33], Takagi-Sugeno (TS) fluffy models for the amalgamation of an obscure data sources corresponding basic eyewitness (PIO) were introduced. Youssef proposed a PIO for a TS fluffy model with obscure sources of info and unfathomable choice factors. The obscure data sources that impacted both the state and result signals were thought to be polynomial, and their kth subsidiaries were limited standards. The plan conditions were laid out in direct grid imbalances (LMIs) structure utilizing the hypothesis of Lyapunov. A mathematical model was given to approve their methodology. The given model showed the adequacy of the inferred conditions since both state and obscure information sources were very much determined. They inferred that their methodology was a decent procedure for creating shortcoming conclusion calculations.

Furthermore, Shan et al broke down the speed increase recreation mode (ASM) emanation's location frameworks' control component in light of fluffy relative basic subordinate control [34]. Control accuracy was improved by utilizing a control calculation of reasonable plan. They recommended that it might assist with expanding the utilization of ASM discharge's location frameworks. This study checked out at both the dynamic and static parts of the swirl current machine. PID control, fluffy control, and fluffy PID control were likewise researched. The examination technique for investigation was then used to determine the effect of speculative stacked force and time. The control framework technique utilized in the work was fluffy PID control, with the heap force and time capabilities being characterized. Shang concluded that this work analysed several functions of packing torques and time to establish the maximum variability pattern and ideal load torque control curve.

Somewhere else, Obias et al inspected the impact of PID values on the security of an automated airborne vehicle (UAV) framework [35]. As per the ANOVA table, the communication among AC and Stomach muscle was the main component impacting UAV framework blunder, inferring that a corresponding indispensable (PI) regulator and a relative subsidiary (PD) regulator could be sufficient to limit framework mistake extraordinarily. Obias concluded that the three-way PID interaction had no effect on the error and might be effective in other UAV setups, but for the experimental structure created, it was sufficient to use a PD or PI control method to establish a flight that is stable depending on the state of the importance of the relationship between the two controllers. However, they recommended that more repetitions be run and that a Response Surface Methodology (RSM) design be performed in maximizing the PID settings and increasing the robustness of the UAV system. In [36], Aziz and others dealt with fluffy corresponding in addition to partial request basic subsidiary (FP+FOID) regulator plan. As indicated by their hypothesis, the motivation behind creating and introducing the FP+FOID regulator configuration was to further develop the control productivity of a customary PID regulator by joining the upsides of conventional PID, fluffy rationale, and partial request. The outcome was analysed utilizing the steam refining process model, and the appropriate PID gain not entirely settled by applying AMIGO tuning techniques. Utilizing an experimentation technique, the genuine size of the partial request differentiator and fragmentary request integrator was changed to get the worth that more qualified the systemic structure. The presented model by Aziz was equally matched with three unlike types of models: fuzzy PID controller, FP+ID controller, and PID controller. According to the data obtained, the recommended model wonderfully transmitted amazing outputs. Twin Rotor MIMO System (TRMS) Nonlinear Modelling and PID Control system was examined by Ramalakshmi and Manoharan in [37]. The mathematical formulation of the TRMS in the two degrees of freedom (2-DOF) was developed in this work to evaluate and regulate the nonlinearity of the system. The control was developed using simple and traverse-linked a PID controller and simulated results were produced. They concluded that for various reference inputs, the PID control outputs and process output errors were analyzed, and the overall sine wave error was minimized. Also, Husodo and Ayob carried out a PID controller design for an impedance-source inverter in [38] where they asserted that the proposed controller controlled the input side's DC-link voltage to control the output AC voltage. The control variables were implemented using a Bode plot, and a mathematical algorithm was developed. Simulations with load perturbations and source were run, and the output demonstrated how excellently reliable the design was. Kumiawan et al [39], investigated using the cross-entropy method (CEM) of tuning fractional order PID (FOPID) controller for the dc motor control model. With improved results as compared to PID control systems that were tuned using the Ziegler-Nichols method, they successfully simulated FOPID control systems that were tuned using the CEM algorithm utilizing a DC motor model as the plant. Furthermore, when compared against FOPD, FOPI, PID with fractional order and PID that were tweaked using the same technique, FOPID controllers still produced good results. It might be demonstrated using rise time, settling time, overshoot performance characteristics and transient response curves. They concluded that to verify if the controller's performance matched expectations, it was crucial to choose parameters that were appropriate for the design aims.

Besides, in a shut circle Z-source inverter-took care of enlistment engine drive, Srivastava et al [40] explored the utilization of either a PI or PID-based speed regulator. The unique model of the Z-source inverter and the drive framework control technique were created. The drive was demonstrated for both PI and PID-based speed regulators, considering various varieties in reference speed and burden force. With each adjustment of reference speed and burden force, they thought about and read up the outcomes for the two regulators. All in all, the recreation results showed that the drive with a PID-based speed regulator beat the one in light of PI [40].

The mathematical modelling, validation, and practical test of two alternative control algorithms utilized to govern the orientation of a real multirotor platform were the main topics of this study by Gargioli et al [41]. The control techniques were verified by several computer simulations, and the simulation was made more accurate by adding white noise to the state detection process. Subsequently, a real prototype was created to test the control rules experimentally. Each state responded promptly that met the target's requirements for control strategy. It was determined that, considering the nonlinearity of the model, a more realistic model of the aircraft was explored to enhance the multirotor attitude control. Yet, in that situation, it was imperative to strike a careful balance between control performance increase and control architectural sophistication, which would likely result in higher computing requirements [41].

According to Sharma et al [42], a fuzzy-tuned PID control of a paper machine head-box was worked on. Following the results of using both the fuzzy logic computing PID (FLC-PID) methodology and the autonomous tuning technique, it was observed that FLC-PID offered significantly improved and tolerable efficiency based on settling time. As a result, the FLC method for fine-tuning the PID controller, which was dependent on the partial membership degree, was very well received by the headbox in the paper machine. They suggested that different soft computing methods be used for future work, if possible [42].

In [43], Tajuddin et al examined the buck converter small-signal alternating current (AC) modelling method in conjunction with digital signal processing (DSP) based PID controller. The converter's practical elements were considered during the design. Phase margin testing was done on the entire system to determine its reliability. A modulator was added to the feedback loop's forward channel to optimize the loop gain and attain the desired efficiency. A standardized Buck converter with a PID controller module was provided to simplify development. Design criteria were offered in a straightforward, stage process format. The use of MATLAB/Simulink was applied to develop the entire design. The simulated design was developed as a prototype. To validate the converter design and process, the test findings were presented. The study demonstrated that a switch power supply may be designed with good results using a basic proper control technique and a conventional mathematical methodology [43].

