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Analysis of Four Quadrant Operation of Thruster Motor in an AUV using an Optimized H Infinity Speed Controller

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Abstract

The four-quadrant operation of a BLDC motor used as thruster motor coupled with a propeller in an Autonomous Underwater Vehicle (AUV) is studied through simulation in MATLAB/SIMULINK. The robust control of thruster motor is an essential requisite for the smooth operation of AUV in the presence of uncertainties such as un-modeled vehicle parameters and external disturbances due to weather. An H infinity speed controller whose coefficients of weights being optimized by Particle Swarm Optimization (PSO) is proposed for achieving robust control of BLDC motor when there is a change in reference speed and load variation. The MATLAB function *hinfsyn* is used for synthesizing H infinity controller. The design of H infinity controller and PI controller with their weights and gains optimized by PSO respectively are discussed and their simulation results are compared. It is observed that during the forward braking region, the torque ripples with the proposed controller strategy are found to be reduced by 8.709 Nm. Similarly, in the reverse braking region, a reduction of 7.161 Nm in torque ripples is observed with the proposed controller strategy compared with PI controller. This shows that the proposed strategy reduces the vibration and noise of the vehicle during braking which is a vital factor to be considered when the AUV is used in military applications.

Keywords: AUV, four-quadrant operation, PSO, H infinity, weights

INTRODUCTION

Autonomous Underwater Vehicle (AUV) as the name indicates is a self-controlled robot for performing a predefined task undersea or ocean. It is an independent swimming robot which has its power pack, guidance, control, navigation, sensors and thrusters intact on board. AUV finds its applications in various fields such as conservation of marine biodiversity, provision of exact information regarding coral reefs, the concentration of fish population, quality of water like its oxygen concentration, pH concentration and so on. Also, it is used in military applications such as detection of underwater mining, torpedo propulsion and so on where precision and accuracy is of primary concern.

A computer-based mission control system has been designed and implemented in MARIUS AUV for the simple communication with the end user [1]. In this, vehicle guidance and control block provides the reference speed to be achieved based on the reference trajectory inputs from mission control system and navigation system, to the actuator control system. This is necessary for the proper trajectory tracking in the presence of uncertainties such as variation in vehicle parameters and also due to external disturbances such as varying sea currents due to weather disturbances. In recent years, a lot of research work is going on in trajectory tracking control laws and path following techniques of AUV for precise maneuvering.

Thruster motors with dedicated controller play an important role in the propulsion of AUV for maintaining the speed. Brushless Direct Current motors with hall sensors used as thruster motors have been found in the literature for propelling AUV [2]. A seven-phase BLDC motor for the propulsion of AUV has been functionally modeled and simulated in MATLAB/SIMULINK for studying its dynamic characteristics [3].

Though the PID controller is one of the widely used actuator controllers because of its simplicity, the tuning of gains of this controller poses a problem. Usually, it has been tuned by trial and error method based on the experience of the control engineer. Various tuning strategies have been found in the literature including the Ziegler- Nichols method, PSO, GA optimization techniques and generalized Kalman-Yakubovich–Popov(KYP)synthesis [4], [5]. PSO technique to tune the parameters of PID controller is one of the commonly implemented techniques because of its ability to avoid premature convergence of GA and to provide a high-quality solution with better computation efficiency [6].

Due to the non- linearity that exists in the design of speed and position control of the BLDC motor, various robust control techniques have been proposed and validated in the literature. Designing of a robust Fuzzy speed controller of BLDC motor described by Takagi-Sugeno (TS) Fuzzy model has been carried out by Wudhichai Assawinchaichote *et al*. Sufficient conditions for the BLDC motor to achieve H infinity performance have been derived using the Linear Matrix Inequality (LMI) approach in order to overcome the effects of non- linearity and disturbance [7]. An experimental validation of continuous sliding mode (CSM) and fractional order sliding mode (FOSM) controller in the speed control of BLDC motor has been carried out in order to prove the better trajectory tracking the performance of FOSM compared with CSM [8]. For achieving a robust position tracking system of BLDC motor, in the presence of disturbances such as friction and backlash, a robust linear quadratic sliding mode controller has been proposed [9]. This control algorithm combines a linear quadratic control and non-linear sliding mode control. A comparative study of PI and H infinity controllers with their gains and weights optimized by PSO for speed control of BLDC motors used as propulsion motors in submarines has been conducted by the author for achieving improved maneuverability [10, 11].

