DC Motor Control using Ant Colony Optimization

By

Sara Amr Mansour

11056

Supervisor: Assoc. Prof. Dr. Irraivan Elamvazuthi

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UNIVERSITI TEKNOLOGI PETRONAS

Bandar Seri Iskander

31750 TRONOH

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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(Assoc. Prof. Dr. Irraivan Elamvazuthi)

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December 2011

CERTIFICATION OF ORIGINALITY

This is to certify that the work done have not been undertaken or done by unspecified sources or persons, that the original work is my own except as specified in the references and acknowledgements, and that I am responsible for the work submitted in this project.

Sara Mansour

Sara Amr Salah Eldin Mansour

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Table of contents

List of figures:

Tables:

CHAPTER 1: INTRODUCTION

1.1- Background

PID controller is a control loop feedback mechanism widely used in industrial control systems. The PID controller calculation involves three separate parameters, proportional, integral and derivative values. Tuning of PID controller is done in order to achieve the desired performance for the motor. Practically, it is difficult to simultaneously achieve all the desirable qualities for the motor.

Generally, There are several conventional and numeric controller types intended for controlling the DC motor as PID Controller, Fuzzy Logic Controller; PID-Particle Swarm Optimization, Ant colony optimization . In this project, micro DC motor manufactured by FAULHABER that's used for the application of a prosthetic leg is to be controlled by the PID based Ant colony optimization (ACO) controller.

The first appearance of an ACO system was in a Ph.D. thesis in 1992 by Marco Dorigo at Politecnico di Milano. It was called Ant System (AS). Since 1995 various other extended versions of AS have been developed, including Ant Colony System (ACS) and MAX-MIN Ant System (MMAS). In 1999 Dorigo proposed the Ant Colony Optimization (ACO) meta-heuristic that became the most successful and recognized algorithm based on ant behaviour [1].

A controlled prosthetic leg is chosen to be the application for this project. It's manufactured by the German company FAULHABER to help the disabled who lost a limb perform their daily activities normally. The motor used in this prosthetic leg is also manufactured by FAULHABER and it's a micro-motor to be light and reliable.

1.2- Problem Statement

1- The performance of PID controller of DC motors is not fully efficient.
2- PID controller has a relative slow response that needs to be improved by ACO optimization.
3- Prosthetic legs (application) need specific micro motors with fast response that requires improvements for PID.

1.3- Objectives

1- To improve the performance of a PID controller of a micro DC motor by using ACO method in terms of rise time, settling time and overshoot.
2- Compare the performance of PID controller of a dc motor that is tuned using some trial and error methods with PID-Ant colony optimization ACO.
3- Micro DC manufactured by FAULHABER is taken as an application for this project .Prosthetic legs can help some of the disabled perform their daily activities naturally.

1.4- Scope of Study

The scope of study of the project is as follows:

1- Research about PID controller and PID based Ant colony optimization technique for better understandings of the theory and the literature review.
2- Simulation using Simulink/MATLAB to determine the performance of both controllers (PID and PID-ACO).
3- Compare and analyze both performances in order to achieve the optimum one.

CHAPTER 2: LITRATURE REVIEW

2.1- DC Motor

An electric motor converts electrical energy into mechanical energy. Most electric motors operate through the interaction of magnetic fields and current-carrying conductors to generate force. The simplified operating principle of DC motor is when a current passes through the coil wound around a soft iron core, the side of the positive pole is acted upon by an upwards force, while the other side is acted upon by a downward force. According to Fleming's left hand rule, the forces cause a turning effect on the coil, making it rotate. To make the motor rotate in a constant direction, "direct current" commutators make the current reverse in direction every half a cycle (in a two-pole motor) thus causing the motor to continue to rotate in the same direction [2].

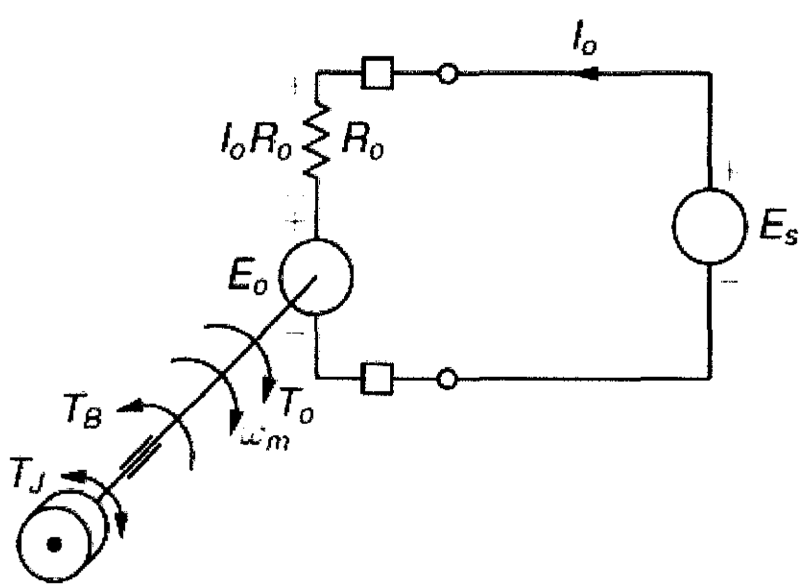


Figure1: Equivalent DC motor circuit [3]

A DC torque motor can be represented by the following transfer function for simplified servo analysis. This transfer function ignores motor induction, friction and shaft resonances [4].

