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Optimization Design of PID Controller Parameters Based on Nelder Mead Algorithm for Stepper Motors

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Abstract**—**This paper presents a design of optimized PID controller for stepper motor system used in robotics. Currently, PID controller has been used to operate in stepper motor system because its structure is simpler compared to others. However, the issue of tuning and designing PID controller adaptively and efficiently is still open. This paper presents an improved PID controller efficiency from tuning by Nelder Mead method. The parameters of PID controller shall be obtained from the Nelder Mead optimization procedure. Errors between desired magnitude response and actual magnitude response are calculated by using the Integral of Absolute Error (IAE). The proposed Nelder Mead based PID design method is simpler, more efficient and effective than the existing traditional methods included Ziegler Nichols, PSOGSA and Genetic algorithm (GA). Simulation result shows that the performance of PID controller using this proposed method is better than traditional methods and resistant to disturbance.

Keywords**—**Stepper motor, disturbance, PID controller, PID parameters, Nelder Mead optimization.

I. Introduction

STEPPER motor is one of many motors available today. It uses digital pulse inputs to analog shaft motion outputs which widely uses in our daily life especially in robotic systems. In addition, the current controller design that is popular for use with stepper motor, such as PID control [1,2], neural network [3] and fuzzy logic control [4-8]. It is the fact that the PID control design is popular and easiest way for stepper motor; however, it may involve with the problems of nonlinear system [9], time delay and disturbance. Nowadays, there are many methods for tuning PID, such as Ziegler-Nichols [10], PSOGSA [11], Genetic algorithm (GA) [12], Cohen-Coon [13], Direct Synthesis [14], differential evolution (DE) [15], and multi-objective optimization algorithms [16]. All of these methods do not deliver good tuning since rise time, overshoot and settling time still occur and may be not suitable for stepper motor systems.

This paper proposed Nelder Mead-based PID controller for solving these problems because the proposed method has been successful for electric furnace temperature system [17]. It is used to determine the optimal parameters of PID controller using the calculation of Integral of Absolute Error (IAE), which is traditional method for finding the best value in form of nonlinear. After applying Nelder Mead Algorithm, then the parameters k_p, k_i and k_d are obtained. These results will be compared with traditional methods included Ziegler-Nichols [10], PSOGSA [11] and Genetic algorithm (GA) [12] and different disturbances.

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II. PID Controller

PID controller consists of Proportional, Integral and Derivative control. Proportional control is responsible for faster enter steady state, Integral control is responsible for reducing overshoot in steady state and Derivative control is responsible for making the system more stable.

This paper introduces a single-input single-output (SISO) PID controller, which consists of PID controller $D(s)$ and controlled plant $G(s)$ are shown in Figure 1 which is simple and effective.

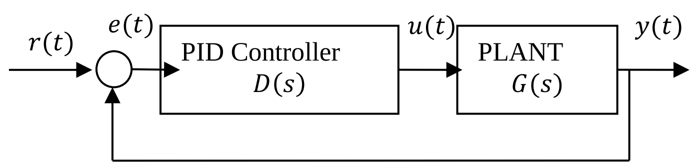

Figure 1 A control system with PID controller.

where $D(s)$ is transfer function of PID Controller, $G(s)$ is transfer function of controlled plant, $r(t)$ is input signal to controlled plant, $e(t)$ is the system error, $u(t)$ is controlled input and $y(t)$ is output signal.

From **Figure 1**, the equation of standard PID Controller is

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \quad (1)$$

and can be written in the form of transfer function is

$$D(s) = \frac{U(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s \quad (2)$$

where $U(s)$ is transfer function of controlled input, $E(s)$ is transfer function of the system error $e(t)$, k_p, k_i and k_d are proportional gain, integral gain and derivative gain, respectively.

From (2), PID controller can be written as

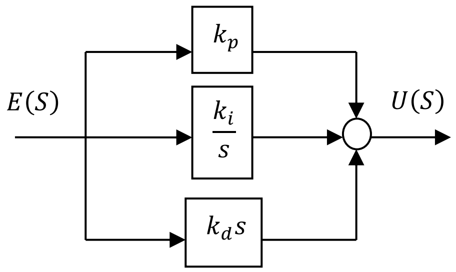

Figure 2 Block diagram of PID controller.

III. Stepper Motor System

The model of the permanent magnet stepping motor consists of two parts, and electrical and a mechanical part [18] which controller is used to control the analog shaft motion outputs of stepper motor is shown as **Figure 3**.

