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Research Article

Optimal Speed Control of Hybrid Stepper Motors through Integrating PID Tuning with LFD-NM Algorithm

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Abstract:

In order to regulate the speed of hybrid stepper motors (HSM), this work presents an optimally tuned proportional-integral-derivative (PID) controller. The combination of algorithms known as the combined Levy flight distribution and Nelder Mead (LFD-NM) method essentially considers it unique to tune the PID. The accurate local search properties of the Nelder Mead (NM) technique are combined with the exploratory capabilities of the Levy flight distribution (LFD) algorithm in this method. A combination LFD-NM approach improves PID controller parameter optimisation efficiency by striking a balance between exploration and exploitation. The efficacy of the suggested method is validated by comparative simulations against the original LFD algorithm and many metaheuristic algorithms including cuckoo search and genetic algorithms. The assessment of performance includes statistical testing, robustness analysis, management of load disturbances, evaluation of energy efficiency, assessment of transient and frequency responses, and consideration of control signal constraints. Additional experimental verification confirms that a recommended LFD-NM-based PID controller is successful. Analyses conducted in comparison with the latest PID controllers demonstrate its exceptional efficacy in attaining ideal control over the speed of hybrid stepper motors (HSM).

1. Introduction

Stepper motors, invented in the 19th century, found their modern form thanks to Thomas and Fleischauer in 1957 [1]. These motors are prevalent across various industries due to their exceptional precision in controlling positioning [1]. Their operation relies on a pulse system, dictating the step-by-step rotation of the shaft [2]. Stepper motors offer several advantages over their counterparts, including unmatched precision, straightforward control methods, high reliability, and efficient heat dissipation [3-5]. These benefits make them ideal for applications in automated machinery, computer peripherals, and digital equipment [6,7]. Precise speed control is vital for many stepper motor applications. Compared to other motor types, stepper motors excel in this area [8]. Traditionally, PID controllers have been the go-to choose for stepper motor speed control due to their simplicity, affordability, and dependable performance [9-16]. However, optimizing PID controllers for peak performance can be a complex task [17-21].

Recent advancements have seen a rise in using metaheuristic algorithms for PID controller tuning. These algorithms efficiently search for the optimal PID controller settings without requiring deep system knowledge [22-26]. This document proposes a new approach that integrates the Levy Flight Distribution (LFD) algorithm with Nelder Mead (NM) simplex search to improve PID controller optimization for stepper motors [27-40, 41]. This approach aims to strike a balance between exploration, where the algorithm searches for new possibilities, and exploitation, where it refines promising areas identified during the optimization process.

2. Research Approach

The development of specialised algorithms has great potential to solve difficult control systems and optimisation issues. In order to present a hybrid strategy in this field, this endeavour combines the Nelder Mead (NM) and Levy flight distribution (LFD) algorithms. The main goal is to provide a novel algorithmic framework that efficiently strikes a balance between exploration and exploitation in order to improve optimisation capabilities.

The recommended algorithm, known as LFD-NM, will also be used in this study to create and build a PID tuned controller specifically designed for a hybrid stepper motor (HSM) speed control system. By aiming to maximise the integral of time-weighted absolute error (ITAE) objectives function, the LFD-NM method is expected to perform better than other widely used algorithms in this field.
The graphical depiction of the performance evaluation technique is shown in Figure 1. To confirm the efficacy of the suggested strategy, a number of studies will be carried out, including testing with statistics, load disturbance assessments, robustness evaluations, and time domain analysis and frequency domain analysis. These evaluations seek to verify the superiority of the LFD-NM algorithm by contrasting it with its original form and with algorithms such as the genetic algorithm (GA) and cuckoo search algorithm (CS).