In H infinity control design, the weights are tuned in order to obtain satisfactory performance margins such as rise time, percentage overshoot, settling time and steady-state error. But the adjustment of these weights is based on experience and engineering intuition. Many researchers addressed this problem by various methods, which have been detailed below. A first-order approximation of the controller is a function of small weight adjustment done in the initial control design problem itself. This avoids the next step of synthesis involving the adjusted weights [12]. PSO based weight selection has been implemented for the pneumatic servo system in order to track the reference signal, reject disturbances and to provide robust performance in the presence of model uncertainties [13].

In this work, the four-quadrant operation of the BLDC motor used as thruster motor coupled with propellers in AUV has been studied due to their applications in sea surface area exploration, sea border surveillance and their role in the underwater study. The four quadrant operation of the BLDC motor has been simulated and a comparative study has been conducted with both PI and H infinity speed controllers with their gains and weights being optimized by PSO respectively.

THEORY

The design of speed controllers such as H infinity controller with its coefficients of weights optimized by PSO and PI controller with its gains optimized by PSO has been discussed for the theoretical understanding of their implementation in the following sections.

Design of H infinity speed controller with PSO optimized weights

The aim of speed controller design is to minimize the effects of disturbance and at the same time, track the speed commands with specified damping and response time. The modern approach to design controllers which are robust against model uncertainties is provided by adaptive control, fuzzy control, Lyapunov method, parameter estimation techniques as well as H_2 and H infinity control theory.

H infinity controller provides maximum amplification of a sinusoidal signal of frequency ω as it passes through the plant. Let *P* be a Linear Time Invariant (LTI) system. Let *K*, *u* and *y* represent controller, control input and measured output respectively. *w* can be exogenous inputs like reference commands, load disturbances, and sensor noise whereas the robust output variable *z* can be tracking errors, performance variables, and actuator signals [10]. From the H infinity control problem which is the closed loop interconnection as shown in Figure 1, the primary aim of the controller design is to achieve a robust output *z*, that is independent of *w*.

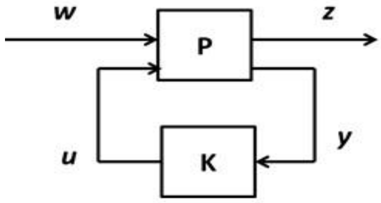

Figure 1: Block diagram showing H infinity control problem

For H infinity synthesis, the uncertainty factors of the system must be translated into the weights. The weight function W_1 of the sensitivity function should be so chosen such that it reflects the desired time response characteristics [14]. A low pass filter is used with the low frequency gain approximately equal to the inverse of the desired steady state error and high frequency gain to limit overshoot.

Hence a simple low pass filter represented by equation (1) has been selected for W_1.

$$W_1 = \frac{1}{M_s}\frac{\tau_p s+1}{\tau_p s+{}^{A}/_{M_s}} \tag{1}$$

Where $\tau_p = {}^{1}/_{M_s\omega_h}$

M_s represents the maximum value of the sensitivity function, *A* represents the maximum allowed steady state offset and ω_b represents the system bandwidth [15]. For the choice of other weights, the recommendation put forth by Christiansson A. K., *et al* [16] has been taken into consideration, which says that in order to keep the controller order low, the choice of as many weights as possible to be made constant. Moreover, in order to keep the control signal to a limited value, a constant has been assigned for W_2 and W_3.