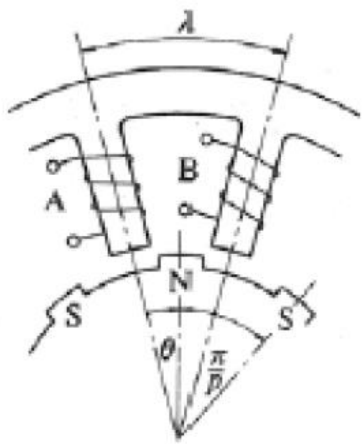

Figure 3: Permanent magnet stepper motor [18].

where θ is the rotational angle of the rotor and λis the tooth pitch in radians.

Table I The Parameters of stepper motor

Parameter	Value
Stator resistance (r) ohm	33
Self inductance (L) H	$5.4x10^{-3}$
Mutual inductance (M) H	$0.4x10^{-3}$
Rotor inertia (J) g.m^2	$0.16x10^{-4}$
Number of rotor teeth (N_r)	6
Viscous friction (D) (N.m.s/rad)	$1.35x10^{-5}$
Tooth pitch (λ) rad	$\frac{\pi}{12}$
Stationary current (I_o) Ampere	0.15
Flux linkage $(n\Phi_M)T.m^2$	$1.2x10^{-3}$

In this paper, transfer function of stepper motor is chosen as

$$G(s) = \frac{\frac{r}{L} w_{np}^2}{s^3 + \left(\frac{r}{L_p} + \frac{D}{J}\right) s^2 + \left(\frac{rD}{L_p J} + w_{np}^2 (1 + k_p)\right) s + \left(\frac{r}{L_p}\right) w_{np}^2} \quad (3)$$

where

$$L_p = L - M, w_{np}^2 = \frac{2N_r^2 n\Phi_M I_o cos\left(\frac{N_r\lambda}{2}\right)}{J},$$

$$k_p = \frac{n\Phi_M sin^2\left(\frac{N_r\lambda}{2}\right)}{L_p I_o cos\left(\frac{N_r\lambda}{2}\right)}$$

From (3), the parameters that used in this equation are shown in **Table I**.

IV. Nelder Mead Optimization for PID Controller

In this paper, Nelder Mead optimization is used for searching the best parameters of PID controller for use with the furnace temperature control system. This method had been introduced by Nelder and Mead in 1965. It is a basic principle for determining minimum of nonlinear multiple variable equations.

Structure of control system by using Nelder Mead Optimization for PID controller is shown in Figure 4.

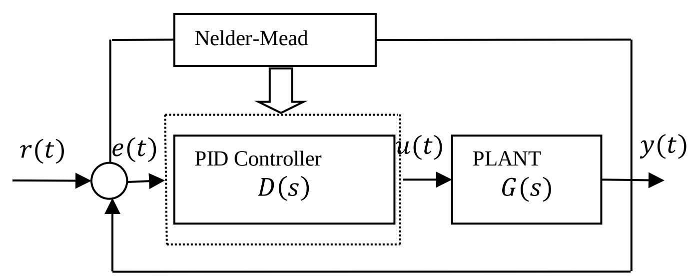

Figure 4 Structure of Nelder Mead with a control system and PID controller

In this paper, the result of the optimization is based on the error from the calculation of IAE. Result is shown in (4) and (5), which is based on the desired magnitude response and the actual magnitude response.

$$Error(K) = f(K) = \sum_{t=0}^{n} |e(t)|, t = 0, t_s, 2t_s, \ldots, n \quad (4)$$

$$e(t) = 1 - y(t), \qquad t = 0, t_s, 2t_s, \ldots, n \quad (5)$$

where t_s is sampling time, n is maximum time for optimization, $Error(K)$ or $f(K)$ is IAE, K is parameters of PID controller, $e(t)$ is system error, $y(t)$ is control output or actual magnitude response and 1 is desired magnitude response.

Nelder Mead Optimization consists of B (Best point), G (Good point), W (Worse point), M (Mid point), E (Expansion Point), R (Reflect point), C (Construction point) and S (Shrink point).

A. *Initial Triangle BGW*

Let $f(K)$ be the function that used for minimizing which Nelder Mead method will find the three points of a triangle as

$$B = f(K_1), G = f(K_2), and\ W = f(K_3) \quad (6)$$

That B is the best point (value less than G and W), G is good point (next to best), and W is the worst point.

