Robust Steering Control of Autonomous Underwater Vehicle: based on PID Tuning Evolutionary Optimization Technique

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ABSTRACT
This paper is devoted to a robust steering control of Autonomous Underwater Vehicle (AUV) based on tuning of PID controller using Genetic Algorithm (GA) and Harmonic Search Algorithm (HSA). Tuning of PID parameters is important because, these parameters have a great effect on the stability and performance of the control system. A harmonic Search Algorithm (HSA) technique uses to tune the PID parameters in AUV system. The HS algorithm mimics behaviors of music players in an improvisation process, in order to find a better state of harmony which can be translated into a solution vector in the optimization process.Numerical solutions based on the proposed PID control of an AUV system for nominal system parameters. In control strategies, like PID controller are succesfully designed to control the autonomous underwater vehicle. The elementary focus is to simulate the controller response.

Index Terms
Autonomous Underwater Vehicle; Genetic Algorithm; PID controller; Simulation; System Identification.

1. INTRODUCTION
A UV refers to an autonomous underwater vehicle equipped with suitable sensors and actuators which enable to navigate through unknown environments while performing certain user specified tasks. AUV have 3-degree of freedom (DOF) and the subsystem is coupled with strong interaction [1]. It executes the assigned mission without any external human intervention. Some applications surveillance, navigation and monitoring. Horner and Goldberg [4] applied a GA model to bridge-music composition in the minimalist style. It turns out that Harmony Search is a special case of Evolution Strategies. The HS algorithm initializes the Harmony Memory (HM) with randomly generated solutions. The number of solutions stored in the HM is defined by the Harmony Memory Size (HMS). The parameters that are used in the generation process of a new solution are called Harmony Memory Considering Rate (HMCR) and Pitch

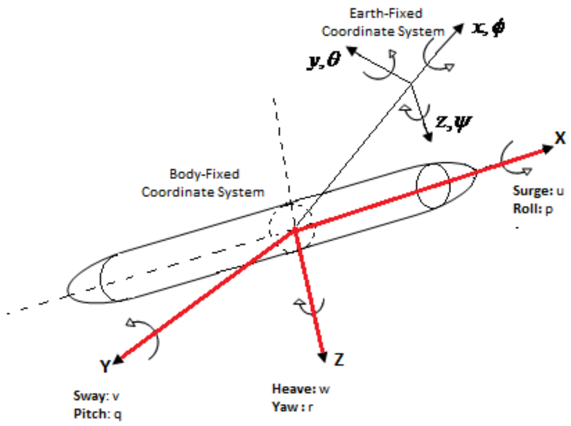

Fig1: The 6-Degree of Freedom of AUV

adjusting Rate (PAR). In this study, another evolutionary algorithm (harmony search or HS), inspired by music improvisation, is applied to music composition. The proposed HS algorithm was created by analogy to the music improvisation process. It is known that AUV systems also include uncertainties. Thus, robustness analysis of the system becomes very important and must be considered. In this paper in order to achieve a more realistic design, the robust stability region of the system is identified by using the GA (Genetic algorithm).GA is a heuristic that mimics the process of natural selection [5] which determines the performance of the genetic algorithm performs is the diversity of the population [6]. One of the first proponents JohnHolland in 1975 [8]. A collection of a number of individuals is called a population [9]. The basic goal of GA is to optimize functions called fitness functions and evaluate by this function [10]. However, the melody developed by GA could not be evaluated because there was no appropriate fitness function.The HS was superior to the GA in most cases because it overcame the drawback of the building block theory of GA [12].

This paper is organized as follows. Section II, modelling AUV system is presented. Then in Section III &IV design and tuing of PID controller using HSA and GA is described respectively. Section V, shows the simulation results.Finally, Section VI, gives conclusions.

TABLE I
POSITION AND VELOCITIES OF AUV

Motion Direction	EARTH-FIXED FRAME (POSITION)	Body-Fixed Frame(velocity)
Surge	x	u
Sway	y	v
Heave	z	w
Roll	ϕ	p
Pitch	ϕ	q
Yaw	ψ	r

2. GENERALIZED MATHEMATICAL MODELLING OF AUV

A further goal is the consideration of coordinated control designs for multiple AUV applications. In that case, the particular limitations in underwater sensing and communication of the AUV team should be taken into consideration**.** Modelling of the proposed controller on a nonlinear six degrees of freedom (DOF), wherein only four DOF (x, y, z,p) are actuated and the rest of them are considered intrinsically stable.This paper discuses tuning of PID controller using genetic algorithm (GA).

