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Research Article

Performance of an HSDBC Optimised Hybrid Fuzzy Logic Controller for a Path Tracking Unicycle Robot

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Abstract

In this paper, we discuss the performance of applying hybrid spiral dynamic bacterial chemotaxis (HSDBC) optimisation algorithm on an intelligent controller for a differential drive robot. A unicycle class of differential drive robot is utilised to serve as a basis application to evaluate the performance of the HSDBC algorithm. A hybrid fuzzy logic controller is developed and implemented for the unicycle robot to follow a predefined trajectory. Trajectories of various frictional profiles and levels were simulated to evaluate the performance of the robot at different operating conditions. Controller gains and scaling factors were optimised using HSDBC and the performance is evaluated in comparison to previously adopted optimisation algorithms. The HSDBC has proven its feasibility in achieving a faster convergence toward the optimal gains and resulted in a superior performance.

Keywords: *Hybrid controller, fuzzy logic controller, optimisation, unicycle robot, path tracking*

1. Introduction

Differential drive robots are commonly used as classical robot platforms to test various control strategies due to their instable and coupled nature. We inevitably need to model the differential drive robot and understand how it steers toward the desired trajectories in order to design a proper stabilizing controller. The differential drive wheeled mobile robot has two wheels. These wheels can turn at different rates so it maneuvers around turns and paths. In this study, the performance of the applying and optimized intelligent hybrid fuzzy logic control that is developed by Almeshal et al (2013a) is analysed. A unicycle model of the differential drive robot is used as a basis platform in our analysis.

There exist different types of controllers that were developed and adopted by various researches on controlling the differential drive robot. Carona *et al.* (2008) investigated the control of a unicycle type robots by two different controllers based on kinematic and dynamic model of the unicycle robot. The authors have proposed an inner loop nonlinear controller with a dynamic model controller on the outer loop. The robot was commanded to follow a predefined trajectory and was simulated with different movement scenarios such as motion stop scenario and circular trajectories. Simulations were presented and showing a successful control strategy over the unicycle robot.

Lee and Chiu (2013) have presented an intelligent control approach for a differential drive robot. A higher level navigation controller combined with a lower level fuzzy logic based controller were designed and implemented for the differential drive robot and allows it to stabilise over slopes and manoeuvre in terrains and mazes. The robot was implemented and tested experimentally and proved the feasibility of the controller in achieving the desired trajectories and paths.

An adaptive controller was developed by Martins *et al.* (2014) based on both the kinematic and dynamic model of a unicycle. The authors utilized a robust updating law to avoid the drifting of the robot and kept the control error in bounded region to overcome instability problems. The authors presented a successful control results both in simulation and experimentally using Pioneer 2-DX robot platforms.

Fuzzy logic control (FLC) strategy has been adopted by Castillo *et al.* (2012) and Martinez *et al.* (2009) to control a unicycle robot. The authors have utilised a FLC based on back stepping control to ensure a stable performance of the robot and to drive the unicycle robot toward the reference path with a superior performance.

In this paper, we discuss the performance of applying hybrid spiral dynamic bacterial chemotaxis (HSDBC) optimisation algorithm on an intelligent controller for a differential drive robot. Simulations showing the performance of the optimised controller

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are presented and analysed showing the superior performance of the optimisation algorithm.

2. The unicycle robot model

The dynamics of the unicycle type of the differential drive robot are represented as follow:

$$\dot{x} = v \cos\emptyset \quad (1)$$
$$\dot{y} = v \sin\emptyset \quad (2)$$

$$\dot{\emptyset} = \omega \quad (3)$$

Where:
v is the speed.
ω is the angular velocity.
x y represent the position in the horizontal and vertical axes.
$\emptyset$ is the heading angle (yaw angle) of the robot.