B. Mid point

The building process uses the Mid point of the line from B and G as

$$M = \frac{B + G}{2} \quad (7)$$

C. Expansion point

The Expansion point is calculated from Mid point and Worst point as

$$E = 3M - 2W \quad (8)$$

D. Reflection point

The Reflection point is calculated from Mid point and Expansion point as

$$R = \frac{M + E}{2} \quad (9)$$

E. Contraction point

The Contraction points that used on this paper have 2 points. The first point is calculated from Worst point and Mid point and the second point is calculated from Reflection point and Mid point as

$$C_1 = \frac{W + M}{2}\ or\ C_2 = \frac{R + M}{2} \quad (10)$$

That the Contraction point is selected from the minimal value between $C_1\ and\ C_2$.

F. Shrink Point

The Shrink point is constructed from Best point and Worst point as

$$S = \frac{B + W}{2} \quad (11)$$

All points that used for Nelder Mead method are shown as Figure 5

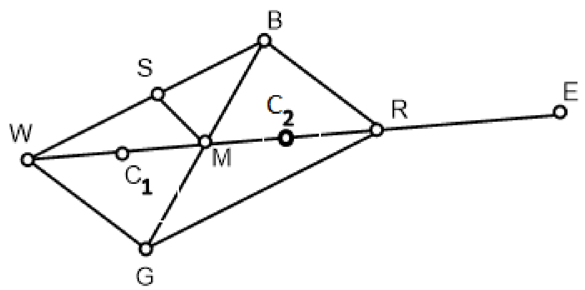

Figure 5 All points that used for Nelder Mead method

According to the calculation, the algorithm steps are shown as below:

(1) Generate an initial configuration K randomly, where $K_1 = [k_{p1}\ k_{i1}\ k_{d1}], K_2 = [k_{p2}\ k_{i2}\ k_{d2}]$, and $K_3 = [k_{p3}\ k_{i3}\ k_{d3}]$.

(2) Calculate $f(K_1), f(K_2), f(K_3)$ for finding B, G, W, where B < G < W.

(3) Compute M, E and $f(E)$.

(4) Compare $f(E)$ and $f(G)$, if $f(E) < f(G)$ replace W with E, go to step 8; else Compute R and $f(R)$ go to step 5.

(5) Compare $f(R)$ and $f(W)$, if $f(R) < f(W)$ replace W with R go to step 6.

(6) Compare $f(R)$ and $f(G)$, if $f(R) >= f(G)$ Compute C and $f(C)$ go to step 7; else go to step 8.

(7) Compare $f(C)$ and $f(W)$, if $f(C) < f(W)$ replace W with C go to step 8; else compute S, replace G with M and replace W with S go to step 8.

Rearrange the B, G, W, where B < G < W and repeat step (3) until some predefined stopping criteria.

The Pseudo code of Nelder Mead is shown in Figure 6.

```
for i=1:1:100
 IF f(E) < f(G) THEN
          replace W with E
   ELSE
          Compute R and f(R)
          IF f(R) < f(W) THEN
                 replace W with R
          END

          IF f(R) >= f(G)
                 Compute C and f(C)
                 IF f(C) < f(W)
                        replace W with C
                 ELSE
                        Compute S
                        replace G with M
                        replace W with S
                 END
          END
   END
END
```

Figure 6 Pseudo code of Nelder Mead method for optimization the PID controller

where i is the iteration for optimization which sets the maximum number of iterations $i_{max} = 100$.

V. Design Example And Simulation Result

The input signal $r(t)$ that used on this section is unit step function.

$$r(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \quad (12)$$

from (12) is shown as **Figure 7**.

The disturbance $n(t)$ that used on this section is square wave signals from -0.1 to 0.1, -0.2 to 0.2, -0.3 to 0.3, -0.4 to 0.4, -0.5 to 0.5 and -0.6 to 0.6 that is shown as **Figure 8**.