A. Kinectic Equation of motion of AUV

A generic 6 degree of freedom modal suitable for AUV control application with respect two reference frames i.e. earth-fixed frame and body-fixed frame [11].The earth coordinate system of this model is defined by three orthogonal axes originating at an arbitrary point. North corresponds to x-axis, East corresponds to y-axis and increasing depth corresponds to z-axis. The velocity parameters of the AUV are determined from the body-fixed frame and using a transfer- mation matrix, the velocity in the earth-fixed frame is determined [13, 14].

$$v = [u \quad v \quad w \quad p \quad q \quad r]^T \tag{1}$$

$$\eta = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^T$$

(2)

The first step in developing an accurate simulation is modeling the dynamic equations of the AUV. The complete transformations between body-fixed and earth-fixed frames represent the kinematics equation of the AUV which is given as follows [15]:

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_1) & 0 \\ 0 & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{3}$$

Where,

$$\dot{\eta}_1 = [\dot{x} \quad \dot{y} \quad \dot{z}]^T$$

$$\dot{\eta}_2 = [\dot{\phi} \quad \dot{\theta} \quad \dot{\psi}]^T$$

It represents the AUV velocities in the earth-fixed frame.The corresponding body-fixed velocities of the AUV are η_1= [u, v, w] and η_2 = [p, q, r].Vehicle's path relative to the earth-fixed coordinate system is:

$$\dot{\eta}_1 = J_1(\eta_2)v_1$$

Where,

$J_1(\eta_2)$ is the transformation matrix as follows [16]:

$$J1(\eta 2) = \begin{bmatrix} c\psi c\theta & -s\psi c\theta + c\psi s\theta s\varphi & s\psi s\theta + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\theta + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix}$$

(4)

Where,

C refers as Cos and S refers as Sin.

The body-fixed Euler vector $\dot{\eta}_2$ and angular vector v_2 are related through transformation matrix as follows [16]:

$$\dot{\eta}_2 = J_2(\eta_2)v_1$$

Where,

$$J_2(\eta_2) = \begin{bmatrix} 1 & \sin\theta\tan\theta & \cos\theta\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \tag{5}$$

The simplified equation of motion in pure steering plane is written by assuming the origin of body fixed frame to coincide with center of gravity as [8]:

$$m(\dot{v} + mu_o r) = \sum Y \tag{6}$$

$$I_{zz}\dot{r} = \sum N \tag{7}$$

Surge speed as constant (u_o = 0.75m/s). For small roll and pitch angle have:

$$\psi = \frac{\sin\phi}{\cos\theta}q + \frac{\cos\phi}{\cos\theta}r \approx r \tag{8}$$

The above equations are expressed in a matrix form as:

$$\begin{bmatrix} m - Y_{\dot{v}} & -Y_{\dot{r}} & 0 \\ -N_{\dot{v}} & I_{zz} - N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} -Y_v & -Y_r + mv_0 & 0 \\ -N_v & -N_r & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} = \begin{bmatrix} Y_{\delta_r} \\ N_{\delta_r} \\ 0 \end{bmatrix} \delta_r \tag{9}$$

Using value of the dimensions, hydrodynamic coefficient and vehicle parameter of NPS AUV II for u_0 = 0.75m/s [18] :

$$\dot{x}(t) = Ax(t) + Bu(t)$$

(10)

Where,

$$A = \begin{bmatrix} -0.1114 & -0.2647 & 0 \\ 0.0225 & -0.2331 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$B = [0.0211 \quad -0.0258 \quad 0]^T$$

(13)

$$U = \delta_r$$

The transfer function between yaw (ψ) and rudder deflection (δ_r) is obtained as:

$$\frac{\psi(s)}{\delta_r(s)} = \frac{-0.0258s - 0.0024}{s^3 + 0.3445s + 0.0319s} \tag{11}$$

3. PID TUNING USING HARMONIC SEARCH ALGORITHM

Harmony search (HS) is a relatively new population-based music-inspired optimization algorithm (Geem et al., 2001) that imitates the music improvisation process and has been applied to various optimization problems includes sudoku, puzzle, logistic, robotics and medical. Music improvisation seeks to produce an ideal state as determined by aesthetic estimation. Similarly, algorithmic optimization seeks to produce an ideal state as determined by objective function evaluation.Recently, HS algorithm was also applied to astronomical data analysis, which was published in Nature (Deeg et al., 2010) [23].The harmony memory (HM) is a matrix of solutions with a size of HMS (Harmony Search size).In this step, the solutions are randomly constructed and rearranged in a reversed order to HM, based on their objective function values:

$$HS = \begin{bmatrix} a_1^1 & a^1{}_2 & . \; . \; . & a_N{}^1 \\ a^2{}_1 & a^2{}_2 & . \; . \; . & a_N^2 \\ . & . & . \; . \; . & . \\ . & . & . \; . \; . & . \\ . & . & . \; . \; . & . \\ a_1^{HMS} & a_2^{HMS} & . \; . \; . & a_N^{HMS} \end{bmatrix} \begin{bmatrix} F(a^1) \\ F(a^2) \\ . \\ . \\ . \\ F(a^{HMS}) \end{bmatrix} \qquad (12)$$

$$Fitnessvalue = \min(J)$$

HMCR (Harmony Memory Considering Rate) – The rate choosing a value from HM and varies from 0.7 to 0.99.