The inputs to system are v and ω. With the model described, the control inputs can be designed, such that the robot converge to the desired input signals, by adjusting the control inputs of the linear and angular velocities. The robot linear velocity relates to the right and left wheel velocities such that:

$$v = \frac{R}{2}\,(v_r + v_l) \quad (4)$$

Similarly, the robot angular velocity is expressed as:

$$\omega = \frac{R}{l}\,(v_r - v_l) \quad (5)$$

Solving equations (4) and (5) for v_r and v_l, we get the following left and right wheels linear velocities as:

$$v_r = \frac{2v+\omega L}{2R} \quad (6)$$
$$v_l = \frac{2v-\omega L}{2R} \quad (7)$$

Where L is the distance between the two wheels and R is the radius of the wheels.

3. Hybrid fuzzy logic control strategy

The hybrid FLC controller was developed by Almeshal *et al*. (2013a) and has been proven to be efficient in controlling highly nonlinear and coupled robotic vehicle as presented by Almeshal *et al*. (2013a, 2013b, 2012a, 2012b) and Agouri *et al*. (2013). The advantage of using the hybrid FLC is that it is a model free controller that can be applied to systems with variables that are continuously changing with time. Moreover, it can be widely used in robotic vehicles with properly tuned scaling factors and gains. The hybrid FLC will be used to control the unicycle robot with proper fuzzy rules tuning and adjustments of the controller gains.
The system consists of two control loops with two hybrid FLC controllers. Each hybrid FLC controller is composed a proportional-derivative plus integral controller followed by a fuzzy controller that work together to fine tune the control signal and thus driving the robot to the desired reference path. The hybrid FLC is presented in Figure 1.

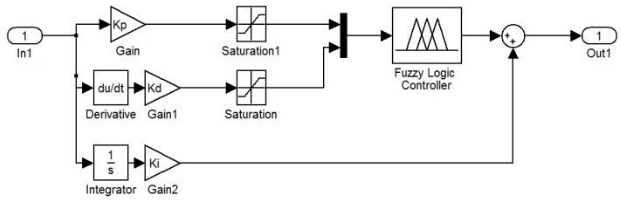

Fig.1 Hybrid fuzzy logic controller block diagram

The fuzzy inference engine will be selected as a Mamdani-type with Gaussian membership functions that would result in smoother output values. The inputs for the hybrid FLC are the error signal, change of error and the sum of previous errors. The fuzzy membership functions are presented in Figure 2.

The linguistic variables describing the inputs and outputs were chosen as Positive Big (PB), Positive Small (PS), Zero (Z), Negative Big (NB) and Negative Small (NS) with 25 fuzzy rule base described in Table1.

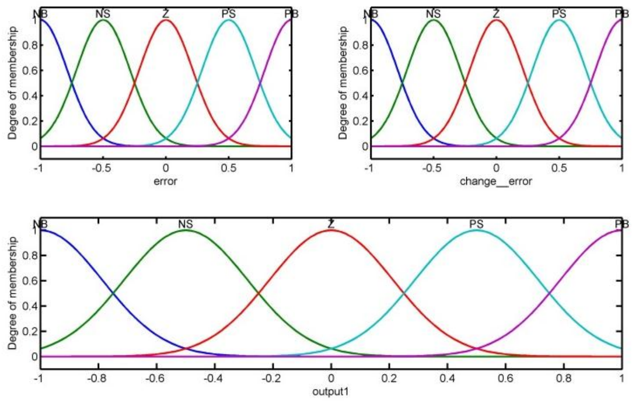

Fig. 2 fuzzy membership functions of the hybrid FLC

Table 1 Fuzzy rules base

e \ e'	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

In the next section, a hybrid spiral dynamics bacterial chemotaxis optimisation will be integrated into the control system to find the optimal controller gains of the hybrid FLC that would minimise the overall system errors.