ω = speed (radian/second)

V = voltage input (volt)

K_b = back EMF constant (volt)

T_m = mechanical time constant (second)

$$\frac{\omega}{V} = \frac{1/K_b}{T_m\, s + 1}$$

To include the effect of motor inductance, the transfer function is modified to include an additional term which is the time constant electrical. Time Constant, Electrical (T_e) is the time required for the armature or winding current to reach 63.2% of its steady state conditions. It can be mathematically derived from the following formula:

$$\mathbf{T_e} = \frac{\mathbf{L_a}}{\mathbf{R_t}}$$

$\mathbf{L_a}$: Armature inductance (Henry)

$\mathbf{R_t}$: Terminal Resistance (Ohm)

Therefore, the transfer function for the selected motor is

$$\frac{\omega}{V} = \frac{1/K_b}{(T_m\, s + 1)\,(T_e\, s + 1)}$$

2.1.1- Micro-motor

A micro-motor is a special class of low power motor, typically fitting within a frame that is 35 mm square. A micro-motor may also be called a fractional horsepower motor and is usually rated at or below 746 watts. Micro-motors are typically run off of DC power supplies and are often used in actuator or control applications as servomotors or stepper motors.[5]

FAULHABER is the manufacturer for the micro-motor used in this project .It has low starting voltage, high dynamic performance due to low inertia, low inductance coil. It's light , compact, smooth with accurate speed, position and torque control. The model for the selected motor is series 1024012S.It was selected because it has the highest output power among this series. Check the data sheet in the appendix.

Features and benefits of the micro motor selected according to its manufacturer FAULHABER .

- No cogging
- High power density
- Extremely low current consumption
- Low starting voltage
- Highly dynamic performance due to a low inertia, low inductance coil
- Light and compact
- Smooth and accurate speed, position, and torque control
- Precise speed control
- Simple to control due to the linear performance characteristic

2.2- PID Controller

A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems .PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set-point. The controller attempts to minimize the error by adjusting the process control inputs [6].

The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted *P*, *I*, and *D*. Heuristically, these values can be interpreted in terms of time: *P* depends on the *present* error, *I* on the accumulation of *past* errors, and *D* is a prediction of *future* errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, or the power supplied to a heating element [6].

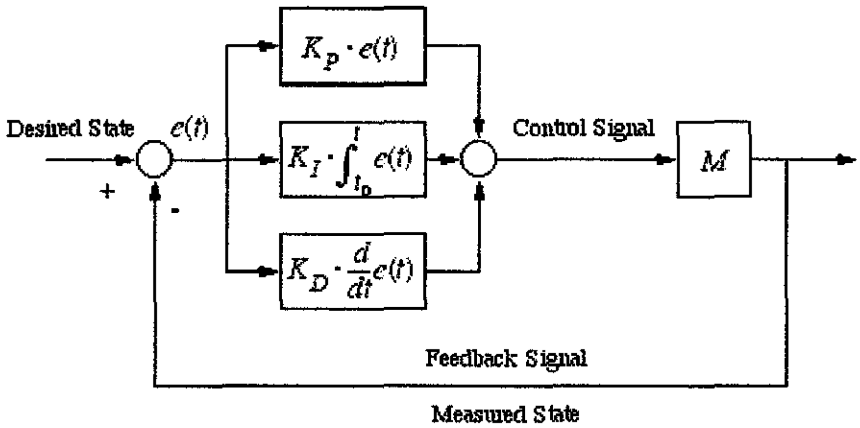


Figure 2 :PID controller [7]

By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation.

2.3- Ant Colony Optimization (ACO)

Ant colony optimization algorithm (ACO) is a probabilistic technique for solving computational problems which can be reduced to finding good paths through graphs.

This algorithm is a member of ant colony algorithms family, and it constitutes some meta-heuristic optimizations. Initially proposed by Marco Dorigo in 1992 in his PhD thesis, the first algorithm was aiming to search for an optimal path in a graph, based on the behaviour of ants seeking a path between their colony and a source of food. The original idea has since diversified to solve a wider class of numerical problems, and as a result, several problems have emerged, drawing on various aspects of the behaviour of ants [8].

ACO's are especially suited for finding solutions to different optimization problems. A colony of artificial ants cooperates to find good solutions, which are an emergent property of the ant's co-operative interaction. Based on their similarities with ant colonies in nature, ant algorithms can be applied to different versions of the same problem as well as to different optimization problems .The main traits of artificial ants are taken from their natural model. These main traits are artificial ants exist in colonies of cooperating individuals, they communicate indirectly by depositing pheromone they use a sequence of local moves to find the shortest path from a starting position, to a destination point using local information to find the best solution.

If necessary in order to solve a particular optimization problem, artificial ants have been enriched with some additional capabilities not present in real ants. An ant searches collectively for a good solution to a given optimization problem. Each individual ant can find a solution or at least part of a solution to the optimization problem on its own but only when many ants work together they can find the optimal solution. Since the optimal solution can only be found through the global cooperation of all the ants in a colony, it is an emergent result of such this cooperation. While searching for a solution the ants do not communicate directly but indirectly by adding pheromone to the environment. [9]

Based on the specific problem an ant is given a starting state and moves through a sequence of neighbouring states trying to find the shortest path. It moves based on a stochastic local search policy directed by its internal state, the pheromone trails, and local information encoded in the environment. Ants use this private and public information in order to decide when and where to deposit pheromone. In most application the amount of pheromone deposited is proportional to the quality of the move an ant has made. Thus the more pheromone, the better the solution found. After an ant has found a solution, it dies; i.e.it is deleted from the system

These are the equations that will be used to perform the Ant colony optimization technique.[10]

The probability (P_{ij}^{A} (t)) of choosing a node at node is defined in the equation (1). At each generation of the algorithm, the ant constructs a complete solution using, starting at source node.

$$P_{ij}^{A}(t) = \frac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{i,j\in T^{A}}[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}} \quad (1)$$

Where

$\eta_{ij} = \frac{1}{K_j}$ and j=[p,i,d]

α and β are constants that determine the relative influence of the pheromone.