- PAR (Pitch Adjust Rate) – This rate choose from a neighbourhood value and varies from 0.1 to 0.5.
- HMS (Harmony Memory Size) – Size of the HM and varies from 1 to 100.

Pseduo Code for the HS algorithm [23]:

Begin
DefineFitnessFunction f (a) a= $(a_1, a_2, \ldots\ldots\ldots a_N)^T$
Define (HMCR), (PAR)

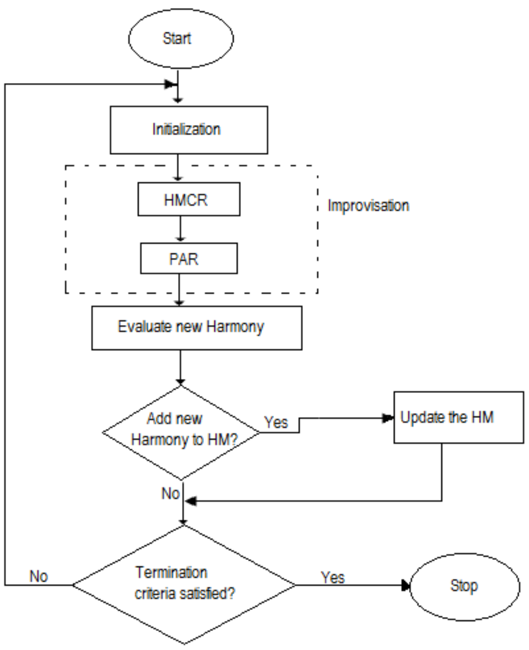

Fig2: Flow chart of Harmonic Search algorithm

Define maximum number of iteration (NI)
HM ← Generate Initial Population ()
Minimum=Minimum Visible Value
Maximum=Maximum Visible Value
While (iter ≤ N1) do
While ($a_i \leq$ number of variables) do
If (rand ∈ (0, 1) ≤ HMCR)Then
Choose a value from HM for i
If (rand ∈ (0, 1) ≤ PAR) Then
Adjust the value of i by;
$a_{inew} = a_{iold}$ + rand ∈ (0, 1) xbw
End if
Else
Choose a random variable
a_i=min+ rand ∈ (0, 1) x(max-min)
End if
End while
If
(FitFun (newharmonysolution)) ≤ worst (FitFun (HM))) Then
Accept the New Harmony and replace the worst in HM with it
End if
End while
Best=fine the current best solution
End

4. DESIGN AND TUNING OF PID CONTROLLER USING GA

In respect MATLAB /SIMULINK is a best tool used for it. PID controller is successfully implemented in control systems that provide sufficient stability margins and good time responses. Here PID controller is designed to study the behavior of AUV. This paper discuses tuning of PID controller using genetic algorithm (GA).The current population reproduces new individuals that are called the new generation. The new individuals of the new generation are supposed to have better performance than the individuals of the previous generation [19].

A. Fitness function

The fitness function is used to provide a measure of how individuals have performed in the problem domain [20].The most crucial step in applying GA is to use the fitness function that is used to evaluate fitness of each chromosome.The fitness not only indicates how good the solution is but also corresponds to how close the chromosome it to the optimal one.Here in this paper integral of square of error is used as a fitness function. It is given as:

$$J = \int_0^t e(t)^2 . dt \qquad (13)$$

Fitness approximation may be appropriate, especially in the following cases:

- Fitness computation time of a single solution is extremely high.
- Precise model for fitness computation is missing.
- The fitness function is uncertainity.
-

Table II HSA Specifications

HSA	VALUES
HMS	100
No.of Iiteration	1000
HMCR	0.95
PAR	0.3

B. Fitness value

The PID controller is designed to study the behavior of AUV and more rigorously in the term of error criteria to minimize the value of performance indices and because of the smaller the value of performance indice of the corresponding chromosome the fitter the chromosome will be vice-versa.The fitness of chromosome as:

Table IV
Cost Comparison for GA Tuned PIDFor YAW Control

Controller	ISE
PID [24]	4.8520
PID (GA)	2.0834
PID(HSA)	1.4458

TABLE III
GA SPECIFICATIONS

GA	VALUES
Generation	100
Population	1000
Mutation(gaussian)	1.0
Crossover(scattered)	0.8

$$Fitnessvalue = \min(J) \quad (14)$$

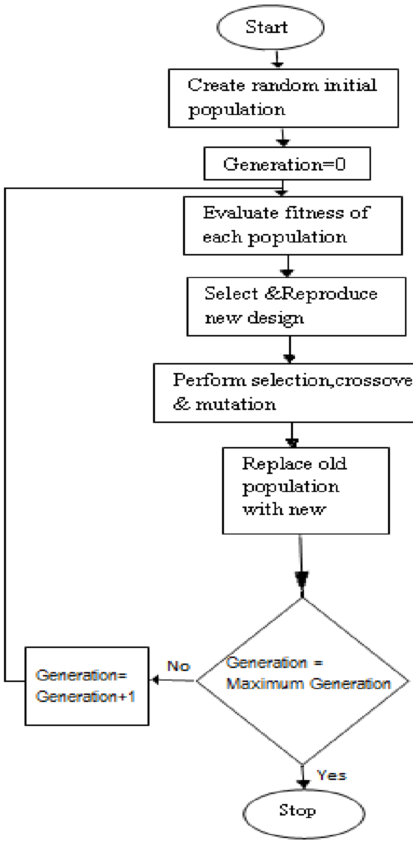

Fig3: Flow chart for tuning of PID for Yaw control

5. SIMULATION AND RESULTS

Evolution of the parameters for the PID controller using GA and PID controller using HSA is shown in fig. 5 and fig. 6 respectively. Figure (4) shows unit step response by resultant controller along with the results by [24]. The final values of PID parameters used for AUV control are given in table V.The Simulation result for AUV control using PID (GA) (fig.5) and PID (HSA) (fig.6) shows that AUV can be controlled in horizontal plane using optimization technique. The transient performance of PID using GA and HSA is given in tableVI. The cost comparison between the GA and HSA is given in tableIV. This paper addressed the path following control problem of an Autonomous Underwater Vehicle and also the formation control of multiple Autonomous Underwater Vehicles. Simulation shows that the control is able to provide reasonable depth and heading station keeping control. From the above simulation result it can be see that the AUV is tuning its desired path.

TABLE VI
PID, GA AND HSA TUNED PID Controller Transient Performance

Controller	% Overshoot	Settling Time
PID[24]	1.27 %	72.50 sec
PID(GA)	1.23 %	36.52 sec
PID(HSA)	1.4 %	29 sec

Table V

Evolved Parameter of PID/PD Controlle for YAW Control

Controller	k_p	k_i	k_d
PID[24]	-7.1678	-0.2916	-5.4321

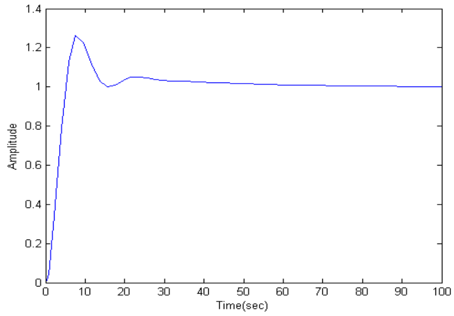

Fig4: Unit step responses by respective controllers

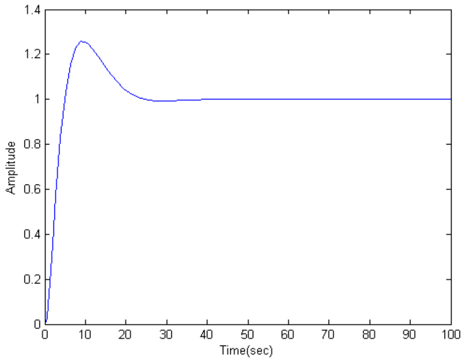

Fig5: Evolution of PID controller by GA

6. CONCLUSIONS

In this paper, a PID controller design method for the Autonoumous underwater vehicle system has been presented. PID controller parameters that guarantee stability of the system are computed by harmonic search algorithm and genetic algoritm. Numerically speaking our method performs better than the method of [24], it is observed that PID controller using GA gives more error than PID using HSA. Now from the simulation results, designed of the PID controller, which produces good results for the stability of AUV system. It is seen that the response of yaw for PID using HSA is better than PID using GA used proper tuning of PID using HSA.

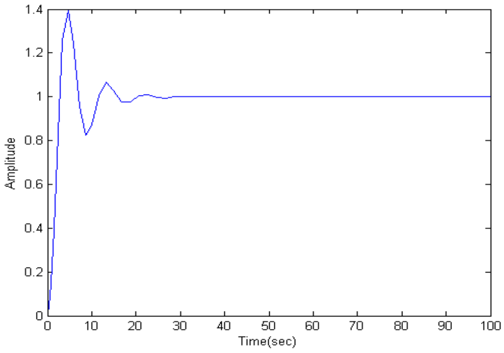

Fig6: Evolution of PID controller by HSA

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