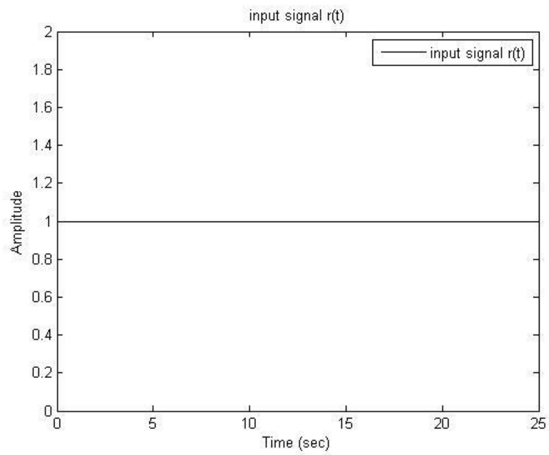

Figure 7 The input signal $r(t)$

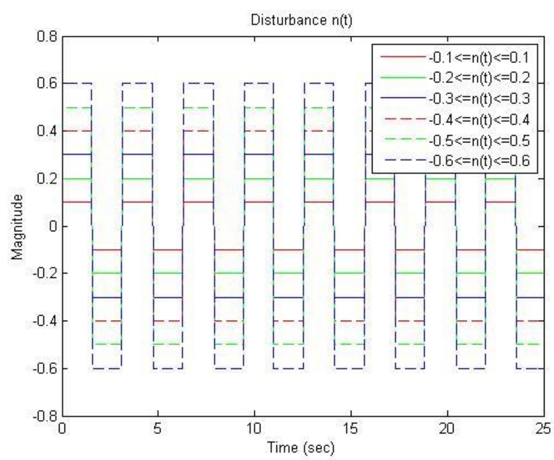

Figure 8: The disturbance $n(t)$

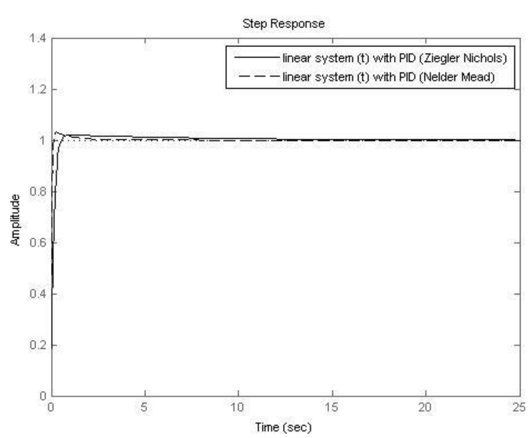

Figure 9 The step response for linear system under different methods based PID controller

A. Optimized PID controller design for linear system with Nelder Mead Algorithm

The transfer function of linear system is

$$G(s) = \frac{1}{s^2} \tag{13}$$

Setting the ranges of k_p, k_i and k_d are between 0 to 30, maximum time for optimization $n = 25\,s$, sampling time $t_s = 0.05\,s$ and maximum number of iterations $i_{max} = 100$.

The step response for linear system under different methods based PID controller is compared in **Figure 9**.

The error of step response for linear system under different methods based PID controller is compared in **Figure 10**.

The performances of these methods are evaluated by these indices including rise time, %overshoot, settling time and Error (IAE) that are shown as **TABLE II**.

From **TABLE II**, rise time and $Error(K)$ of Nelder Mead is smaller than Ziegler Nichols; settling time and %overshoot of Nelder Mead is close to Ziegler Nichols.

Then, the results show that the transient response and steady-state performances obtained by Nelder Mead for linear system are better than Ziegler-Nichols [10].

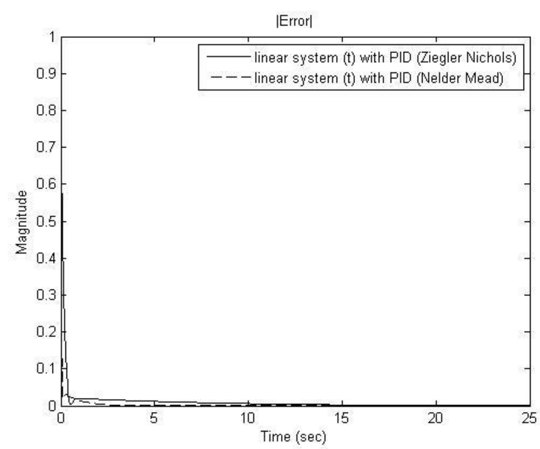

Figure 10 The error of step response for linear system under different methods based PID controller

TABLE II COMPARATIVE PERFORMANCE OF STEP RESPONSE FOR LINEAR SYSTEM UNDER DIFFERENT METHODS

Method / Performances	Ziegler Nichols	Nelder Mead
k_p	1.2024	29.6558
k_i	0.0481	0.4977
k_d	7.5075	28.3216
Rise time	0.2689	0.0699
%overshoot	1.9341	3.0587
Settling time	0.4391	0.6836
$Error(K)$, $n = 25\,s$, $t_s = 0.05\,s$	5.8903	1.9151

B. *Optimized PID controller design for nonlinear system with Nelder Mead Algorithm*

The transfer function of nonlinear system is

$$G(s) = \frac{1}{s^2 + 1} \tag{14}$$

Setting the ranges of k_p, k_i and k_d are between 0 to 30, maximum time for optimization $n = 25\,s$, sampling time $t_s = 0.05\,s$ and maximum number of iterations $i_{max} = 100$.

The step response for nonlinear system under different methods based PID controller is compared in **Figure 11**.