There are a total of six coefficients of parameters *a, b, c* and *d* of W_1, *g* of W_2 and *h* of W_3 respectively which are to be chosen properly in order to attain suitable weights. In this work, these coefficients of weights are optimized using PSO in order to achieve robust control.

$$W_1 = \frac{a(s+b)}{cs+d} \tag{2}$$

$$W_2 = g \tag{3}$$

$$W_3 = h \tag{4}$$

The optimization problem is the minimization of global best cost which is equal to the sum of absolute values of error which is achieved by finding out the best coefficients for the weighting functions using PSO. With this global best cost, W_1, W_2 and W_3 are generated and the transfer function of the controller is obtained. This controller has been used as a speed controller whose output will be the torque reference.

The objective function of the problem is defined with conventional PSO as

$$min\ f(W1,W2,W3) = \sum_{n=1}^{T/dT} \left(\left|\omega_{r(n)} - \omega_{(n)}\right|\right) \qquad (5)$$

Where W_1, W_2 and W_3 are the weights

T is the simulation time

dT is the step size

$\omega_{r(n)}$ – Reference speed at nth sample

$\omega_{(n)}$ – Estimated speed at nth sample

The flowchart for obtaining optimized H infinity controller using PSO [17] is shown in Figure 2.

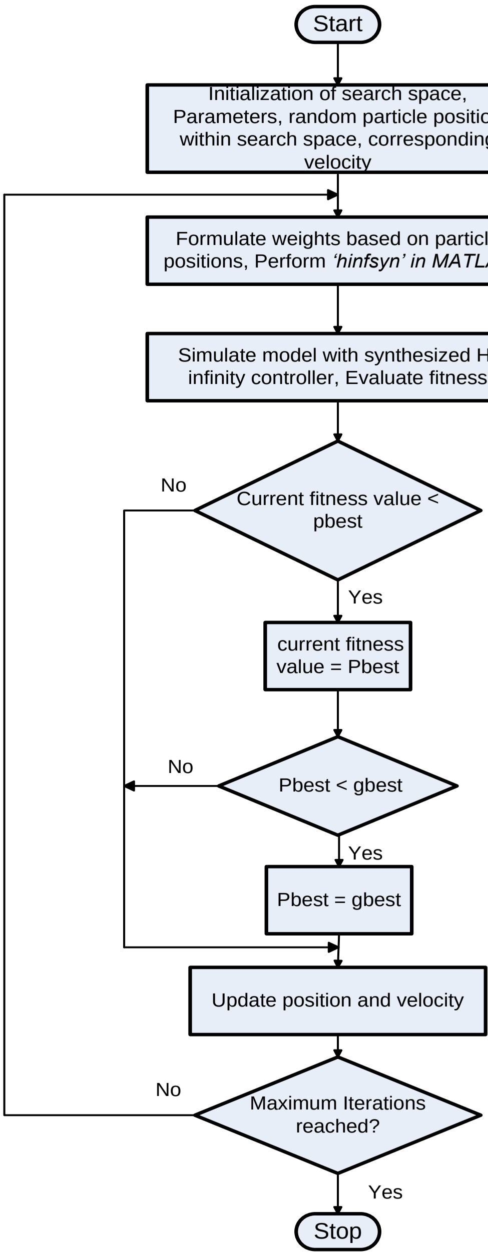

Figure 2: Flowchart for obtaining optimized weights using PSO

Design of PI speed controller with PSO optimized gains

PI control is one of the common control techniques used in industry as it is easy to implement and does not involve many complex algorithms. But it is suitable only when the system parameters are fully known and modelled. It offers low robust control when the system has uncertainties and modelling errors especially when the operating environment changes due to weather, temperature and so on. For comparison purpose, the speed controller is modelled with PI control with its gains being optimized by PSO [6] and the flowchart of which is shown in Figure 3. The The output of the PI controller $U(s)$ can be obtained for an input $E(s)$ as (6)

$$U(s) = \left(K_p + \frac{K_i}{s}\right)E(s) \qquad (6)$$

Where K_p represents proportional gain and K_i represents integral gain.