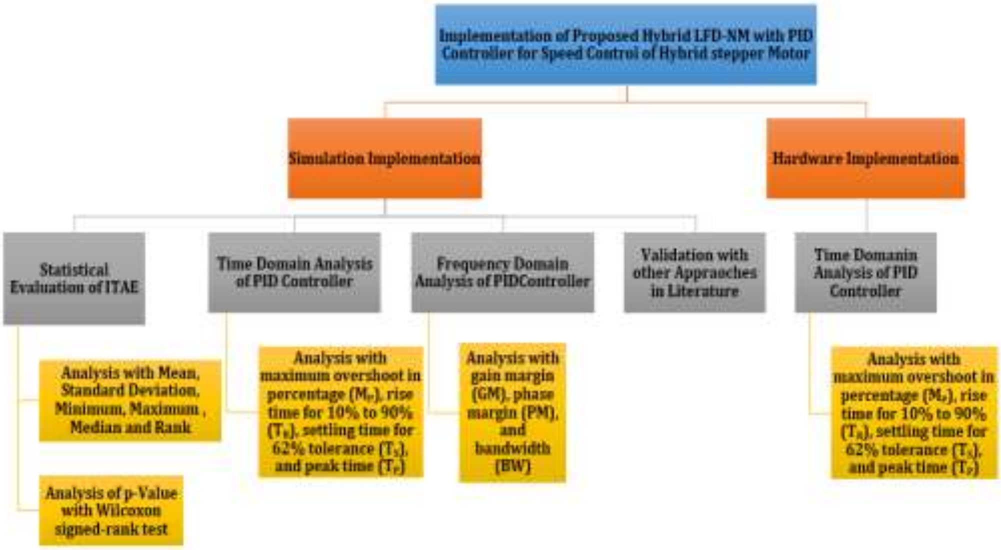

Figure 1. *Proposed Performance Analysis Approach of Study*

The ultimate evaluation will offer more proof of the dominance of the combined algorithm in accomplishing optimisation goals utilising a different, commonly-used time domain-based objective function. By achieving these specific goals, the research aims to promote innovation and development in related fields by making a contribution to optimisation algorithm and control system improvements.

3. Proposed LFD-NM based PID Controller for Speed Control of HSM

In order to overcome the inherent limitations of each algorithm, the Levy flight distribution (LFD) and Nelder Mead (NM) algorithms are integrated. This approach aims to balance exploration and exploitation in optimisation tasks, specifically when it comes to adjusting the limits of PID controller for a hybrid stepper motor (HSM).

Despite being well-known for its robust exploratory capabilities, the LFD algorithm's very poor local search performance frequently prevents it from being fully utilised. On the other hand, the LFD algorithm has wider exploration capabilities, whilst the NM approach is superior in local search. This disparity provides the impetus for creating the LFD-NM algorithm, which combines the best features of both methodologies.When the LFD-NM algorithm is used for optimisation problems, it effectively combines the complementary features of the LFD and NM algorithms to give a balanced approach by seamlessly combining the stages of exploration and exploitation. The choice of a suitable objective function is essential for maximising a system's stability and dynamic reaction, which in turn affects the likelihood of attaining better system performance. Since it can accurately represent both transient and steady-state performance indicators, the integral of time-weighted absolute error (ITAE) was selected as the goal function for this investigation. Furthermore, the gain parameters of the PID controller were limited to values within the range of [0.001, 20], in order to ensure a practical parameter search space.

$$ITAE = \int_0^T \left|(\omega(t)) - (\omega_{ref})\right| t.dt \qquad (1)$$

The implementation technique of the suggested LFD-NM algorithm for changing the speed regulation of the PID-controlled hybrid Stepper motor system is as follows:

Step 1: Initialization of Parameters

This step involves establishing the parameters needed for the NM and LFD algorithms. Step sizes, population sizes, convergence criteria, and other algorithm-specific parameters are examples of these parameters.

Step 2: Creating a Random Population

A random population is generated using the gain parameters for proportional, integral, and derivative gain, which represent potential solutions. The first collection of potential solutions for the optimisation procedure is this random population.

Step 3: Iterative Algorithm Execution of LFD-NM

An iterative algorithm is used to run the LFD-NM method. In every iteration:

- **LFD Exploration:** The solution space is explored using the LFD algorithm. It entails using LFD operators, which are intended to make global exploration easier, to generate new candidate solutions.
- **Exploitation using NM:** Local exploitation is done using the NM algorithm following the exploration phase (Takenaga et al. 2023). This entails employing the NM simplex search method to iteratively update the solutions acquired from the LFD phase in order to improve them.
- **Fitness Function Evaluation:** The fitness function is assessed for each candidate solution found using the LFD-NM method. The ITAE, which measures the effectiveness of the PID-controlled motor speed system, serves as the fitness function in this instance.

Step 4: Termination Criteria

Until a predetermined termination criterion is satisfied, the iterative procedure is carried out. Usually, this criterion is dependent on the number of iterations that can be reached.

Step 5: Best-performing Parameter Selection

The algorithm stops when the termination requirement is satisfied, and the candidate solution with the best-performing PID gain parameters is chosen using the lowest ITAE value. The PID controller's optimised settings are represented by these particular parameters.