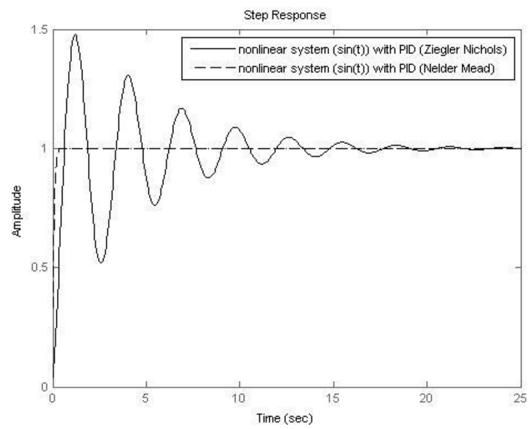

Figure 11: The step response for nonlinear system under different methods based PID controller.

The error of step response for nonlinear system under different methods based PID controller is compared in **Figure 12**.

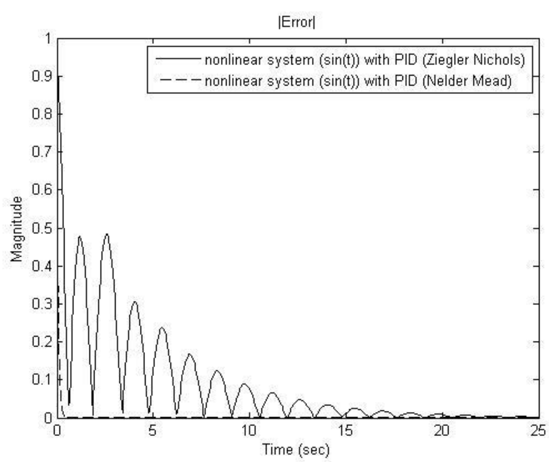

Figure 12 The error of step response for nonlinear system under different methods based PID controller.

The performances of these methods are evaluated by these indices including rise time, %overshoot, settling time and Error (IAE) that are shown as **TABLE III**.

From **TABLE III**, the results show that the transient response and steady-state performances obtained by Nelder Mead for nonlinear system are better than Ziegler-Nichols [10].

C. *Optimized PID controller design for stepper motor system with Nelder Mead Algorithm*

In this experiment, the transfer function of stepper motor from (3) will be chosen for simulating the design of PID controller which uses Nelder Mead optimization to determine the best parameters of PID controller by setting the ranges of k_p, k_i and k_d are between 0 to 30, maximum time for optimization $n = 25\,s$, sampling time $t_s = 0.05\,s$ and maximum number of iterations $i_{max} = 100$.

The step response for stepper motor under different methods based PID controller is compared in **Figure 13**.

TABLE III COMPARATIVE PERFORMANCE OF STEP RESPONSE FOR NONLINEAR SYSTEM UNDER DIFFERENT METHODS

Method / Performances	Ziegler Nichols	Nelder Mead
k_p	4.2059	0.0774
k_i	3.6849	14.7575
k_d	1.2001	14.9913
Rise time	0.4863	0.1465
%overshoot	47.2999	0
Settling time	15.7695	0.2605
$Error(K)$, $n = 25\,s$, $t_s = 0.05\,s$	44.7304	2.2304

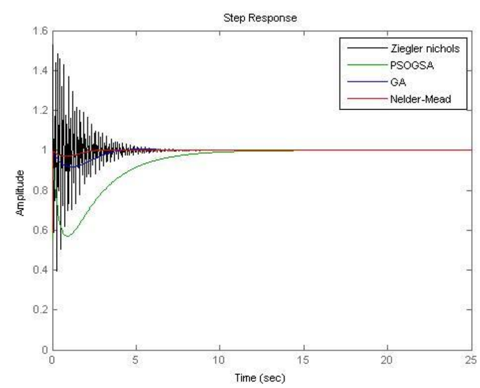

Figure 13 The comparison of step response of closed loop system under PID controller

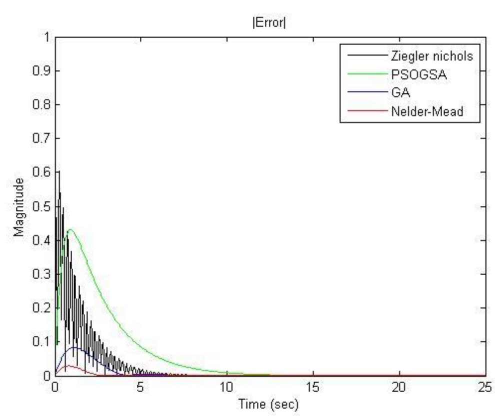

Figure 14 The comparison of error of closed loop system under PID controller

The error from step responses of stepper motor under different methods based PID controller is compared in **Figure 14**.