Lai and Liang [44] investigated an F-0 control model for singing synthesis based on a PID controller. For Taiwanese children's songs, a FO control model for producing FO contouring was suggested. A second-order transfer function was controlled by the FO control model, which was modelled on a PID controller. The PID controller's parameters were changed to produce the appropriate overreach and preparatory variations. The obtained FO outlines were given fine variation to give them a more realistic result. It was concluded according to the findings, that the suggested FO control model, as opposed to the stepwise FO from the rhythm of predetermined sounds, could significantly increase the genuineness of the perception of hearing.

Also, Qiu et al tested the PID controller using the metamorphic testing (MT) technique in [45]. The findings of the mutation study demonstrated that MT had an adequate ability to detect failures. They suggested that their future research should focus on testing more complicated controller programs.

Additionally, Alves et al. [46] chipped away at the power portion technique utilized in the cutting edge latent optical systems administration (NG-PON) that utilizes optical code-division numerous entrance (OCDMA) and PID calculations considering the Foschini/Miljanic (FM) and Verhulst (V) models. Utilizing PID plans created by DPCA-FM and DPCA-V, separately, conveyed power control calculations (DPCA-PID-FM) and DPCA-PID-V were created to go past the sign to-commotion in addition to impedance proportion (SNIR) gauge limits. The numerical outcomes showed that for accurate SNIR estimates, DPCAFM attained a full agreement with less iteration than DPCA-V. Furthermore, DPCA-V exhibited more grounded combination and a lower deviation from the best power vector arrangement in approximated feeble sign situations than DPCA-FM. Furthermore, the likelihood and combination rate comparative with DPCA-V were unaffected by the consideration of the corresponding and differential systems in DPCA-V to make DPCA PID-V. Be that as it may, DPCA-PID-FM had the option to essentially support its proficiency by modifying the incomplete conclusion pattern of DPCA-FM. They concluded that all the DPCAs examined in this investigation suffered from convergence errors when the channel error estimate was increased [46].

Furthermore, Pandey and Laxmi researched twin-rotor MIMO system (TRMS) control using a PID controller with a derivative filter coefficient [47]. MATLAB/SIMULINK was used to create the theoretical formulation of TRMS in two degrees of freedom (DOF). The system's horizontal and vertical motions were managed by two PID controllers with derivative filters. With sine wave and step reference signals, the effectiveness of the developed controllers was assessed. It was demonstrated that TRMS accomplished the intended inclination more precisely and effectively. Comparisons were made between the simulation outcomes of the PID controller with derivative filter and the traditional PID controller. In conclusion, the findings demonstrated that, in comparison to the standard PID controller, the suggested controller with a derivative filter outperformed in terms of both transient and steady-state responsiveness [47].

In addition, Naccache and Gannod controlled self-healing adaptive content (SHAC) systems with the aid of a PID [48]. They tried to higher the frequency of responses with a full resolution while adhering to the response time service level agreement (SLA). They accomplished this by fostering an independent chief that was started from a queueing organization (QN) model which was created during the sending of a SHAC-empowered framework and utilized a PID regulator as a shut circle input framework. Additionally, it was demonstrated that the autonomous manager could sustain response speeds even when the system was under increasing stress from programs that were out of the web server's purview. They suggested incorporating additional survival studies and an industrial implementation in future work. Another option they would like to investigate was integrating extra survivability studies into the SHAC strategy to support server loads more prominent than those that could be upheld at the base goal [48].

A magnetic levitation system's PID and state feedback control were researched by Dragos et al. in [49]. A magnetic levitation device with two electromagnets was placed using one of three control algorithms (MLS2EM). The MLS2EM nonlinear model was reduced to seven working areas. The suitable state input gain network was found, and a state criticism control structure (SFCS) was created to increment solidness. The SFCS was unable to deliver a steady state control error of zero, leading to the creation of seven PID controllers. The aftereffects of the ongoing tests showed that the PID-C control structures were viable in working on the presentation of the control framework as for step alterations of the information signal. They likewise ensured no consistent state control mistake, a fast-settling time, and a speedy overshoot [49].

In another study, Li and Yuan looked at a nonlinear-PID (NPID) based latent factor (NSLF) model that included stochastic gradient descent (SGD). In this work, a novel NSLF model that incorporated the NPID controller into such an SGD-based LF model was proposed to quickly close and achieve adequate predictive performance for imperfect data of a strong and dense (HiDS) matrix. Even while NSLF performed better than expected when dealing with HiDS matrices, there were still unresolved concerns. Numerous hyperparameters had to be carefully and manually tweaked because of the observations. The interaction took some time, and it appeared to be truly possible to carry out self-transformation of hyperparameters for NSLF. Early research [50] suggest that a technique based on evolutionary computation, such as particle swarm optimization, may contribute to the effective development of hyper-parameter adjustments for LF models. They sought to tackle this challenging issue as part of their ongoing endeavour [51].

In [52], When a subject was captured using a photographic optical system in various locations, Yu et al. introduced a versatile fluffy rationale PID (AFL-PID) control calculation that could make up for the aggravation changeability, burden, and gravity enhancements of the compact part in the small-scale picture adjustment (AF) voice curl engine (VCM) actuator with protecting power. Quick unique achievement and insignificant consistent state blunder were highlights of this methodology (SSE). They suggested that the initial fixed PID settings for a standard PID controller might be corrected during training or development by drawing conclusions from fuzzy logic. The AF places of the AF VCM actuator with maintenance force vacillated because of varieties in burden and aggravation, yet it was expressed that a transformation component created an additional info sign to ensure the AF VCM actuator functioned admirably. The AFL-PID control created a magnificent response time when the AF position was 0.3mm; explicitly, the settling time was 2.7ms, the SSE was 2m, and the greatest overshoot was under 1%. Besides, a rectification force and a holding force were utilized to adjust a lopsided burden unsettling influence in the AF VCM actuator. At the point when versatile fluffy rationale PID control was utilized, the suggested AF VCM actuator with maintenance power's credits fulfilled the optical determinations for AF in a visual optical framework [52].

In [53], Gao et al explored on fractional-order PID linear active disturbance rejection control (FOLADRC) plan and boundary improvement for hypersonic vehicles with actuator deficiencies. For hypersonic vehicles with actuator disappointments, the FOLADRC technique—a mix of the FOPID technique and traditional LADRC technique put forth. The benefits of both FOPID and LADRC were merged into the intended FOLADRC controller. The effects of the actuator model on the FOLADRC-based closed-loop control system's anti-disturbance capabilities and parameter tuning were then examined. The FOLADRC controller's control settings were optimized using the frequency-domain analysis technique. The 6-DOF nonlinear hypersonic design was then deployed using the FOLADRC approach to validate the control performance. The simulated experiments' results showed that the FOLADRC approach performed better than the FOPID and LADRC methods under both normal conditions of operation and actuator fault conditions.