Step 6: Hybrid Stepper Motor Speed System Implementation

In the context of HSM speed regulation, the integration of a Tuned PID controller within the system is pivotal, with its parameters fine-tuned using the optimal PID gain parameters determined through the LFD-NM algorithm. These parameters intricately govern the behaviour of the PID controller, directly influencing the system's efficacy in maintaining desired speeds. The proposed methodology adeptly exploits the complementary strengths of the NM and LFD algorithms, efficiently navigating the solution space. Through this integration, the algorithm meticulously seeks out the optimal PID parameters for HSM speed regulation, guided by the ITAE objective function. This iterative optimization process continuously refines the PID parameters, ensuring a gradual convergence towards an optimal solution that markedly enhances the system's speed regulation performance. By dynamically adjusting and updating the PID parameters based on the ITAE objective function, the algorithm facilitates precise and reliable speed regulation in high-speed machining applications, thereby underscoring its significance in optimizing system performance and efficiency.

4. Performance of LFD-NM Implementation on Speed Control of HSM

In the analysis, the original LFD algorithm, the Cuckoo search algorithm (CS) [42-58], and the Genetic Algorithm (GA) [59], two other well-known optimisation algorithms, were put to rigorous testing alongside the proposed LFD-NM algorithm. The goal was to demonstrate the proposed algorithm's greater performance in maximising a hybrid stepper motor's speed control.

The proposed approach was built up with certain parameter settings that were carefully selected to guarantee an impartial and thorough study, as shown in Table 1 and 2. These constraints placed on the proportional (K_P), integral (K_I), and derivative (K_D) terms of the PID controller fell between [0.001, 20]. This allowed for adequate solution space exploration while still preserving practical viability in the context of HSM speed control. Each algorithm optimisation process was carried out across 25 separate runs, enabling a reliable statistical analysis.

Table 1. *Parameters of Proposed Algorithms*

Algorithm	LFD-NM
Size of Population	20
Threshold	2
Step Size Control Parameter (Csv)	0.5
Power Law Exponent (b)	1.5
Learning Rate (al)	10
Factor of Reflection (a)	1
Factor of Expansion (g)	2
Factor of Contraction for Outside Contraction (d1)	0.9
Factor of Contraction for Inside Contraction (d2)	0.1
Factor of Shrinkage (d)	0.5

Moreover, a termination condition was developed in order to standardise the comparison: the optimisation process ended when the maximum number of iterations reached 100. By ensuring a uniform evaluation framework for all algorithms, this termination criteria made it possible to compare their performances in a meaningful way.An additional factor taken into account throughout the assessment was the optimisation process's effectiveness. For every algorithm, the average amount of time that passed between optimisation iterations was noted. The average elapsed time per iteration for the proposed LFD-NM method was 5.4 seconds, which was somewhat faster than the average of 4.9 seconds for the original LFD algorithm, according to the results. In the meanwhile, the average elapsed durations per iteration for the CS and GA algorithms were 3.9 and 3.6 seconds, respectively.
The performance characteristics of each algorithm in the Hybrid Stepper motor speed control system optimisation were thoroughly understood due to these meticulously planned experiments and studies. The documented information not only made a comparative analysis easier, but it also clarified the effectiveness and processing requirements of every algorithm, offering insightful information about the choice and use of optimisation algorithms.

4.1 Statistical evaluation of performance

The study's statistical analysis sought to offer a thorough grasp of the effectiveness of the various algorithms used for HSM speed control. With the use of objective function of the integral of time-weighted absolute error (ITAE), a number of statistical parameters, including mean of ITAE, standard deviation of ITAE, minimum, maximum, and median values of ITAE, were derived for the analysis. These metrics are important measures of how well the algorithms work and how well they can control the speed of the HSM motor.
The proposed LFD-NM method consistently beats the other algorithms across all analysed parameters, as can be seen by looking at the statistical results shown in Table 3. The LFD-NM method outperforms the LFD, CS, and GA as shown by the mean of ITAE, standard deviation of ITAE, minimum, maximum, and median values of ITAE that were achieved. The LFD-NM method, in particular, has the lowest worst value, indicating that it may perform better even in the face of difficult circumstances or anomalies. The algorithm also shows the best values for the average and standard deviation, which suggests that it performs with more consistency and dependability.