The performances of these methods are evaluated by these indices including rise time, %overshoot, settling time and Error (IAE) that are shown as **TABLE IV**.

From **TABLE IV**, rise time of Nelder Mead is close to GA but smaller than Ziegler Nichols and PSOGSA; settling time and $Error(K)$ of Nelder Mead are smaller than Ziegler Nichols, PSOGSA and GA; %overshoot of Nelder Mead is bigger than GA and PSOGSA but smaller than Ziegler-Nichols.

Then, the results show that the transient response and steady-state performances obtained by Nelder Mead for stepper motor are better than Ziegler-Nichols [10], PSOGSA [11] and Genetic algorithm (GA) [12].

TABLE IV COMPARATIVE PERFORMANCE OF NELDER MEAD WITH DIFFERENT METHODS

Method / Performances	Ziegler Nichols	PSOGSA	GA	Nelder Mead
k_p	3.5313	0.93068	7.0441	20.8836
k_i	85.1524	0.75203	6.1391	26.6070
k_d	0.0366	0.74726	6.0816	12.4866
Rise time	0.0231	0.0244	6.0186 $x10^{-4}$	3.1796 $x10^{-4}$
% overshoot	61.9625	0	2.7994	15.4599
Settling time	5.0416	8.2317	0.0013	0.0012
$Error(K)$, $n = 25\ s$, $t_s = 0.05\ s$	13.6756	29.6686	4.9689	1.9751

D. Optimized PID controller design for stepper motor system with disturbance

The experimental results from *C.* showed PID controller based on Nelder Mead for stepper motor are better than traditional methods, then this experiment presents about optimized PID controller design for stepper motor system with disturbance $n(t)$ that it is shown in **Figure 15**.

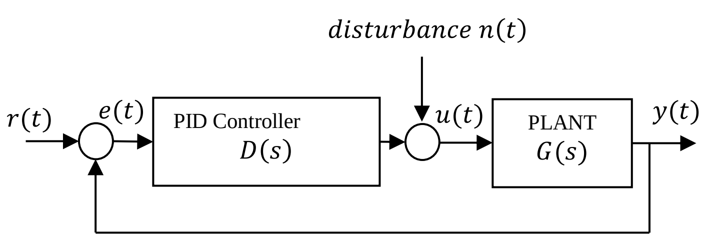

Figure 15 A control system and PID Controller with disturbance

From Figure 15, the control output $y(t)$ is calculated from $y_1(t)$ and $y_2(t)$, then

$$y(t) = y_1(t) + y_2(t) \quad (15)$$

and can be written in the s-domain is

$$Y(s) = Y_1(s) + Y_2(s) \quad (16)$$

$$Y_1(s) = \left(\frac{G(s)D(s)}{1 + G(s)D(s)}\right)R(s) \quad (17)$$

$$Y_2(s) = \left(\frac{G(s)}{1 + G(s)D(s)}\right)N(s) \quad (18)$$

where $y(t)$ is the control output, $y_1(t)$ is control output from input signal, $y_2(t)$ is control output from disturbance, $D(s)$ is transfer function of PID Controller, $G(s)$ is transfer function of controlled plant, $r(t)$ is input signal to controlled plant, $e(t)$ is the system error and $u(t)$ is controlled input.

In this experiment, the transfer function of stepper motor from (3) will be chosen for simulating the design of PID controller which uses Nelder Mead optimization to determine the best parameters of PID controller by setting the ranges of k_p, k_i and k_d are between 0 to 30, maximum time for optimization $n = 25\ s$, sampling time $t_s = 0.05\ s$ and maximum number of iterations $i_{max} = 100$.

The step response of control output from input signal $y_1(t)$ of stepper motor under different disturbances based PID controller is compared in **Figure 16**.