T^{A} = is the path effectuated by the ant at a given time.
The quantity of pheromone $\tau_{ij}(t)$on each path may be defined as:

$$\Delta\tau_{ij} = \frac{L^{min}}{L^{A}} \quad (2)$$

Where,

L^{A} is the value of the objective function found by the ant .
L^{min} is the best solution carried out by the set of the ants until the current iteration.

The pheromone evaporation is a way to avoid unlimited increase of pheromone trails. Also it allows the forgetfulness of the bad choices.

$$\tau_{ij}(t) = p\tau_{ij}(t-1) + \sum_{A=1}^{NA}\Delta\tau_{ij}^{A}(t) \quad (3)$$

Where

NA: number of ants
P: evaporation rate 0<p<1

2.4- Project Application (Controlled prosthetic leg)

FAULHABER found a technological reliable way to help the disabled who lost any of their legs perform their daily activities normally. Previously it took nature a long time to develop the perfect "apparatus" to allow humans to move around. All the solutions which have been tried to date, from wooden legs to high-tech prostheses using state-of-the-art materials, have worked in a purely passive way. Something that these devices all have in common is that their function doesn't change during movement. Now, however, a new solution has been developed, centred around the use of microprocessor-controlled prostheses. Just like natural limbs, these can react automatically, adapting to the current situation. Lightweight micro-motors, combined with intelligent control technology, offer the chance to walk in a way that feels very similar to natural movement – providing clear benefits for users in terms of both safety and comfort.[]

CHAPTER 3: METHODOLOGY

3.1 Methodology

The sequence of the project is as follows:

1- Choosing the suitable motor type. Since the application of this project is for prosthetic legs that uses micromotors manufactured by Faulharbour.
2- Getting the transfer function of the chosen motor by referring to the datasheet of the manufacturer.(Check the Appendix)
3- Testing the PID only performance so it can be compared later to the PID-ACO controller. Testing is done by using MATLAB Simulink to obtain the motor response and also several trials were done for further monitoring understanding for the performance of the PID.
4- By using MATLAB code for Ant colony optimization technique to calculate the optimum value for the PID parameters and show the response of the motor.
5- Analyzing the performance of the obtained response.

3.2 Flow Chart

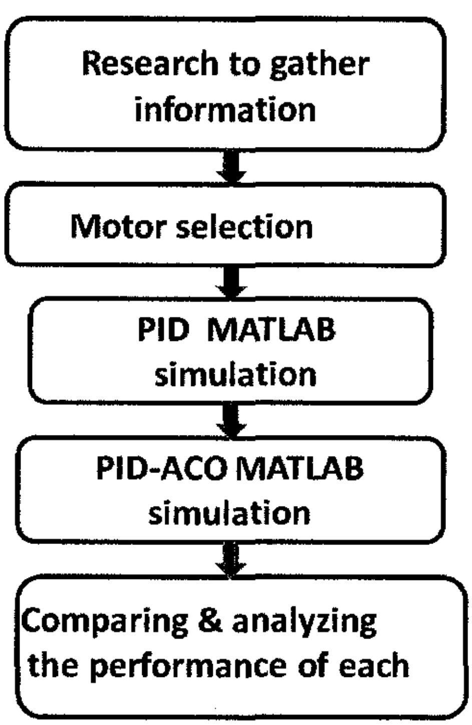


Figure3: Flow chart of the project

3.3 ACO Implementation Algorithm

The ACO Algorithm is as the following [10] :

Step 1

Initialize randomly potential solutions of the parameters (K_p K_i K_d) by using uniform distribution. Initialize the pheromone trail and the heuristic value.

Step 2

Place the A^{th} ant on the node. Compute the heuristic value associated in the objective (minimize the error).

Step 3

Use pheromone evaporation given by eqn (3) to avoid unlimited increase of pheromone trails and allow the forgetfulness of bad choices.

Step 4

Evaluate the obtained solutions according to the objectives.

Step 5
Display the optimum values of the optimization parameters.

Step 6

Globally update the pheromone, according to the optimum solutions calculated at step 5. Iterate from step 2 until the maximum of iterations is reached.