Lastly, Nan and Zhang analysed the predictive modelling on PID neural networks (PID-NN) and quantum neural networks (QNN) in [54]. They stated that QNN was a prospective topic in the study of quantum computation and quantum information. Numerous models had been put forth in the research, but for most of them, it was unclear what kind of controller would be needed to implement the models. The model of generalized-QNN (GQNN), which is based on QNN and the theory of artificial-NN-PID (ANN-PID), was examined in this study. Since the model of GQNN had a defined operator, n quantum numbers could be employed to execute it. While GQNN may create the 2n2n quantum input space, its fundamental nonlinearity might more effectively represent the beginning information of nonlinear systems. The GQNN's expectation was substantially more exact to get the results of forecast when the example information was precise and adequate, which could conquer the downsides in light of the fact that customary NN explored gradually, and the prescient exactness rate was poor. Traditional NN could only make current predictions.

Analysis of more existing methods

Below are some of the already researched areas and methodologies deployed in the design of a PID controller and their applications.

Self-Controllable Fuzzy Logic SISO/MIMO Systems for PID

For the construction of a fuzzy PID controller for single-input single-output (SISO) and multiple-input multiple-output (MIMO) scenarios, a systematic methodology was created by the authors [55].

$$\Phi_m = \frac{\pi}{2}\left(\frac{\mathrm{Am}-1}{\mathrm{Am}}\right) \quad (3)$$

The approach required methodology through relay experiments and was centred on parameters for gain (Φ_m) and phase (A_m-1) margins. The gain was viewed as a fuzzy set in the SISO scenario concerning Eq. 3, and the fuzziness of the gain and phase margins were handled in the MIMO scenario to enable sequential design according to Eq. 4. In several case studies, the fuzzy PID controller effectively showed superior performance over the traditional PID controller, especially for nonlinear plants. The fuzzy PID controller could also tolerate a variety of bad controller gain development choices.

$$G_{c,i}(s) = k_i\left(\frac{\mathrm{Ais2} + \mathrm{Bis} + \mathrm{Ci}}{s}\right) \quad (4)$$

The main objective of the authors of this approach was to offer plant managers an approach for fast attaining crisp control over uncertain mono-variable (SISO) and multivariable (MIMO) systems using a fuzzy PID technique that was simple to comprehend. The main objective of the authors of this study was to offer plant managers an approach for fast attaining crisp control over uncertain mono-variable (SISO) and multivariable (MIMO) systems using a fuzzy PID technique that was simple to comprehend [55].

Pre-searched Genetic Algorithms for PID MIMO System

The authors of [56] used a revised real-value type (RGA) to fine-tune the PID controller's variables to regulate the TRMS in 2-DOF. The outcomes of the simulation demonstrated that the new control scheme could more effectively direct the TRMS to a certain point and trace a specified course. Both the sine wave and square wave's total error in set-point control and type of research were decreased. A personal computer running Intel P4/3.0 simulations was used. For cross-coupled simulation, the updated RGA had 50 runs with 500 generations each, with an average computational cost time of 51s. The starting search range, initial population, fitness function, and other criteria all had an impact on the RGA's searched solution. The TRMS was highlighted by complex and highly nonlinear functions with some measurement-impossible values. As such, it may be viewed as a difficult engineering problem [57]. In their work, they offered a fitness function with a systemic performance metric for simultaneously solving many variables as well as a new method for determining the initial search range. The cross-coupled PID controller's control settings rapidly reached appropriate conclusions. Simulations demonstrated that the suggested PID control employing NCD and RGA outperformed traditional PID and GA-PID controllers in terms of overall performance.

MIMO Predictive PID Controller Using State Space Representation

In [58], It was discussed how to develop MIMO predictive PID controllers using the state space representation, which was the best way to match PID control signals. The author had to resolve a sophisticated control approach; therefore, the technique required a lot of calculations. However, because the controller had a PID structure, it could be simply applied to the system. But without a requirement approximation, the suggested technique could handle future set points and integrate process dead time. The first-order 2120 system's controller was simplified to a typical PID controller with the same architecture. It was demonstrated that a method resembling a model-based predictive controller (MPC) could be used to determine the ideal PID gain values as depicted in figure 5.

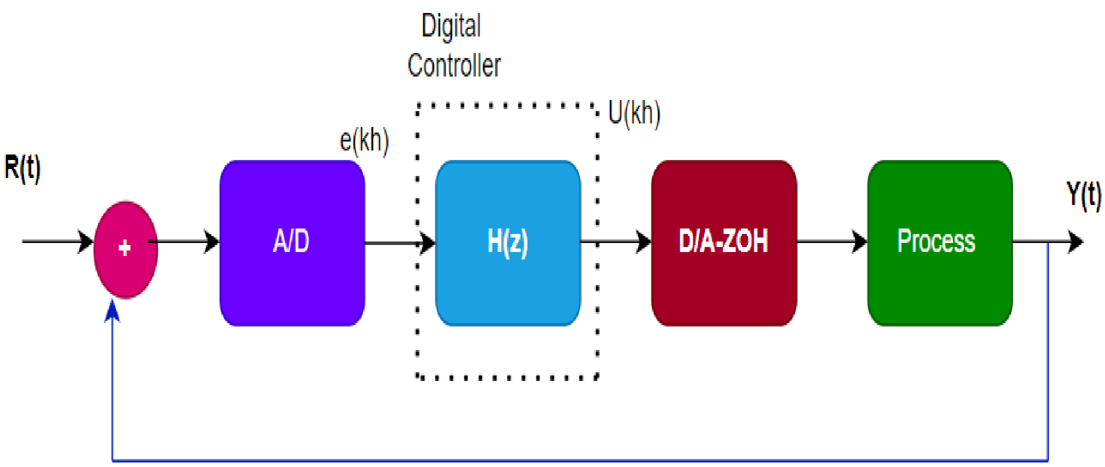

Fig. 5. Digital process's closed-loop block diagram

To demonstrate the reliability and effectiveness of the suggested strategy, many standard processes were used as examples. One of the key benefits of the suggested controller was that it could be applied to systems of any order and that its effectiveness could be altered using PID tuning [58].

Robust MIMO PID Tuning Technique

The Palmor decentralized PID tuning approach for 2120 systems was first adapted for MIMO systems in this study. There were two parts to the tuning process. The required critical point, which was made up of a critical frequency and M loops' steady state gains, was discovered in the first stage. The Ziegler Nichols principle or its variants were employed to tune the PID controller in stage 2 using the information gathered from the selected critical point. The decentralized PID controller for MIMO plants was then tuned using additional factors as depicted in figure 6. The system's bandwidth frequency was utilized to compute the desired critical point (DCP) in the suggested technique [59].