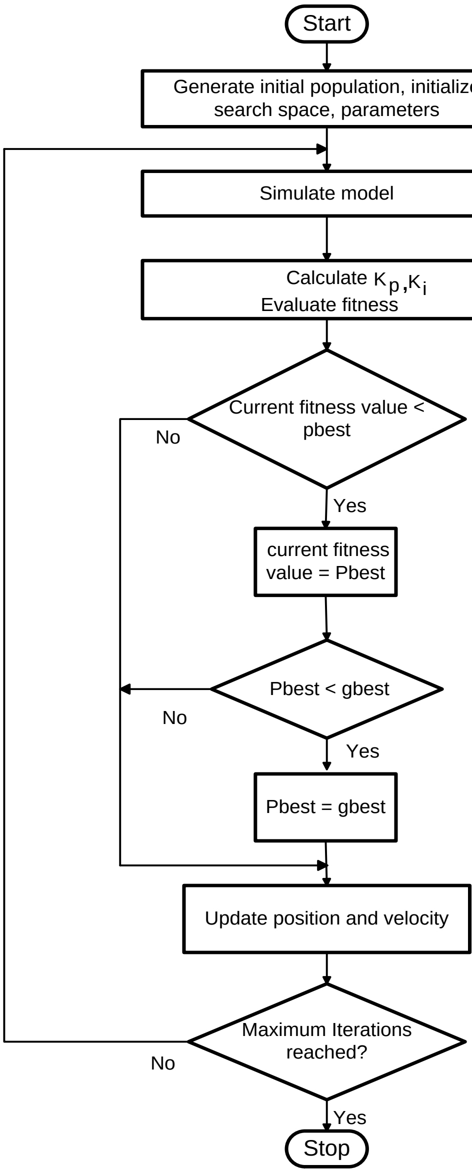

Figure 3: Flowchart for PSO optimized gains of PI controller

EXPERIMENTAL PROCEDURE

An electric motor can be operated in two modes – motoring and braking or regenerating. In motoring mode, it converts electrical energy to mechanical energy that supports its motion. In braking mode, it acts as a generator and converts mechanical energy into electrical energy that opposes its motion. As a case study, reference speed of BLDC motor is set at 1000 rpm. The specifications of BLDC motor based on which the simulations have been carried out are shown in Table 1.

Table 1: Specifications of BLDC motor used in AUV

Rated Voltage	48 V DC
Rated Current	17.95 A
Rated Power	660W
Rated Torque	2.1 Nm
Rated Speed	3000 rpm
Line to line Resistance	0.07Ω
Line to line inductance	0.1mH
Rotor inertia	0.00024Kgm^2
Torque constant	0.117Nm/A

The transfer function of the motor has been derived as (7). Table 2 shows parameters involved in the generation of optimal controllers using PSO. The PSO optimized gains of PI controller and weights of H infinity controller are shown in Table 3.

$$G(s) = \frac{0.117}{2.8e-08s^2 + 2.265e-05e-3s + 0.1205} \qquad (7)$$

Table 2: Parameters of PSO algorithm for both PI and H Infinity controllers

Parameters	PI	H infinity
C1	0.12	1.5
C2	1.2	2.5
Dimension	2	6
Damp ratio	0.95	0.95
Inertia	$1.1058*10^{-9}$	$3.3267*10^{-10}$
No. of birds	20	20
Bird steps	20	20
Variable Low	[0.1 0.00001]	[0.05 1 0.1 0.1 0.001 0.0001]
Variable High	[1 1]	[1.8 500 200 50 0.16 0.02]

Table 3: Gains and weights of controllers

Gains of PI controller		Weights of H infinity controller		
K_p	K_i	W_1	W_2	W_3
0.9977	0.8561	$\frac{0.0796s + 500}{0.1s + 27.3579}$	0.14	0.015

Figure 4 and Figure 5 represent the convergence plots of PSO for both PI and H infinity controllers respectively. It can be observed that the cost to obtain the optimal H infinity controller is less than that of the PI controller when optimized with PSO for the same number of evaluations.