Table 2. *ITAE Statistical Analysis Parameters*

Algorithm	Mean	Standard Deviation	Minimum	Maximum	Median	Rank
LFD-NM	0.002	$0.58*10^{-4}$	0.0015	0.0017	0.0015	1
LFD	0.004	$1.24*10^{-4}$	0.0039	0.0042	0.0038	2
CS	0.005	$1.73*10^{-4}$	0.0049	0.0054	0.0051	3
GA	0.01	$4.09*10^{-4}$	0.009	0.011	0.0099	4

The supremacy of the LFD-NM algorithm is further reinforced by the algorithm ranking according to statistical performance. Among the compared algorithms, the LFD-NM algorithm achieves the highest rank, indicating that it is the optimal choice for motor speed control based on the ITAE objective function. The algorithm is an attractive option for real-world applications because of its ability to continuously give optimal performance across various parameters, as demonstrated by this rating.

4.2 Evaluation of time domain and frequency domain performance

The work provides insight into the performance of PID-controlled HSM speed systems in the time and frequency domains utilising a variety of optimisation methods, such as LFD, CS, GA-tuned PID controllers, and the LFD-NM algorithm. Transfer functions were produced using matching PID-controlled HSM speed systems for LFD, CS, GA algorithm tuned PID controllers, and proposed

LFD-NM PID controllers, respectively, by replacing the gain values found in Table 4, 5.

Table 3. *Gain Parameters*

PID Parameters	LFD-NM	LFD [40]	CS [58]	GA [59]
K_P	19.56	17.21	13.93	8.86
K_I	5.16	4.41	8.08	6.06
K_D	3.41	3.08	2.18	1.46

The time domain performance analysis's findings are shown in Table 6, which also includes peak time (T_P), rising time for 10% to 90% (T_R), settling time for 62% tolerance (T_S), and maximum overshoot in percentage (M_P). Figure 2 shows the relative speed step responses of the motor speed systems under the direction of various algorithms.

Table 4. *Time Domain Performance Parameters*

Time Domain Parameters	LFD-NM	LFD	CS	GA
M_P (%)	0	0.08	1.91	2.61
T_R (sec)	0.055	0.064	0.083	0.125
T_S (sec)	0.092	0.114	0.131	0.889
T_P (sec)	0.157	0.294	0.270	0.451

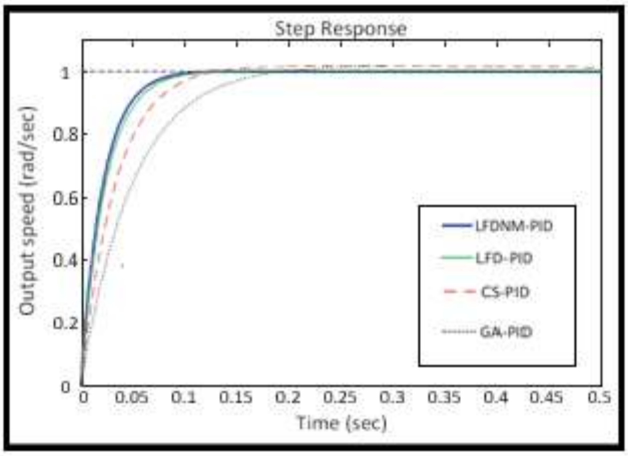

Figure 2. *Time Domain Step Response Analysis*

The LFD-NM-based PID controller that has been proposed has better temporal response characteristics than the LFD, CS and GA tuned PID controllers. These features include null overshoot, shorter rise time, settling time, and peak time, as can be seen in the table and figure 3. This suggests that the HSM speed control system can benefit from improved stability, quicker damping, and no overshoot provided by the proposed controller structure.

A comparison of the frequency domain characteristics for PID based on the LFD-NM algorithm and other approaches also includes gain margin (GM), phase margin (PM), and bandwidth (BW). The LFD-NM algorithm-tuned motor system has the maximum stability in terms of frequency response, as shown in the related figure 4 and table 4.

Table 5. *Frequency Domain Performance Parameters*

Frequency Domain Parameters	LFD-NM	LFD	CS	GA
GM (dB)	∞	∞	∞	∞
P_M (deg.)	180	180	171.01	169.05
BW (Hz)	47.34	42.62	30.93	20.69

For HSM speed regulation, the comprehensive analysis of performance measures in the time and frequency domains validates the improved effectiveness of the LFD-NM algorithm-based tuning of PID controller. It is a viable choice for real-world applications requiring high-performance speed control systems because, in comparison to other algorithms, it can provide precise, fast, and dependable control.

5. Real Time Implementation of LFD-NM on Speed Control of HSM

The LFD-NM-based PID controller's performance and practicality were confirmed by an essential experimental validation procedure. An experimental setup was used during the study's validation phase to confirm the results of the simulations. This method combines the Levy Flight Distribution (LFD) algorithm with Nelder Mead (NM) simplex search (LFD-NM). To validate this approach, they constructed a physical testbed consisting of the stepper motor, driver, power supply and a data acquisition system (DAQ). This setup interfaced with a LabVIEW control program for real-time control and data collection.