M- relays investigations were used to establish the system gains at crossover frequencies, which were necessary for the correct DCP allocation of the MIMO PID system. The technique's effectiveness and robustness were matched to the Palmor method. The outcomes demonstrated that the approach converged relatively quickly and was more reliable than the Palmor method [59].

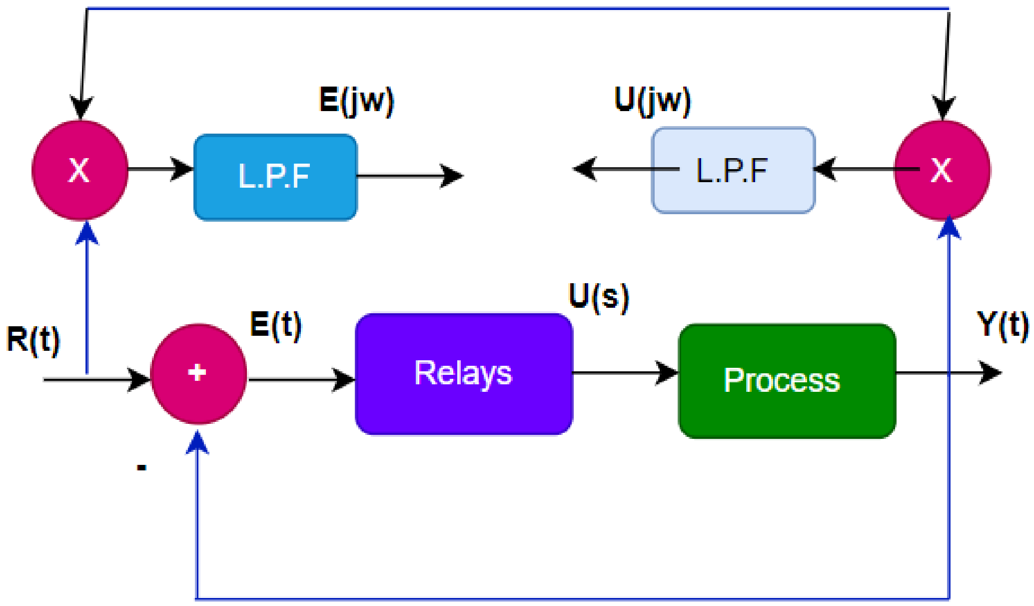

Fig. 6. Inputs and outputs at frequency ω_b in the i^{th} relay test

Decoupled PID for MIMO Systems Technique

The recommended control strategy by the authors of [60] was a straightforward multi-variable controller. It could be constructed with standard PID controllers and a proportional controller D, but it addressed a lot of real-world control issues. Effective design techniques for decoupled PID control were desired. In this paper, such a technique was established, assuming that the interaction was not too harsh. The interaction indices k_1 and k_2 were used to quantify potential PID controller detuning. The necessity of set point weighting for PID controllers in multivariable systems was a key point stated in the article. If set-points $b_1 = b_2 = 0$ were used, the interaction between the control loops might be significantly reduced.

They considered the design of a linear controller C for a linear stable process G, which is a multivariable control problem. Astrom et al. assumed the system had two inputs and two outputs to keep things simple, making G a transfer function of the following form:

$$G(s) = \begin{pmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{pmatrix} \quad (5)$$

$$D = \begin{pmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{pmatrix} \quad (6)$$

$$\text{Where} D = G^{-1}(0) \quad (7)$$

Eq. 7 is the decoupling matrix [60].

Tabulation and Summary of the Literature Reviews

This subsection entails the summary of the review of the related works on PID controllers and AI/ML applications. These are contained in Table (2.0) below:

Table-1. Tabular review of related works

SN	Authors	Title	Aim of the study	Methodology	Result	Research Gap
1	I. N'Doye, S. Asiri, A. Aloufi, A. Al-Awan, and T-M. Laleg-Kirati	Intelligent PID (iPID) control-based functions of modulating for pointing laser beam and stabilization	To design, implement, and test a PID controller system, and equally use it to stabilize a beam of the laser	The iPID controller's performance was examined in a closed-loop and was matched to the traditional PID and the robust PID (RPID) controllers	It was gotten from the real-time experiment that the iPID controller achieved better results, emphasizing the positivity of the proposed controllers in form of robustness	As a result, this study adds to the body of knowledge by outlining and assessing brand-new strategies for laser beam stabilization and aiming that include intelligent modulating functions with the PID control framework.
2	M. J. Er and Y. L. Sun	hybrid fuzzy proportional-integral with traditional derivative control of nonlinear and linear systems	To normalize fuzzy logic controller (FLC) using GA for the building of the fuzzy region to be easier and more analytical	They introduced a new idea of using genetic algorithms (GAs) for the perfect design of their hybrid-PID controller (PHC) model	The TCS demonstrated by the simulation results showed that the presented controller model outshone traditional PID controllers and many other fuzzy PID systems based on overall performance grades	The research gap surrounding the creation and use of a hybrid control strategy that combines traditional derivative control with fuzzy proportional-integral (PI) control for both linear and nonlinear systems is addressed in this study.
3	B. Huang, B. Lu, Q. Li, and Y. Tong	normal stay time (ADT) based smooth exchanging (SS) direct boundary differing (LPV) PID control for a F-16 airplanes	They planned the regulator to have the SS ability in the change subspaces between adjacent LPV subsystems	A SS gain plan PID control strategies for LPV frameworks was introduced. They planned regulator to have the SS ability in the change subspaces between adjacent LPV subsystems	With an ADT changing sign to guaranteeing gauged L2-gain (space of square-incorporate capable capabilities) result and soundness, the circumstances for different boundary subordinate Lyapunov capabilities were shown up at for the shut circle framework	The research gap relating to the creation and use of a smooth switching, linear, parameter-varying proportional, integral, derivative (PID) control technique specifically designed for an F-16 aircraft is addressed in this study.
4	A. Salem, M. A. Moustafa Hassan, and M. E. Ammar	tuning PID controllers using AI techniques as applied to direct-current (DC) motor and automatic voltage regulator (AVR) systems in	To tune the PID controller using AI techniques as applied to direct-current (DC) motor and automatic voltage regulator (AVR) systems in	The PID controllers was tuned with GA and Particle Swarm Optimization (PS0)	The controller with the best performance was the one tweaked with PSO algorithms (very little rise time, no overshoot, and steady-state error was equally zero). Simulations of PID PSO-tuned PID controllers demonstrated that they produced solutions of greater quality and greater computational effectiveness	In the context of DC-motor and Automatic Voltage Regulator (AVR) systems, the work fills a research need relating to the use of artificial intelligence techniques for tuning proportional-integral-derivative (PID) controllers.
5	G. Chengwei, and J. Qian	enhanced PID control strategies with recreation for lower appendage utilitarian electrical feeling	To explore enhanced PID control strategies with recreation for lower appendage utilitarian electrical feeling.	The recommendation of a nonlinear autoregressive organization with exogenous sources of info (NARX) model with a	it was demonstrated the way that the point of the knee could be moved by the regulator successfully and impeccably	The work fills a research gap in proportional-integral-derivative (PID) control techniques for lower limb functional electrical stimulation (FES) systems