The transfer function of the H infinity controller is obtained as (8)

$$KT = \frac{186.5s^2 + 4462s + 5.044e07}{s^3 + 371.6s^2 + 2.867e05s + 8.747e07} \qquad (8)$$

Similarly, the transfer function of the PI controller is obtained as (9)

$$KT = 0.9977 + \frac{0.8561}{s} \qquad (9)$$

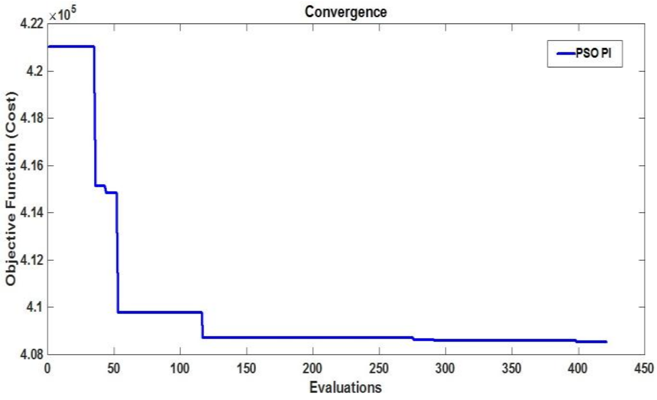

Figure 4: Convergence plot of PSO for PI controller

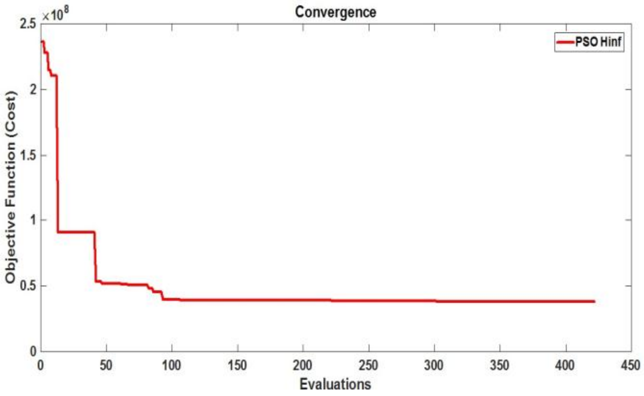

Figure 5: Convergence plot of PSO with H infinity controller

These speed controller transfer functions are used for attaining speed control of BLDC motor and their simulation results are compared for four-quadrant operation.

RESULTS AND DISCUSSIONS

A simple trapezoidal trajectory is enough to increase the velocity of the vehicle from zero to desired value and then to reduce it back to zero. It should be kept in mind that while generating a trajectory, the acceleration and velocity should be limited based on a vehicle's capabilities [18]. As part of the analysis in the four quadrants, the reference speed and load torque are set [19] as shown in Table. 4. As a detailed study, the performance of the motor is analyzed in each quadrant.

Table 4: Reference speed and load torque values

Quadrant	Mode	Time in seconds	Speed (ω)	Torque in Nm	Power
I	Forward Motoring	0.5	1000	1	+ve
IV	Reverse Braking	0.7	-1000	1	-ve
III	Reverse Motoring	1.0	-1000	-1	+ve
II	Forward Braking	1.2	1000	-1	-ve

Accordingly, the simulation has been carried out with both speed controllers in order to compare their performance with the motor drive under four quadrant operations. The speed waveforms of the motor in the first and fourth quadrants as well as in the third and second quadrants with both controllers are shown in Figure 6 and Figure 7 respectively.

It can be inferred that in the forward and reverse motoring region (I & III quadrants), the H infinity control strategy tracks the reference speed with less overshoot of 2% than PI controller. Similarly when there is a change in reference speed at 0.7 seconds during reverse braking region (IV quadrant) and at 1.2 seconds during forward braking region (II quadrant), the proposed strategy tracks the reference speed with lesser deviation than PI controller. These features make the proposed strategy more robust than the PI controller in the presence of disturbances such as load reversals and reference speed change.