4. Hybrid spiral dynamic bacteria chemotaxis optimisation algorithm

The Hybrid Spiral Dynamics Bacterial Chemotaxis algorithm (HSDBC) for global optimisation was developed by Nasir *et al* (2012). The HSDBC algorithm is hybridization between the Spiral Dynamics Algorithm (SDA) developed by Tamura *et al* (2011) and the Bacterial Foraging Algorithm (BFA) algorithm developed by Passino *et al* (2002). The BFA algorithm has faster convergence speed to feasible solutions in the defined search space but has some oscillations toward the end of the search operation. The SDA algorithm has a faster computation time and a better accuracy than the BFA algorithm. Furthermore, the SDA algorithm has better stability, due to the spiral steps, when searching toward the optimum point. The HSDBC algorithm combines the strengths of BFA and SDA into a faster, stable and accurate global optimisation algorithm. This is achieved by incorporating the BFA chemotaxis part into the SDA and thus reducing the computational time and retaining the strength and performance of the SDA.

Table 2 HSDBC algorithm nomenclature

Parameter	Description
θ_{tumble}	Bacteria angular displacement on $x_i - x_j$ plane around the origin for tumbling.
θ_{swim}	Bacteria angular displacement on $x_i - x_j$ plane around the origin for swimming.
r_{tumble}	Spiral radius from bacteria tumble.
r_{swim}	Spiral radius for bacteria swim.
m	Number of search points.
k_{max}	Maximum iteration number.
N_{sw}	Maximum number of swim.
$x_i(k)$	Bacteria position.
R^n	n x n matrix.

The HSDBC optimisation pseudo code is as follows:

Step 0: **Preparation**
Select the number of search points (bacteria) $m \geq 2$, parameters $0 \leq \theta_{tumble}, \theta_{swim} < 2\pi, 0 < r_{tumble}, r_{swim} < 1$ of $S_n(r,\theta)$, maximum iteration number, k_{max} and maximum number of swim, N_s for bacteria chemotaxis. Set $k = 0,\ s = 0$.

Step 1: Initialization
Set initial points $x_i(0) \in R^n, i = 1,2,...m$ in the feasible region at random and center x^* as $x^* = x_{i_g}(0)$,
$i_g = \arg\min_i f(x_i(0)), i = 1,2,\ldots,m$.

Step 2: Applying bacteria chemotaxis
i. Bacteria tumble
(a)Update x_i

$$x_i(k+1) = S_n(r_{tumble}, \theta_{tumble}) x_i(k) - (S_n(r_{tumble}, \theta_{swim}) - I_n) x^*$$
$$i = 1,2,\ldots,m.$$

ii. Bacteria swim
(a) Check number swim for bacteria i.
If $s < N_s$, then check fitness,
Otherwise set $i = i + 1$, and return to step (i).
(b) Check fitness
1. If $f(x_i(k+1)) < f(x_i(k))$, then update x_i,
Otherwise set $s = N_s$, and return to step (i).
(c) Update x_i

$$x_i(k+1) = S_n(r_{swim}, \theta_{swim}) x_i(k) - (S_n(r_{swim}, \theta_{swim}) - I_n) x^*$$
$$i = 1,2,\ldots,m.$$

Step 3: Updating x^*
$x^* = x_{i_g}(k+1)$,
$i_g = \arg\min_i f(x_i(k+1)), i = 1,2,\ldots,m$.

Step 4: Checking termination criterion
If $k = k_{max}$ then terminate. Otherwise set $k = k+1$, and return to step 2.

The objective functions are expressed in terms of the minimum mean square error of the linear and angular velocities respectively as:

$$v_{MSE} = \min[\frac{1}{N}\sum_{i=1}^{N}(v_d - v_m)^2] \tag{8}$$

$$w_{MSE} = \min[\frac{1}{N}\sum_{i=1}^{N}(w_d - w_m)^2] \tag{9}$$

Thus, the overall cost function of the system can be expressed as:

$$J = \min(v_{MSE} + w_{MSE}) \tag{10}$$

The HSDBC optimisation algorithm will be integrated into the system simulation files to optimise the overall mean square error of the system for both the linear and angular velocities of the robot. The HSDBC parameters were selected as described in Table 3.

Table 3 HSDBC simulation parameters

P	R	Rzw	Ns
2	0.95	0.55	2
Theta	Initial points	Iterations	
π / 4	20	100	

5. Simulation results

The robot was simulated to follow an eight-shaped trajectory to evaluate its performance over complex and smooth turns. The simulation was conducted using MATLAB/Simulink environment and the model was solved differentially using Runge-Kutta method. The HSDBC algorithm was integrated and simulated with 100 iterations and has successfully achieved the minimum cost function value of 0.3682 within 18 iterations approximately. Figure 4 illustrates the convergence plot of the cost function.