				backpropagation PID (BP-PID) control calculation was introduced.		creation and optimization.
6	Y. Cheng, Q. Nan, R. Wang, T. Dong, Z. Tian	the radiofrequency removal (RFA) temperature control framework utilizing fluffy PID control	The goal of this stage was to determine whether the Fuzzy-PID controller could successfully control temperature	The PID regulator was planned and reproduced utilizing the MATLAB Simulink stage, with recreation examination using the unadulterated fluffy control technique and regular PID control	Oneself tuning Fluffy PID regulator beats PID control and unadulterated fluffy control as far as framework security and blunder control capacities	The research gap on the use of fuzzy proportional integral derivative (PID) control for temperature control systems in radiofrequency ablation (RFA) procedures is addressed in this work.
7	M. A. Demetriou	Solitary examination concerning the spatial PID punishment of appropriated agreement channels for topographically dispersed frameworks	To examine the spatial PID punishment of appropriated agreement channels for topographically dispersed frameworks	The system that punished the spatial gradient and perhaps the spatial averages of PDE in addition to pairwise disagreement was examined	A spatial PID consensus controller's implementation was shown. It constituted a paradigm leap in the understanding of unanimity filtering for spatially distributed networks	The application of spatial proportional-integral-derivative (PID) penalization in distributed consensus filters for spatially distributed processes is addressed in this study.
8	T. Youssef, M. Chadli, and M. Zelmat	Takagi-Sugeno (TS) fluffy models for the amalgamation of an obscure data sources corresponding basic eyewitness (PIO)	Youssef proposed a PIO for a TS fluffy model with obscure sources of info and unfathomable choice factors	The plan conditions were laid out in direct grid imbalances (LMIs) structure utilizing the hypothesis of Lyapunov. A mathematical model was given to approve their methodology	The given model showed the adequacy of the inferred conditions since both state and obscure information sources were very much determined	In order to create an unknown inputs proportional integral observation for Takagi-Sugeno (TS) fuzzy models, there is a research need that is addressed in this study.
9	H. Shan, H. Liu, L. Zhang, F. Li, and Q. Liu	the speed increase recreation mode (ASM) emanation's location frameworks' control component in light of fluffy relative basic subordinate control	To breakdown the speed increase recreation mode (ASM) emanation's location frameworks' control component in light of fluffy relative basic subordinate control	This study checked out at both the dynamic and static parts of the swirl current machine. PID control, fluffy control, and fluffy PID control were likewise researched. The examination technique for investigation was then used to determine the effect of speculative stacked force and time	The control framework technique utilized in the work was fluffy PID control, with the heap force and time capabilities being characterized. Shang concluded that this work analyzed several functions of packing torques and time to establish the maximum variability pattern and ideal load torque control curve	The work fills a research need in the area of fuzzy proportional-integral-derivative (PID) control for acceleration simulation mode emissions detection systems.
10	K. C. U. Obias, M. F. Q. Say, E. A. V. Fernandez , A. Y. Chua, and E. Sybingco	A study of the interaction of proportional-integral-derivative control in a Quadcopter unmanned aerial vehicle using design of experiment	To inspecte the impact of PID values on the security of an automated airborne vehicle (UAV) framework	As per the ANOVA table, the communication among AC and Stomach muscle was the main component impacting UAV framework blunder, inferring that a corresponding indispensable (PI) regulator and a relative subsidiary (PD) regulator could be sufficient to limit framework mistake extraordinarily	for the experimental structure created, it was sufficient to use a PD or PI control method to establish a flight that is stable depending on the state of the importance of the relationship between the two controllers.	Using design of experiment (DOE) methodologies, the work fills a research gap concerning the interplay of proportional-integral-derivative (PID) control in a Quadcopter unmanned aerial vehicle (UAV).

11	N. S. A. Aziz, R. Adnan, and M. Tajjudin	Design of fuzzy proportional plus fractional-order integral-derivative controller	to further develop the control productivity of a customary PID regulator by joining the upsides of conventional PID, fluffy rationale, and partial request	The outcome was analyzed utilizing the steam refining process model, and the appropriate PID gain not entirely settled by applying AMIGO tuning techniques	Utilizing an experimentation technique, the genuine size of the partial request differentiator and fragmentary request integrator was changed to get the worth that more qualified the systemic structure	The research hole in the design of a fuzzy proportional plus fractional-order integral-derivative (PID) controller is addressed in this study.
12	H. Shan, H. Liu, L. Zhang, F. Li, and Q. Liu	The control method of acceleration simulation mode emissions detection systems based on fuzzy proportional-integral-derivative control	To examine Twin Rotor MIMO System (TRMS) Nonlinear Modeling and PID Control system	The mathematical formulation of the TRMS in the two degrees of freedom (2-DOF) was developed in this work to evaluate and regulate the nonlinearity of the system.	The control was developed using simple and traverse-linked a PID controller and simulated results were produced. They concluded that for various reference inputs, the PID control outputs and process output errors were analyzed	The overall sine wave error was minimized
13	B. Y. Husodo and S. M. Ayob	Design of proportional integral derivative controller for impedance-source inverter	To carry out a PID controller design for an impedance-source inverter in [16] where they asserted that the proposed controller controlled the input side's DC-link voltage to control the output AC voltage	The control variables were implemented using a Bode plot, and a mathematical algorithm was developed	Simulations with load perturbations and source were run, and the output demonstrated how excellently reliable the design was.	In order to build a proportional integral derivative (PID) controller specifically suited for impedance-source inverters, there is a research gap that is addressed in this study.
14	I. Kumiawan, A. I. Cahyadi, and I. Ardiyanto	Tuning fractional order proportional integral derivative controller for DC motor control model using cross-entropy method	To investigate using the cross-entropy method (CEM) of tuning fractional order PID (FOPID) controller for the dc motor control model	They successfully simulated FOPID control systems that were tuned using the CEM algorithm utilizing a DC motor model as the plant.	With improved results as compared to PID control systems that were tuned using the Ziegler-Nichols method, they successfully simulated FOPID control systems that were tuned using the CEM algorithm utilizing a DC motor model as the plant	The work fills a research gap on the cross-entropy method for tuning fractional order proportional integral derivative (FOPID) controllers for DC motor control models.
15	A. K. Srivastava, D. Kumar, S. M. Tripathi, and P. K. Sen	Comparative study of proportional-integral and proportional-integral-derivative (PI and PID) controllers for Z-source inverter-fed induction motor drive	To explore the utilization of either a PI or PID-based speed regulator in a shut circle Z-source inverter-took care of enlistment engine drive	The unique model of the Z-source inverter and the drive framework control technique were created. The drive was demonstrated for both PI and PID-based speed regulators, considering various varieties in reference speed and burden force	All in all, the recreation results showed that the drive with a PID-based speed regulator beat the one in light of PI	The comparison of proportional-integral (PI) and proportional-integral-derivative (PID) controllers for a Z-source inverter-fed induction motor drive is one of the research gaps that is addressed in this work.
16	A. Gargioli, F. Rinaldi, and F. Quanglioti	Proportional integral derivative and linear quadratic regulation of a multirotor attitude: mathematical	The mathematical modelling, validation, and practical test of two alternative control algorithms utilized to govern the orientation of a real	The control techniques were verified by several computer simulations, and the simulation was made more accurate by adding white noise to	It was determined that, considering the nonlinearity of the model, a more realistic model of the aircraft was explored to enhance the	In order to manage the attitude of multirotor systems, the work fills a research gap relating to the use of proportional integral derivative (PID) and linear quadratic