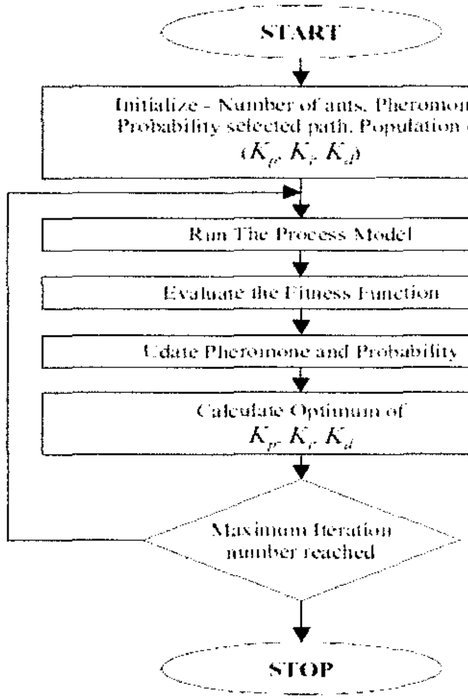


Figure 4: ACO flow chart

The PID-ACO control loop block diagram is as shown in figure

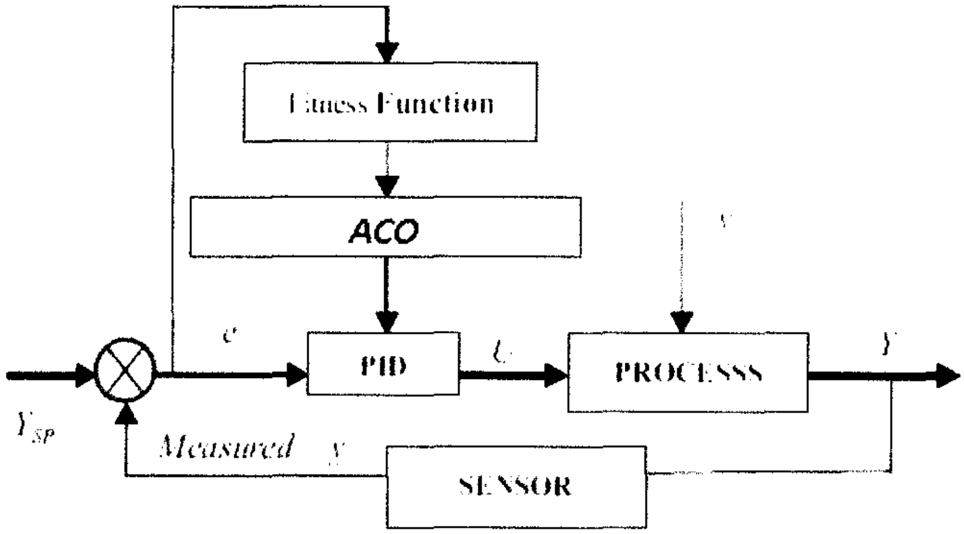


Figure 5 :Intelligent PID-ACO block diagram [10]

CHAPTER 4: DISCUSSION AND RESULTS

As mentioned previously, the objective of this project is to improve the performance of PID controller of a micro motor by using Ant colony optimization technique (PID-ACO) and then compare this performance by the PID performance to analyze and contrast the performance of each.

The following sections describes the results of the motor transfer function obtained, the PID performance obtained using MATLAB tuning and the expected results from the previously referred paper.

4.1 Motor transfer function

According to the datasheet of the micro motor manufactured by FAULHABER attached, the transfer function is found as follows: [4] [5] [13]

ω = speed

V = voltage input

K_b = back EMF constant

T_m = mechanical time constant

L_a : Armature inductance

R_t: Terminal Resistance

$$\frac{\omega}{V} = \frac{1/K_b}{(T_m s + 1)(T_e s + 1)}$$

According to the Data sheet attached for FAULHABER micro motor model number 1016012G [5].

K_b=0.806 mV/rpm ×10 e-3×$\frac{60}{2\pi}$ = 7.696 e-3 Vs /rad

T_m=6 ms

L_a=344 μH

R_t= 31.6Ω

Therefore the transfer function becomes;

$$\frac{\omega}{V} = \frac{1/7.696 \times e-3}{(0.006\,S + 1)(1.08\,e - 5\,S + 1)}$$

$$\frac{\omega}{V} = \frac{129.9}{(6.531e - 8)S^2 + (0.006010)S + 1}$$

4.2 PID controller response

By the aid of MATLAB simulink, the control loop block diagram of PID is drawn as shown in figure . This block diagram shows the PID controller and the transfer function of the micro-motor selected.The scope is to find the response of the motor after making one step input change.

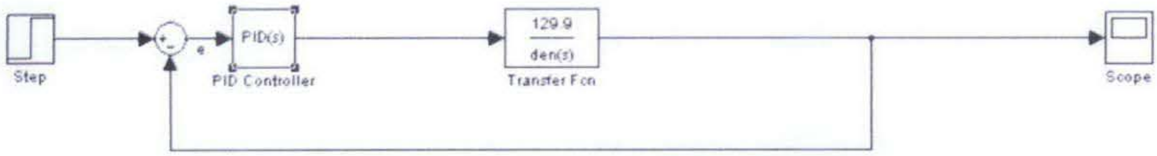


Figure 6 :PID block diagram

The response of the PID controller and its performance is shown in figure 7 and table 7 respectively.

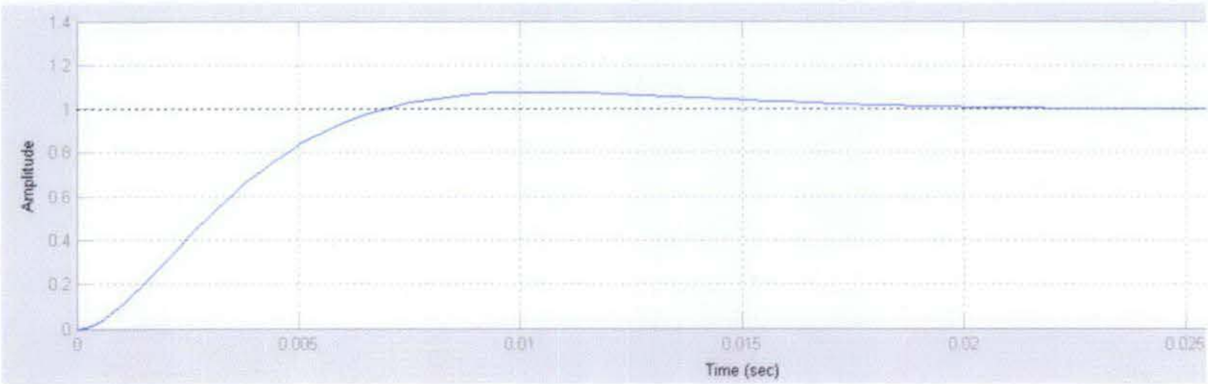
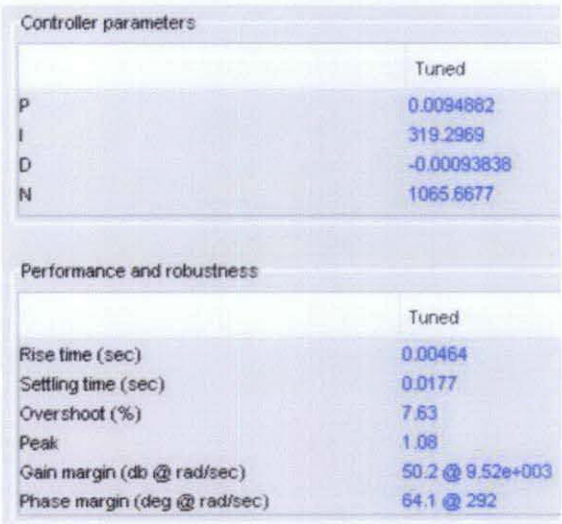