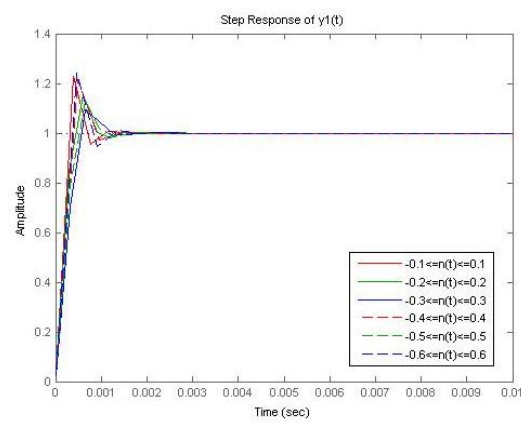

Figure 16 The step response of control output from input signal $y_1(t)$ of closed loop system under different disturbances

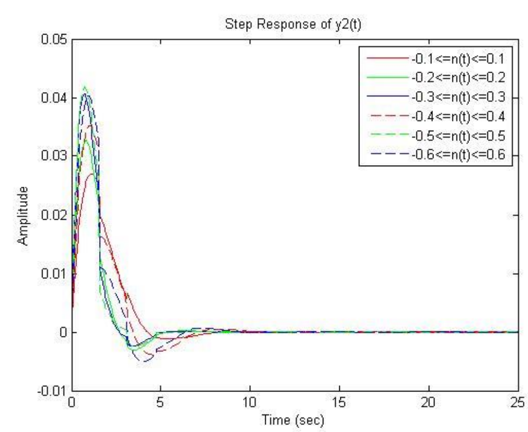

Figure 17 The step response of control output from disturbance $y_2(t)$ of closed loop system under different disturbances

The step response of control output from disturbance $y_2(t)$ of stepper motor under different disturbances based PID controller is compared in **Figure 17**.

Figure 17 shows that the disturbance $n(t)$ is effective only in the initial state. After the initial state, the disturbance will not affect to the control output $y(t)$.

The error of step response of control output from input signal $y_1(t)$ of stepper motor under different disturbances based PID controller is compared in **Figure 18**.

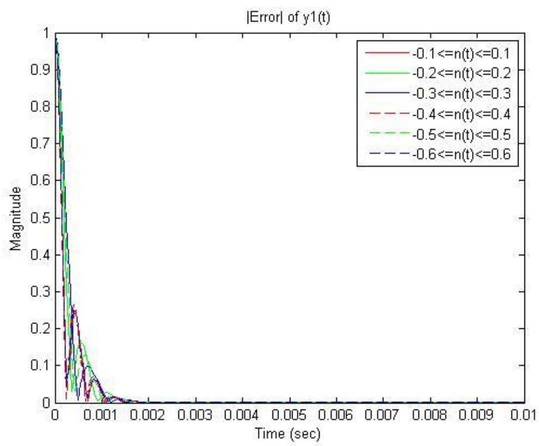

Figure 18 The error of step response of control output from input signal $y_1(t)$ of closed loop system under different disturbances

The step response of control output $y(t)$ of stepper motor under different disturbances based PID controller is compared in **Figure 19**.

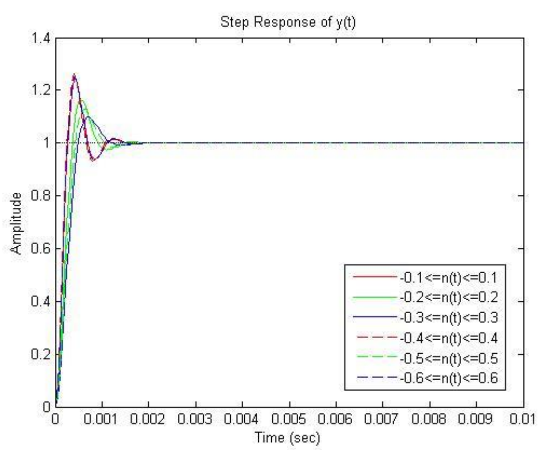

Figure 19 The step response of control output $y(t)$ of closed loop system under different disturbances

The performances of step response from **Figure 16** are evaluated by these indices including rise time, %overshoot, settling time and Error (IAE) that are shown in **TABLE V** and **TABLE VI**.

From **TABLE V** and **TABLE VI**, they are comparative performance of Nelder Mead with low disturbance and high disturbance. The low disturbance consists of square wave signals from -0.1 to 0.1, -0.2 to 0.2 and -0.3 to 0.3. The high disturbance consists of square wave signals from -0.4 to 0.4, -0.5 to 0.5 and -0.6 to 0.6 that the performances from rise time, %overshoot, settling time and $Error(K)$ are not much different.