		modelling, simulations and experimental results,	multirotor platform were the main goals of this study	the state detection process. Subsequently, a real prototype was created to test the control rules experimentally.	multirotor attitude control.	regulation (LQR) control approaches.
17	D. Sharma, R. Kumar, and V. Verma	Fuzzy tuned proportional integral derivative control of paper machine headbox	a fuzzy-tuned PID control of a paper machine head-box was to be worked on	Both the fuzzy logic computing PID (FLC-PID) methodology and the autonomous tuning technique were used in this study	As a result, the FLC method for fine-tuning the PID controller, which was dependent on the partial membership degree, was very well received by the headbox in the paper machine	The research gap concerning the use of fuzzy tuned proportional integral derivative (PID) control for paper machine headbox systems is addressed in this work.
18	M. F. N. Tajuddin and N. A. Rahim	Small-signal AC modelling technique of buck converter with DSP based proportional-integral-derivative (PID) controller	To examine the buck converter small-signal alternating current (AC) modelling method in conjunction with digital signal processing (DSP) based PID controller	The converter's practical elements were considered during the design. Phase margin testing was done on the entire system to determine its reliability. A modulator was added to the feedback loop's forward channel to optimize the loop gain and attain the desired efficiency. A standardized Buck converter with a PID controller module was provided to simplify development. Design criteria were offered in a straightforward, stage process format	The study demonstrated that a switch power supply may be designed with good results using a basic proper control technique and a conventional mathematical methodology	The research hole in the small-signal AC modeling method of a buck converter with a proportional-integral-derivative (PID) controller is addressed in this study.
19	W-H. Lai and S-F Liang,	An F0 control model for singing synthesis based on proportional-integral-derivative controller	To investigate an F-0 control model for singing synthesis based on a PID controller	For Taiwanese children's songs, a FO control model for producing FO contouring was suggested. A second-order transfer function was controlled by the FO control model, which was modelled on a PID controller. The PID controller's parameters were changed to produce the appropriate overreach and preparatory variations	The obtained FO outlines were given fine variation to give them a more realistic result	In order to construct an F0 control model for singing synthesis utilizing a proportional-integral-derivative (PID) controller, there is a research gap that is addressed in this study.
20	T. A. B. Alves, F. R. Durand, B. A. Angelico, and T. Abrao	Power allocation scheme for OCDMA NG-PON with proportional-integral-derivative algorithms	To investigate the power portion technique utilized in the cutting edge latent optical systems administration (NG-PON) that utilizes optical code-division numerous entrance (OCDMA) and PID calculations	Utilizing PID plans created by DPCA-FM and DPCA-V, separately, conveyed power control calculations (DPCA-PID-FM) and DPCA-PID-V were created to go past the sign to-commotion in addition to impedance	The numerical outcomes showed that for accurate SNIR estimates, DPCAFM attained a full agreement with less iteration than DPCA-V. Furthermore, DPCA-V exhibited more grounded combination and a lower deviation from the best	The paper uses proportional-integral-derivative (PID) algorithms to address the research gap on power allocation strategies in optical code-division multiple access (OCDMA) next-generation passive optical networks (NG-PONs).

			considering the Foschini/Miljanic (FM) and Verhulst (V) models	proportion (SNIR) gauge limits	power vector arrangement in approximated feeble sign situations than DPCA-FM	

Conclusion.

In this review paper, the theory of control engineering and its seven categories have been presented concisely. Importantly, the history behind the invention of the PID controller, its types and its mathematical formulation of the proportional, integral, and the derivative portions have been analysed. In addition, a very thorough, recent and insightful review of research works related to the PID controller have been equally discussed. For the results, a tabular review of some selected papers with different tuning and optimization methodologies of a PID controller have been detailed herein, most essentially, stating their research gaps filled and the results obtained. This work is highly recommended and will be handy for any researcher who deems it fit to carry out further investigation in this area as it furnishes with the latest developments in this regard.

Recommendation.

This study bridges knowledge gaps in the mathematical formulation and transfer function representation of the PID controller for researchers, practitioners, and students seeking a deeper comprehension of this important control approach and its effects on numerous industries.

References.