Figure 7 : PID controller response



Controller parameters

	Tuned
P	0.0094882
I	319.2969
D	-0.00093838
N	1065.6677

Performance and robustness

	Tuned
Rise time (sec)	0.00464
Settling time (sec)	0.0177
Overshoot (%)	7.63
Peak	1.08
Gain margin (db @ rad/sec)	50.2 @ 9.52e+003
Phase margin (deg @ rad/sec)	64.1 @ 292

Figure 8 :PID performance

Table 1: PID parameters and performance

PID parameters			Dynamic Performance specifications		
Kp	Ki	Kd	Rise time	Settling time	Peak overshoot
0.0094882	319.2969	-0.00093838	4.64 ms	17.7 ms	7.63 s

4.3 Expected PID-ACO response

After doing several research [10] [11] [12] , these responses were found and they show a comparison between the PID performance using Z-N method and the intelligent PID controllers using several optimization techniques and ACO is one of them.

where,

ZN: Ziegler Nicholas (PID)

ACO: Ant colony optimization

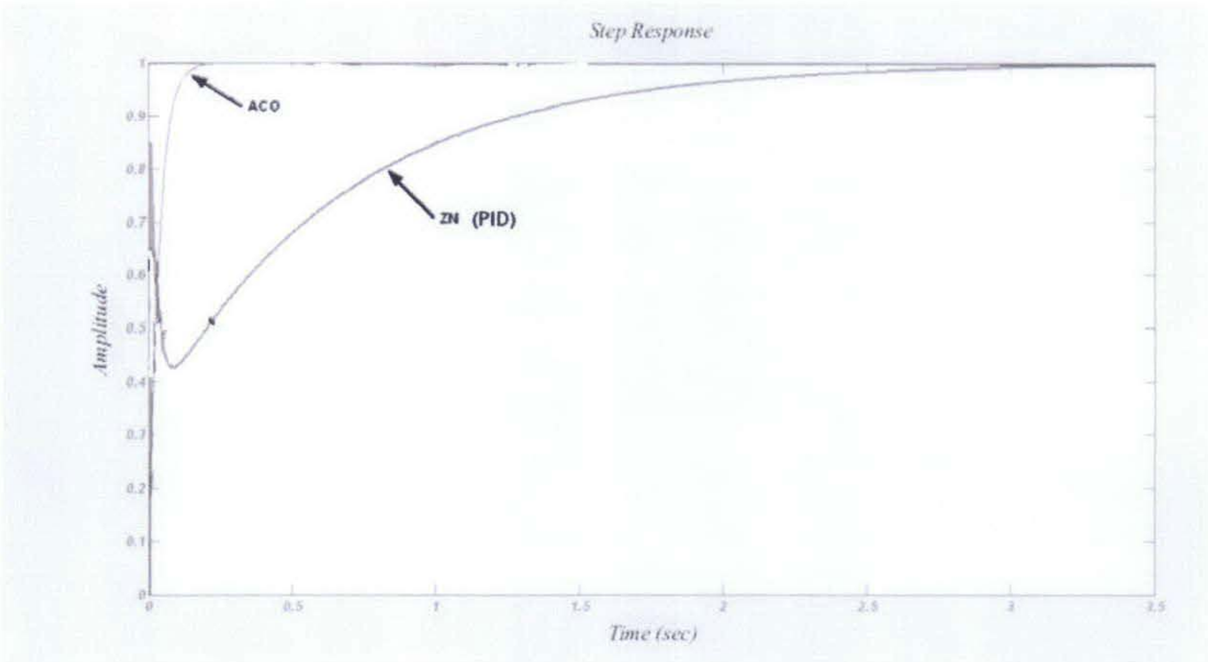


Figure 9: Comparison between ZN and other optimization techniques [?]

Tuning Method	PID Parameters			Dynamic performance specifications			Performance Index
	K_p (Proportional gain)	K_i (Integral gain)	K_d (Derivative Gain)	T_r (Rise time)	T_s (Settling time)	M_p (%) (Peak overshoot)	ISE (Integral square error)
ZN	9.3883	36.4170	0.6051	1.27	2.235	1	2.2926
ACO	10	200	0.21	0. 00105	0.429	0. 0	1.174

Table 2: Comparison between ZN (PID) and ACO

By analyzing the obtained data and comparing the performance of each ZN and ACO, it's concluded that each of the rise time, settling time and the peak overshoot value is being reduced meaning the performance was improved. It's also concluded that among all the optimization techniques, Ant colony optimization was found to give the optimum performance.

By also analyzing the values of the proportional gain, integral gain ad derivative gain,K_p ,K_i and K_d it's concluded that the integral gain has a great effect in the betterment of the performance. It is increased from 36.4170 in ZN and as the performance is improved by several techniques the value of the integral gain increases until it reaches 200 by using ACO technique.

The application of this project which is the controlled prosthetic leg can give the best performance when tuned by PID-ACO technique since the smaller the rise time, settling time and the peak overshoot is the easier and more reliable the performance of the controlled leg will be and therefore the more the patient will be more comfortable using it.

Achieving a desirable performance for a motor is not an easy process. It could be done by tuning and other optimization techniques. PID tuning is very essential in control processes and it could be done by several methods as Ziegler Nicholas, Cohen Coon and other trial and error methods. There are several hybrid approaches for optimization techniques for motor control like Genetic Algorithm, particle swarm optimization, Evolutionary programming and Ant colony optimization.