The LabVIEW program implemented the LFD-NM optimized PID algorithm and sent speed commands to the motor driver. A magnetic encoder provided feedback on the motor's actual speed, closing the control loop. The performance of the LFD-NM PID controller is compared to conventionally optimized controllers. The motor's response to speed commands, including the desired speed, rising time, settling time and overshoot beyond the target speed is also measured. Finally, they compared experimental results with simulations to verify the accuracy of their LFD-NM approach. Experimental results were achieved at a commanded speed. The improved performance of the suggested LFD-NM-based PID tuning is confirmed by an exact correlation between the simulation and experiment results. These consistent results from modelling and experimentation provide more evidence for the effectiveness of the proposed controller architecture in controlling HSM speed.

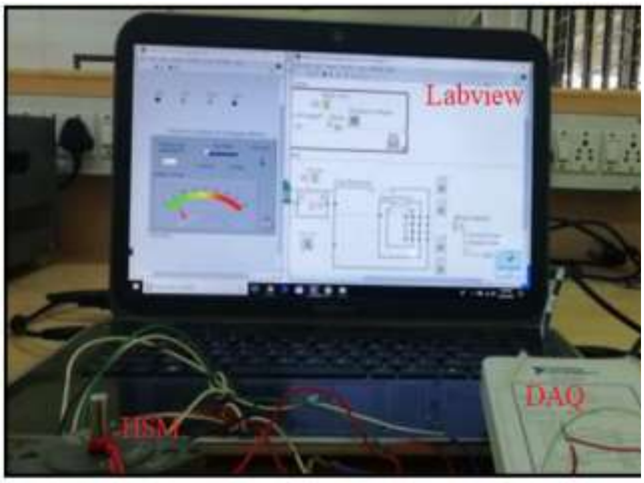

Figure 3. *Physical Setup*

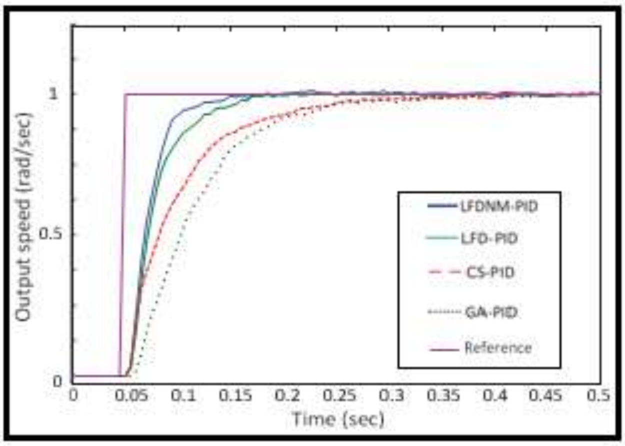

Figure 4. *Experimental Performance Analysis*

Table 6. *Performance Parameters – Experimental Analysis*

Time Domain Parameters	LFD-NM	LFD	CS	GA
M_P (%)	0.82	1.72	1.44	1.15
T_R (sec)	0.741	1.184	2.259	2.496
T_S (sec)	1.851	2.191	4.105	5.301
T_P (sec)	3.343	3.618	7.224	6.812

6. Conclusion

The benefits of the Levy flight distribution (LFD) and Nelder Mead (NM) algorithms are combined in this study to create a hybrid scheme. NM Simplex search method's enhanced localization capacity and LFD algorithm's broad search capability are combined in this hybrid approach. A hybrid stepper motor (HSM) speed regulator is constructed using an efficient proportional-integral-derivative (PID) controller utilising the suggested LFD-NM algorithm. Several comparison evaluations were carried out in order to assess the performance of the proposed LFD-NM-based PID controller. These comprised statistical tests, investigations of time domain analysis response & frequency domain analysis response, robustness evaluations and load disturbance evaluations, and evaluation related to energy control signal. In comparison to PID controllers based on the LFD, CS, and GA, the results of these evaluations showed the LFD-NM algorithm-based PID controller to perform better.

Conclusively, the research indicates that the LFD-NM algorithm provides a proficient method for developing a PID controller intended for integration into a hybrid stepper motor speed control system. The algorithm performs better than existing PID controllers tuning approaches in terms of rigidity, reliability, and performance features, suggesting potential applications in motor control systems.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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