[1]. Control Engineering: What is it? (And its History) | Electrical4U
[2]. D. Lee, W. Yoo, and S. Won, “An integral control for synchronization of a class of unknown non-autonomous chaotic systems,” Physics Letters A, vol. 374, no. 41, pp. 4231 – 4237, 2010.
[3]. Who Made America? | Innovators | Elmer Sperry (pbs.org)
[4]. Z. Lendek, R. Babuska and B. De Schutter, “Stability of Cascaded Fuzzy Systems and Observers,” IEEE Transactions on Fuzzy Systems, vol. 17, no. 3, pp. 641–653, June 2009.
[5]. M. Chadli and T. M. Guerra, “LMI Solution for Robust Static Output Feedback Control of Takagi-Sugeno Fuzzy Models,” IEEE Trans. on Fuzzy Systems, vol. 20, no. 6, pp. 1160–1165, 2012
[6]. A. M. Nagy Kiss, B. Max, G. Mourot, G. Schutz and J. Ragot, “State estimation of two-time scale multiple models. Application to a wastewater treatment plant,” Journal of Control Engineering Practice, vol. 19, no. 11, pp. 1354–1362, 2011.
[7]. A. M. Nagy Kiss, B. Max, G. Mourot, G. Schutz and J. Ragot, “Observers design for uncertain Takagi-Sugeno systems with unmeasurable premise variables and unknown inputs. Application to a wastewater treatment plant,” Journal of Process Control, vol. 21, no. 7, pp. 1105–1114, 2011.
[8]. S. Aouaouda, M. Chadli, M. Tarek Khadir and T. Bouarar, “Robust fault tolerant tracking controller design for unknown inputs T–S models with unmeasurable premise variables,” Journal of Process Control, vol. 22, no. 5, pp. 261–872, 2012
[9]. Gao-jue, “Exploration and Design in Teaching of PID Control Based on Simulink Simulation”, Guangzhou Chemical Industry, vol.41, No.20, pp. 199-200, 212, October. 2013.
[10]. Li-lan.,” Review of adaptive fuzzy control”, Shandong Industrial Technology, vol.10, pp.209-210, October. 2015.
[11]. Alireza Fereidouni, “A new adaptive configuration of PID type fuzzy logic controller”, ISA Transactions, vol.56, pp.222-240, 2015.
[12]. J. L. Piquero et al., “A New Sliding Mode Controller Implementation On An Autonomous Qquadcopter System,” Int. J. Autom. Smart Technol., vol. 9, no. 2, pp. 53–63, Jun. 2019.
[13]. "National Instruments," 5 March 2019. [Online]. Available: https://www.ni.com/en-ph/innovations/white-papers/06/pidtheory-explained.html. [Accessed 10 August 2019].
[14]. M. A. Lukmana and H. Nurhadi, “Preliminary study on Unmanned Aerial Vehicle (UAV) Quadcopter using PID controller,” ICAMIMIA 2015 - Int. Conf. Adv. Mechatronics, Intell. Manuf. Ind. Autom. Proceeding - conjunction with Ind. Mechatronics Autom. Exhib. IMAE, pp. 34–37, 2016.
[15]. A. Visioli, “Practical PID Control”, Springer-Verlag, London 2006
[16]. G. K. & E. B. S. ANUSHA, “Comparison of Tuning Methods of Pid Controller,” BEST Int. J. Manag. Inf. Technol. Eng. (BEST IJMITE), vol. 2, no. 8, pp. 1–8, 2014.
[17]. M. Ruel, “Closed Loop Tuning Vs Open Loop Tuning : Tuning All Your Loops While the Process Is Running Is Now Possible,” Control, 2010.
[18]. I. May and Y. Joglekar, “Dynamic Performance Analysis of PID Controller with one Memristor,” Sci. Technol., pp. 1234–1237, 2011.
[19]. V. Vindhya and V. Reddy, “PID-Fuzzy Logic hybrid Controller for a Digitally Controlled DC-DC Converter,” Int. Conf. Commun. Conserv. Energy, pp. 362–366, 2013.
[20]. W. Li, “Design of a hybrid fuzzy logic proportional plus conventional integral-derivative controller,” IEEE Trans. Fuzzy Syst., vol. 6, no. 4, pp. 449–463, 1998.
[21]. H. He, F. Liu, L. Li, J.-R. Yang, L. Su, and Y. Wu, “Study of PID Control System for Ant Colony Algorithm,” in 2009 WRI Global Congress on Intelligent Systems, 2009, vol. 1, pp. 9–12.
[22]. C. C. Lee, “Fuzzy logic in control systems: fuzzy logic controller. II,” IEEE Trans. Syst. Man. Cybern., vol. 20, no. 2, 1990.
[23]. M. Petrov, I. Ganchev, and A. Taneva, “Fuzzy PID Control of Nonlinear Plants,” Structure, no. September, pp. 0–5, 2002.
[24]. W. L. W. Li, X. C. X. Chang, and J. Farrell, “Stability and performance analysis of an enhanced hybrid fuzzy P+IDcontroller,” Proc. 2001 Am. Control Conf. (Cat. No.01CH37148), vol. 5, no. 3, pp. 3855–3860, 2001.
[25]. M. Brahim, A. Abdelkarim, and M. Benrejeb, “On the design of process fuzzy PID controller,” in 2014 International Conference on Control, Decision and Information Technologies (CoDIT), 2014, no. 1, pp. 483–487
[26]. I. N’Doye, S. Asiri, A. Aloufi, A. Al-Awan, and T-M. Laleg-Kirati, “Intelligent proportional-integral-derivative control-based modulating functions for laser beam pointing and stabilization,” IEEE Transactions on Control System Technology. (2019).
[27]. M. J. Er and Y. L. Sun, “Hybrid fuzzy proportional-integral plus conventional derivative control of linear and nonlinear systems,” IEEE Transactions on Industrial Electronics, VOL. 48, NO. 6, December 2001.
[28]. B. Huang, B. Lu, Q. Li, and Y. Tong, “Average dwell time based smooth switching linear parameter-varying proportional-integral-derivative control for an F-16 aircraft,” Digital Object Identifier 10.1109/ACCESS.2021.3059900.
[29]. A. Salem, M. A. Moustafa Hassan, and M. E. Ammar, “Tuning PID controllers using artificial intelligence techniques applied to DC-motor and AVR system,” Asian Journal of Engineering and Technology (ISSN: 2321 – 2462), Volume 02 – Issue 02, April 2014.