After doing several researches about Ant colony optimization techniques to know the previous experiences and latest updates about it, it was found that this technique is very well known to solve optimization problems like the TSP (Travel sails man problem) that helps the sailor determine the shortest paths to reach his destinations.

Several recent papers [10][11][12] about Motor control using ACO was written but due to copyrights, the MATLAB code is never shared. Due to insufficient references about the exact ACO MATLAB Algorithm, and the inability of running the attached MATLAB code that has some errors that couldn't be solved, the exact results for the selected motor was not successfully achieved. The expected results for the PID-ACO is shown in the coming sections. It is from a very recent paper written in

February 2011.This paper is written by a Professor in Karpagam university-India [?] who is still writing his thesis and expecting to finish it by February 2012. It shows a comparison between the performance of PID tuned by Ziegelr Nicholas method and other optimization techniques as GA, ACO,EP and PSO.

In order to complete this project in the future, the ACO MATLAB code attached needs to be modified in order to reach to the required results. The error might be in the logic of calling the fitness function itself which aims to reduce the error of the control loop. Also several checks needs to be done for the logic of the Ant colony optimization itself.

CHAPTER 5: CONCLUSION

Finally, after doing this research, it's concluded that Motor control is very essential in any control system in order to achieve the desired performance. Motor in this research was selected for a Prosthetic leg application designed by the manufacturer FAULHABER.

PID controllers are very widely spread in the industrial systems nowadays but obtaining an optimum performance for those controllers and for their motors is not an easy procedure. Several Optimization techniques can be used to obtain optimum PID parameters and thus a better performance.

Ant Colony Optimization technique is one of those techniques that can improve the performance of PID controllers. By applying this technique, a better performance in means of rise time, settling time and peak overshoot is improved and thus a better performance for the motor.

The results of this project was not completely achieved as expected due to the inability of running the MATLAB PID_ACO code attached and the insufficient references for such a code due to copyrights but there's one thesis about Motor control using optimization techniques and ACO is one of them is being written by professor Nagaraj (check references) that is expected to be done by February 2012 and his thesis might assist in achieving the expected results.

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[12] Ant Colony Optimization Based PID Tuning for AVR in Autonomous Power Generating Systems A.Soundarrajan1, Dr.S.Sumathi 2,C.Sundar3. Dept. of I.T, EEE Dept. 1, 2, 3 PSG College of Technology Peelamedu, Coimbatore-641004 .Tamilnadu, INDIA

[13]Parameter identification of induction motors using Ant Colony Optimization.Zhenfeng Chen Yanru Zhong, Jie Li

2-Appendix

Ant Colony Optimization MATLAB code

```
function [BestTourLength, BestTour] = ACOPID (Kp, Ti, Td, num, den)
    clc;
    d = initialmatriks (Kp, Ti, Td, 50);
    n = size (d, 1);
    % Number of options
    m = 10;
    % Number of ants
    t_max = 100;
    % Iteratios
    alpha = 1;
    rho = 0.9;
    [NumCL, denCL] = CL (Kp, Ti, Td, num, den);
    [Y, t, x] = step (numCL, denCL);
    % L_nn = sum (abs (1-y));
    % Integral absolute error criterion
    % L_nn = (1-y) '* (1-y);
    % Integral square error criterion
    L_nn = x * abs (1-y);
    % Integral of time absolute error Multiplied
    criterion
    % L_nn = x * ((1-y). ^ 2);
    % Integral of time Multiplied square-error
    criterion
    L_best = inf;
    T_best = 0;
    % Initialization
    %==========================================
    % Pheromone trails
    c = 1 / (n * L_nn);
    tauKp = ones (n, 1) * c;
    tauKpTi = ones (n, n) * c;
    tauTiTd = ones (n, n) * c;
    % Place m ants in n nodes
    ant_tours = zeros (m, 3);
    tt = 1;
    while (tt <= t_max)
    for s = 1: 3
    % Number of options
    for k = 1: m
    % Number of ants
    p = zeros (1, n);
```

```
    for i = 1: n
    if (s == 1)
    p (i) = (tauKp (i, s)) ^ alpha;
    elseif (s == 2)
    p (i) = (tauKpTi (ant_tours (k, 1), i)) ^ alpha;
    elseif (s == 3)


    p (i) = (tauTiTd (ant_tours (k, 2), i)) ^ alpha;
    end
    end
    sum_p = sum (p);
    p = p / sum_p;
    for i = 2: n
    p (i) = p (i) + p (i-1);
    end
    r = rand;
    for i = 1: n
  if (r <= p (i))
select = i;
break;
end
end
ant_tours (k, s) = select;
  if (s == 1)
tauKp (select, 1) = (1-rho) * tauKp (select, 1) + c;
elseif (s == 2)
tauKpTi (ant_tours (k, 1), select) = (1-rho) *
tauKpTi (ant_tours (k, 1), Select) + c;
elseif (s == 3)
tauTiTd (ant_tours (k, 2), Select) = (1-rho) *
tauTiTd (ant_tours (k, 2), Select) + c;
    end
end
end
% UPDATE
% ============================================
best_ant = 1;
for k = 1: m
% Number of ants
KP = d (ant_tours (k, 1), 1);
IT = d (ant_tours (k, 2), 2);
TD = d (ant_tours (k, 3), 3);
[NumCL, denCL] = CL (KP, TI, TD, num, den);
```