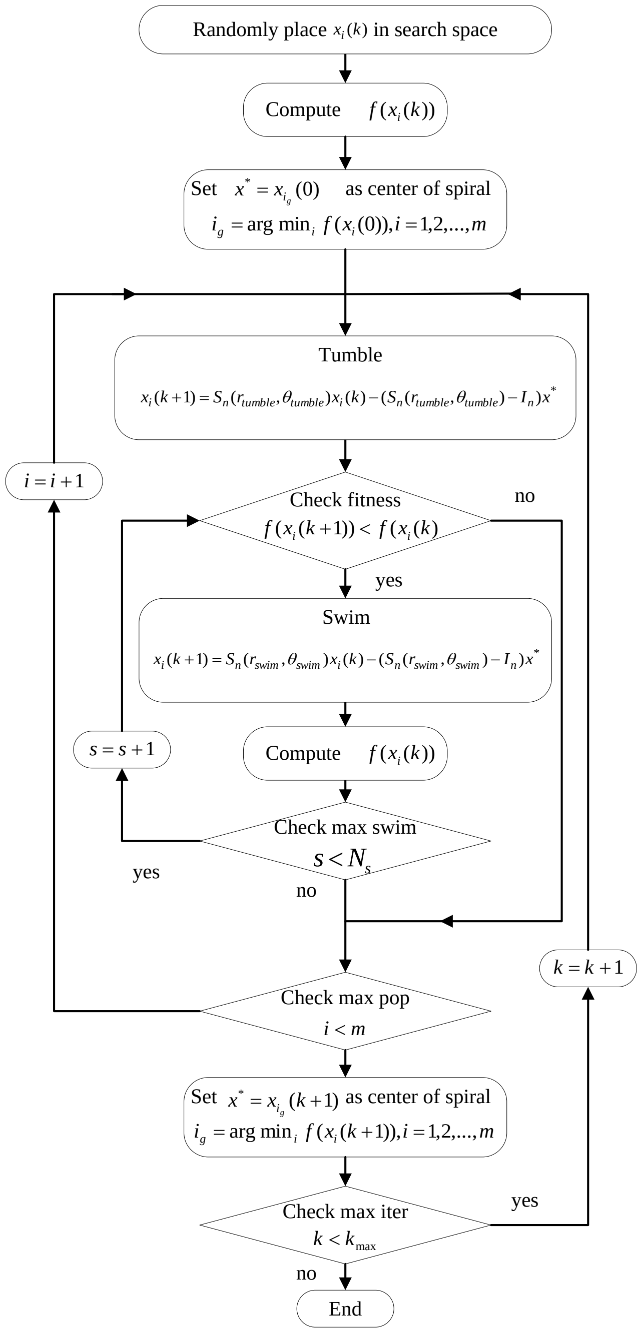

Fig. 3 Flowchart of the hybrid spiral-dynamics bacteria-chemotaxis algorithm (HSDBC) (Nasir,2012)

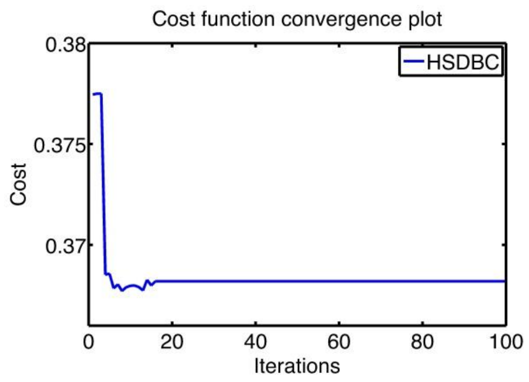

Fig. 4 Cost convergence plot

Figure 5 presents the trajectory of the robot with heuristically tuned gains of the FLC controller. It can be seen that the robot has followed the desired path but with some oscillations that are noticeable on the path. These oscillations can be explained due to the heuristically tuned gains and more specifically the derivative gain of the hybrid FLC controller. Proper tuning of the FLC gains would certainly enhance the robot performance.