TABLE V COMPARATIVE PERFORMANCE OF NELDER MEAD WITH LOW DISTURBANCE

Disturbances / Performances	n(t)		
	-0.1 to 0.1	-0.2 to 0.2	-0.3 to 0.3
k_p	24.8016	20.8836	18.5230
k_i	19.1687	26.6070	22.9697
k_d	18.7108	12.4866	8.8329
Rise time	$2.4907\,x10^{-4}$	$3.1799\,x10^{-4}$	$4.3864\,x10^{-4}$
%overshoot	23.0339	15.4589	9.2666
Settling time	0.0010	0.0012	0.0011
$Error(K)$, $n = 25\ s$, $t_s = 0.05\ s$	2.2502	1.9751	2.0361

TABLE VI COMPARATIVE PERFORMANCE OF NELDER MEAD WITH HIGH DISTURBANCE

Disturbances / Performances	n(t)		
	-0.4 to 0.4	-0.5 to 0.5	-0.6 to 0.6
k_p	21.3935	21.7941	21.3210
k_i	21.9558	24.9376	25.5618
k_d	20.4872	10.3611	19.3308
Rise time	$3.1806\,x10^{-4}$	$3.8552\,x10^{-4}$	$2.9501\,x10^{-4}$
%overshoot	21.4969	12.7148	23.9987
Settling time	0.0011	0.0010	0.0012
$Error(K)$, $n = 25\ s$, $t_s = 0.05\ s$	2.3029	1.9370	2.1641

From **TABLE V** and **TABLE VI** the comparative performances of Nelder Mead with disturbances, the proposed controller can well operate although the stepper motor system exists the disturbances in the system process.

E. Comparison PID controller design for stepper motor system with very high disturbance

The experimental results from *D.* showed PID controller based on Nelder Mead for stepper motor with disturbance, it has shown that the proposed controller can well operate although the stepper motor system exists the disturbances in the system process.

In this experiment, the very high disturbance is square wave signal from -1 to 1 that it is shown as **Figure 20**.

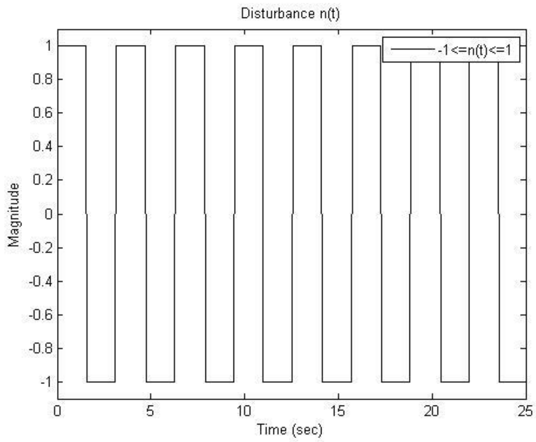

Figure 20 Very high disturbance

The transfer function of stepper motor from (3) will be chosen for simulating the design of PID controller which uses Nelder Mead optimization to determine the best parameters of PID controller by setting the ranges of k_p, k_i and k_d are between 0 to 30, maximum time for optimization $n = 25\ s$, sampling time $t_s = 0.05\ s$ and maximum number of iterations $i_{max} = 100$.

The PID parameters of the traditional methods from **TABLE IV** will be chosen for comparison the performance of PID controller design for stepper motor system with very high disturbance which shows a comparison as **Figure 21**.

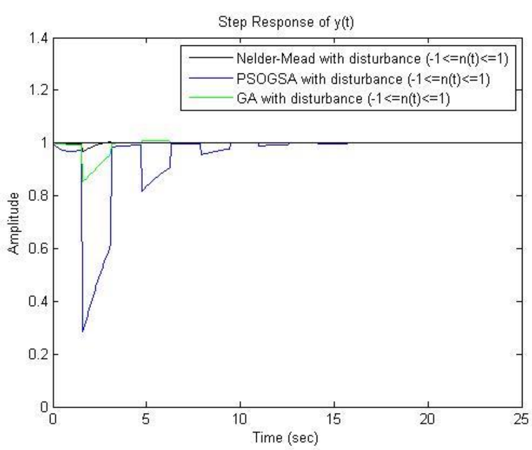

Figure 21 The comparison the performance of PID controller design for stepper motor system with very high disturbance

From **Figure 21**, the comparative performances of Nelder Mead with very high disturbance, the transient and steady-state performances are more robust to disturbance and better than the traditional methods with very high disturbance included PSOGSA [11] and Genetic algorithm (GA) [12].

VI. CONCLUSION

In this paper, the optimization design of PID controller parameters based on Nelder Mead Algorithm for stepper motor used in robotics was considered and simulated in MATLAB. The key operations of this method include maximum time for optimization, sampling time and maximum number of iterations that the performance of this method is depended on disturbance. The obvious advantages of the proposed approach are that 1) the transient and steady-state performances are better than the traditional methods included Ziegler-Nichols [10], PSOGSA [11] and Genetic algorithm (GA) [12] and 2) the proposed controller can well operate although the stepper motor system exists the disturbances in the system process.

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