[30]. G. Chengwei, and J. Qian, "Optimized proportional-integral-derivative control strategies and simulation for lower limb functional electrical simulation," 2011 Fourth International Conference on Information and Computing.
[31]. Y. Cheng, Q. Nan, R. Wang, T. Dong, Z. Tian, "Fuzzy proportional integral derivative control of a radiofrequency ablation temperature control system," 2017 10th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI).
[32]. "Spatial proportional-integral-derivative penalization of distributed consensus filters M. A. Demetriou for spatially distributed processes," 2013 European Control Conferences (ECC) July 17-19, Zurich, Switzerland.
[33]. T. Youssef, M. Chadli, and M. Zelmat, "Synthesis of an unknown inputs proportional integral observation for TS fuzzy models," 2013 European Control Conferences (ECC) July 17-19, Zurich, Switzerland.
[34]. H. Shan, H. Liu, L. Zhang, F. Li, and Q. Liu, "The control method of acceleration simulation mode emissions detection systems based on fuzzy proportional-integral-derivative control," 2015 12th International Conference on Fuzzy Systems and Knowledge discovery (FSKD)
[35]. K. C. U. Obias, M. F. Q. Say, E. A. V. Fernandez, A. Y. Chua, and E. Sybingco, "A study of the interaction of proportional-integral-derivative control in a Quadcopter unmanned aerial vehicle using design of experiment," 978-1-7281-3044-6/19/$31.00 (2019) IEEE.
[36]. N. S. A. Aziz, R. Adnan, and M. Tajjudin, "Design of fuzzy proportional plus fractional-order integral-derivative controller," 2016 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS), 22 October 2016, Shah Alam, Malaysia
[37]. A. P. S. Ramalakshmi, and P. S. Manoharan, "Non-linear modelling and PID control of twin rotor MIMO system," 2012 IEEE International Conference on Advanced Communication Control and Computing Technologies (ICACCCT).
[38]. B. Y. Husodo and S. M. Ayob, "Design of proportional integral derivative controller for impedance-source inverter," 2011 International Conference on Computer Applications and Industrial Electronics (ICCAIE 2011).
[39]. I. Kumiawan, A. I. Cahyadi, and I. Ardiyanto, "Tuning fractional order proportional integral derivative controller for DC motor control model using cross-entropy method," 2018 3rd International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE), Yogyakarta, Indonesia.
[40]. A. K. Srivastava, D. Kumar, S. M. Tripathi, and P. K. Sen, "Comparative study of proportional-integral and proportional-integral-derivative (PI and PID) controllers for Z-source inverter-fed induction motor drive," 978-1-4673-1049-9/12/$31.00 ©2012 IEEE.
[41]. A. Gargioli, F. Rinaldi, and F. Quanglioti, "Proportional integral derivative and linear quadratic regulation of a multirotor attitude: mathematical modelling, simulations and experimental results," 2013 International Conference on Unmanned Aircraft Systems (ICUAS) May 28-31, 2013, Grand Hyatt Atlanta, Atlanta, GA.
[42]. D. Sharma, R. Kumar, and V. Verma, "Fuzzy tuned proportional integral derivative control of paper machine headbox," IEEE INDICON 2015 1570190789.
[43]. M. F. N. Tajuddin and N. A. Rahim, "Small-signal AC modelling technique of buck converter with DSP based proportional-integral-derivative (PID) controller," 2009 IEEE Symposium on Industrial Electronics and Applications (ISIEA 2009), October 4-6, 2009, Kuala Lumpur, Malaysia.
[44]. W-H. Lai and S-F Liang, "An F0 control model for singing synthesis based on proportional-integral-derivative controller," 978-1-4244-9991-5/11/$26.00 ©2011 IEEE.
[45]. K. Qiu, Z. Zheng, and T.Y. Chen, "Testing proportional-integral-derivative (PID) controller with metamorphic testing," 2017 IEEE 28th International Symposium on Software Reliability Engineering Workshops.
[46]. T. A. B. Alves, F. R. Durand, B. A. Angelico, and T. Abrao, "Power allocation scheme for OCDMA NG-PON with proportional-integral-derivative algorithms," VOL. 8, NO. 9/SEPTEMBER 2016/JOURNAL OF OPTICAL. COMMUNITY. NETWORK. 1943-0620/16/090645-11 Journal © 2016 Optical Society of America.
[47]. S. K. Pandey and V. Laxmi," Control of twin rotor MIMO system using PID controller with derivative filter coefficient," 2014 IEEE Students' Conference on Electrical, Electronics and Computer Science.
[48]. H. Naccache and G. C. Gannod, "Using proportional-integral-derivative control in self-healing adaptive content systems," 978-0-7695-3708-5/09 $25.00 © 2009 IEEE, 2009 Congress on Services – I
[49]. C-A. B-Dragos, S. Preitl, R-E. Precup, S. Hergane, E. G. Hughiet, and A.-L. S-Stinean, "State feedback and proportional-integral-derivative control of a magnetic levitation system," SISY 2016 • IEEE 14th International Symposium on Intelligent Systems and Informatics • August 29-31, 2016, Subotica, Serbia.
[50]. J. Li and Y. Yuan, "A nonlinear proportional integral derivative-incorporated stochastic gradient descent-based latent factor model," 2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC) October 11-14, 2020. Toronto, Canada.
[51]. Q.-X. Wang, S.-L Chen, X. Luo, "An adaptive latent factor model via particle swarm optimization," Neuro-computing, vol. 369, no. 5, pp. 176- 184, 2019.
[52]. H-C. Yu, T-C. Chen, and C-S. Liu,"Adaptive fuzzy logic proportional-integral-derivative control for a miniature autofocus voice coil motor actuator with retaining force," IEEE TRANSACTIONS ON MAGNETICS, VOL. 50, NO. 11, NOVEMBER 2014.
[53]. K. Gao, J. Song, X. Wang, and H. Li, "Fractional-order proportional-integral-derivative linear active disturbance rejection control design and parameter optimization for hypersonic vehicles with actuator faults," TSINGHUA SCIENCE AND TECHNOLOGY ISSNll1007-0214 02/10 pp9– 23 DOI: 1 0. 2 6 5 9 9/T ST. 2 0 1 9. 9 0 1 0 0 4 1 Volume 26, Number 1, February 2021.
[54]. D. Nan and Y. Zhang, "Predictive modelling based on proportional integral derivative neutral networks and quantum computation," Proceedings of the 7th World Congress on Intelligent Control and Automation June 25 - 27, 2008, Chongqing, China.
[55]. B. B. M. Pinto, J. G. R. Mota, and O. M. Almeida, "PID self-adjustable fuzzy logic MIMO case: method and application," 2010 9th IEEE/IAS International Conference on Industry Applications - INDUSCON 2010.
[56]. J-G. Juang, M-T. Huang, and W-K. Liu, "PID control using researched genetic algorithms for MIMO system," IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART C: APPLICATIONS AND REVIEWS, VOL. 38, NO. 5, SEPTEMBER 2008.
[57]. TRMS 33-220 User Manual, 3-000M5, Feedback Company, E. Sussex, U.K. 1998.
[58]. M. H. Moradi, "State space representation of MIMO predictive PID controller," Bu Ali Sina University, Dept of Electrical Engineering, Faculty of Engineering, University of Bu Ali Sina, Hamadan, Iran. IEEE XPLORE.
[59]. M. H. Moradi, M. R. Katebi, and M. A. Johnson, "Robust MIMO PID tuning method," 0-7803-7386-3/02/$17.00 0 2002 IEEE.
[60]. K. J. Astrom, K. H. Johansson, and Q-G. Wang, "Design of decoupled PID controllers for MIMO systems," IEEE Transactions on Automatic Control, vol. 48, no. 4, pp. 679-686, April 2003.