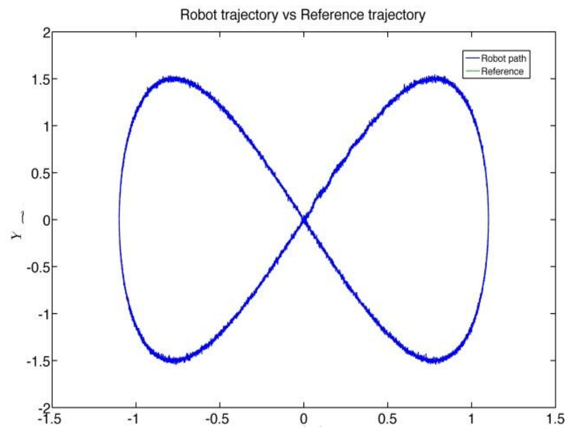

Fig. 5 The robot trajectory versus the reference trajectory with heuristically tunes gains of the FLC

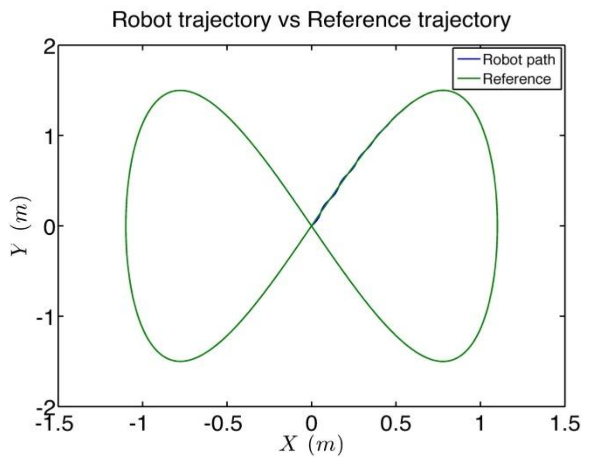

Fig. 6 Reference trajectory vs. actual robot trajectory

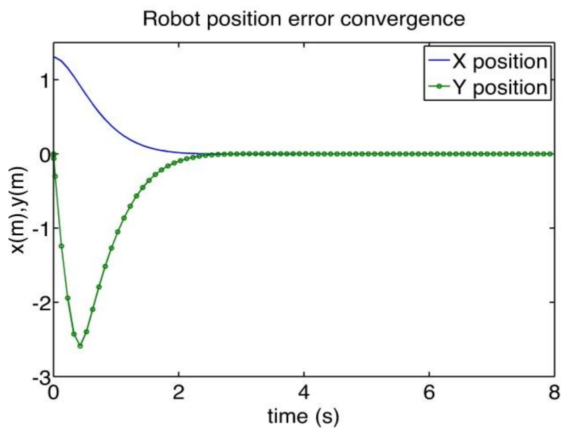

Fig. 7 the robot coordinates error convergence plot

Figure 6 presents the robot actual trajectory on an eight shaped reference path with the optimised hybrid FLC controller. It can be noted that the controller has been able to drive the robot over the reference path with a high degree of accuracy as it can be noted from the error convergence of the linear and angular velocities in Figure 7. The robot started the movement with slight oscillations and has been able to achieve a high accuracy in following the desired trajectory within 2 seconds.

Conclusions

This paper presented the application of HSDBC optimisation algorithm to find the optimal performance of a hybrid FLC controller that is implemented in a unicycle robot system. The hybrid FLC performance highly depends on the proper tuning of its gains and scaling factors. The HSDBC algorithm has been proven to successfully optimise the controller within 18 iterations. The robot system was simulated and the performance of the optimised robot system was shown to be smooth and of a high degree of accuracy in following the desired trajectory. With these promising results, a future work to study the robustness of the optimised controller in counteracting uncertainties and frictions will be carried out.

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