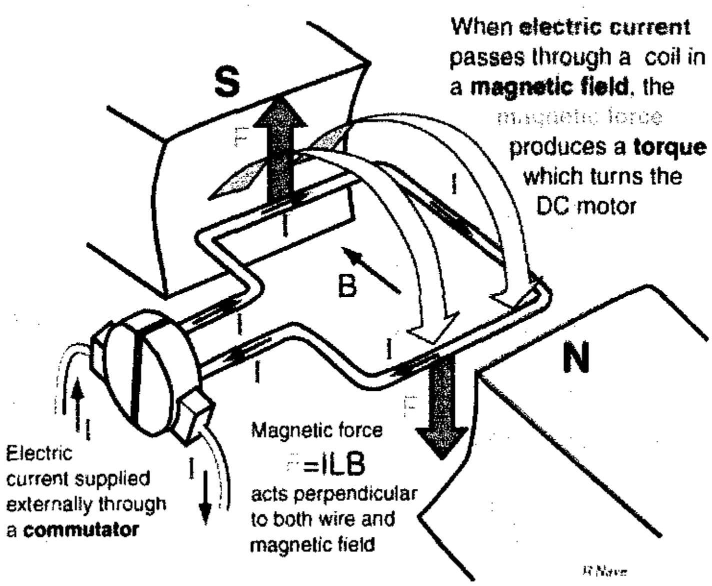
```
[Y, t, x] = step (numCL, denCL);
% L_T (k) = sum (abs (1-y));
% Integral absolute error criterion
% L_T (k) = (1-y) '* (1-y);
% Integral square error criterion
L_T (k) = x * abs (1-y);
% Integral of time Multiplied absolute
error criterion
% L_T (k) = x * ((1-y). ^ 2);
% Integral of time Multiplied square-
error criterion
    if (L_T (k) <L_T (best_ant))
best_ant = k;
    end
end
L_min = min (L_T);
KP = d (ant_tours (best_ant, 1), 1);
IT = d (ant_tours (best_ant, 2), 2);
TD = d (ant_tours (best_ant, 3), 3);
T_min = [KP IT TD];
% Update the pheromone trails
tauKp (ant_tours (best_ant, 1), 1) = (1-rho) *
tauKp (ant_tours (best_ant, 1), 1) + rho / L_min;
tauKpTi (ant_tours (best_ant, 1), ant_tours (best_ant, 2)) = (1-rho) *
tauKpTi (ant_tours (best_ant, 1), ant_tours (best_ant, 2)) + rho / L_min;
tauTiTd (ant_tours (best_ant, 2), ant_tours (best_ant, 3)) = (1-rho) *
tauTiTd (ant_tours (best_ant, 2), ant_tours (best_ant, 3)) + rho / L_min;
```

```
% COMPLETE
% ===========
clc;
tt = tt + 1
ant_tours = zeros (m, 3);
if (L_min <L_best)
L_best = L_min;
T_best = T_min;
end
L_best
end
clc
tt
BestTourLength = L_best
BestTour = T_best
```

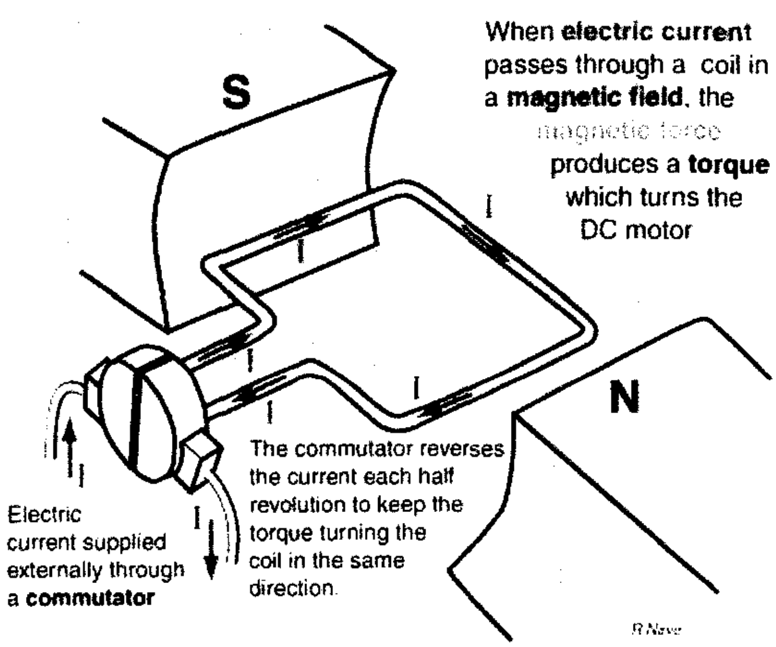
```
KP = BestTour (1);
IT = BestTour (2);
TD = BestTour (3);
figure, step (numCL, denCL)
[NumCL, denCL] = CL (KP, TI, TD, num, den);
figure, step (numCL, denCL)
```

DC motor operation:

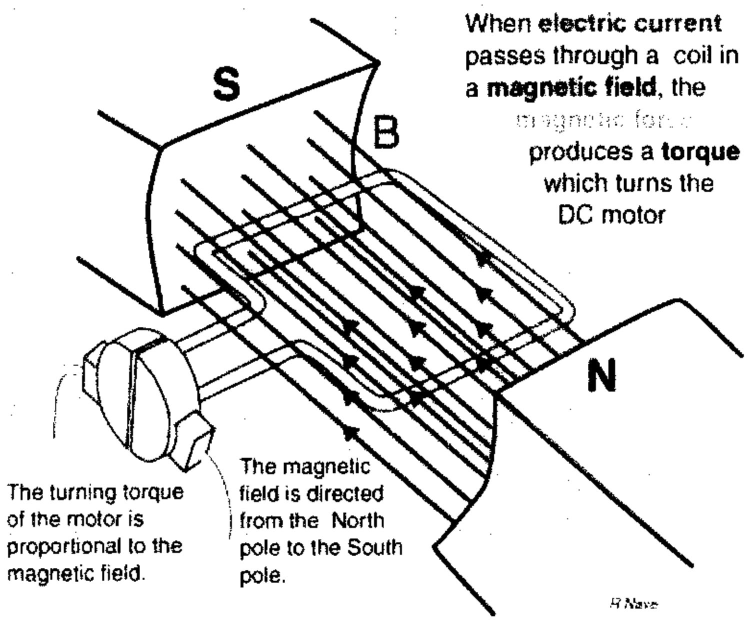
DC Motor Operation



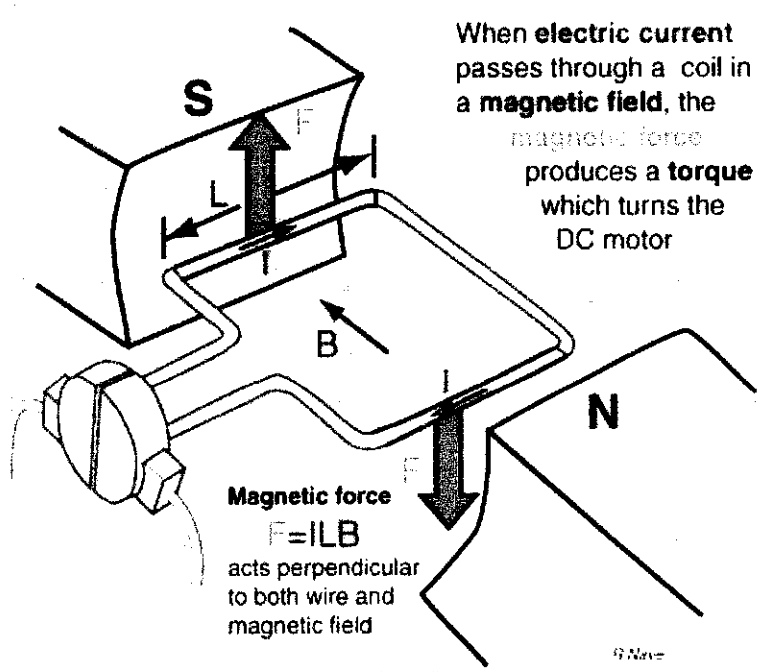
Current in DC Motor



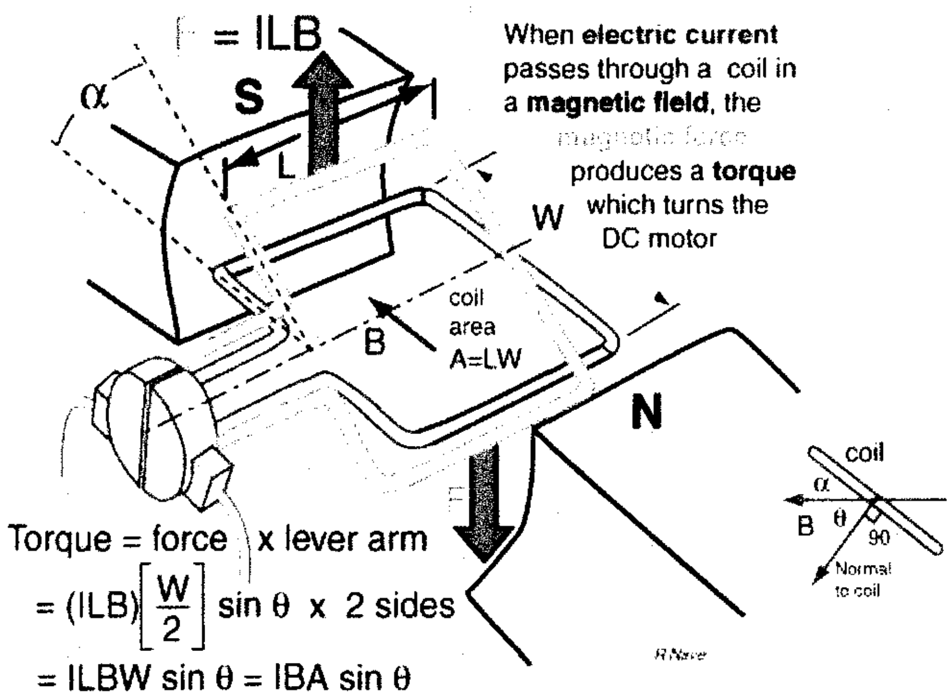
Magnetic Field in DC Motor



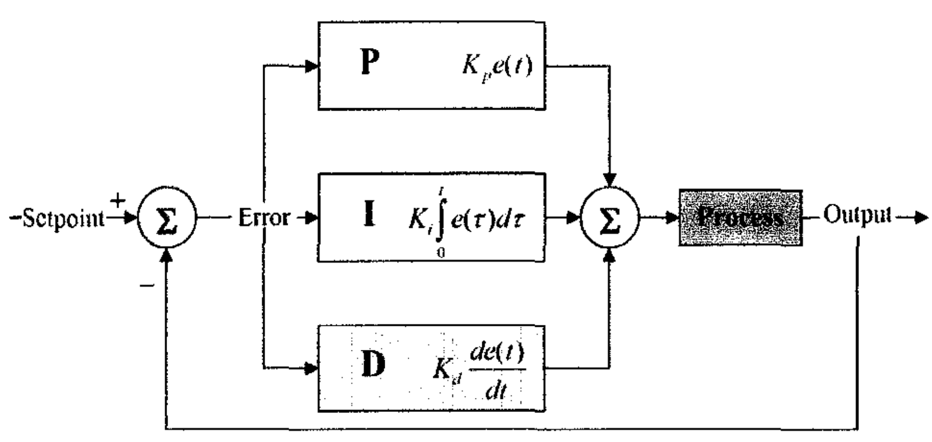
Force in DC Motor



Torque in DC Motor



PID block diagram:



FAULHABER prosthetic leg

FAUHABER micro-motor