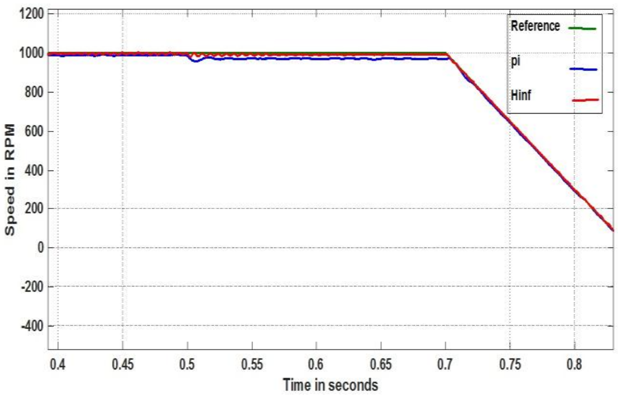

Figure 6: Speed waveform of the motor operating in first and Fourth quadrants

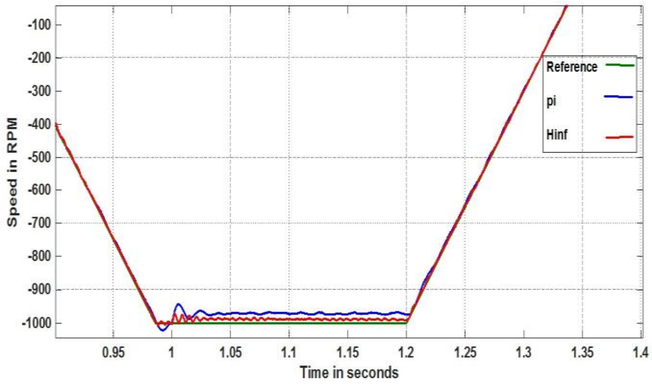

Figure 7: Speed waveform of the motor operating in third and second quadrants

Moreover Figure 8 depicts the electromagnetic torque ripples in first (I), second (II), third (III) and fourth (IV) quadrant operations. It can be inferred that during regenerating modes as shown in second and fourth quadrants, the torque ripples are higher with PI controller compared with proposed H infinity control strategy. It is observed that in the forward braking region (II quadrant), the torque oscillates between 5.464 Nm to -6.217 Nm with PI controller whereas the oscillations are between 1.692 Nm and -1.28 Nm with H infinity controller. Similarly, in the reverse braking region (IV quadrant), the torque oscillates between 5.356 Nm and -5.298 Nm with PI controller whereas it oscillates between 2.014 Nm and -1.474 Nm with the proposed strategy.

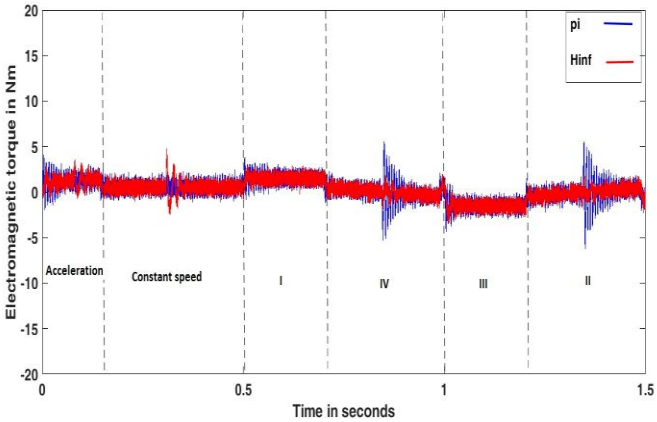

Figure 8: Comparison of Electromagnetic torque of both controllers with the motor in four quadrant operations

CONCLUSION

The four-quadrant operation of the BLDC motor used as electrical thrusters in AUV has been studied with both PI and H infinity controllers with their gains and weights being optimized respectively by PSO. The simulation results confirm the good reference tracking and rejection of load disturbances with the proposed strategy when compared with PI controller. During forward braking region, the torque ripples with the proposed controller strategy are found to be reduced by 8.709 Nm. Similarly, in the reverse braking region, a reduction of 7.161 Nm in torque ripples has been observed with the proposed controller strategy compared with PI controller. This demonstrates the robust behaviour of the proposed H infinity speed controller which helps in achieving a smooth operation of AUV.

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