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# Optimization Control System using the Quantum Behaved Particle Swarm Optimization on Vehicle Steering Control System with Steer-by-Wire System

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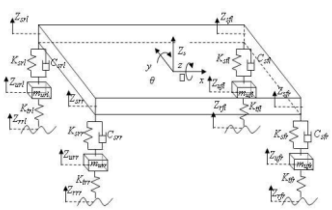

**Abstract**

Fuzzy Logic includes a technique are widely applied to the vehicle steering control system, however, to get the parameters required by a reliable Fuzzy Logic Control (FLC), needed training and learning process. Quantum behaved Particle Swarm Optimization (QPSO) is a simple optimization method that guarantees the achievement of global convergence quickly. This paper aimed to optimize of the steering control system on vehicle with steer-by-wire system using QPSO. The vehicle steering control system consists of Fuzzy Logic Control (FLC) and the Proportional, Integral and Derivative (PID) control are built in cascade, in which FLC is used to minimize the lateral motion error and PID control is used to suppress yaw motion error of the vehicle. The parameters of the control system are optimized by QPSO consists of three parameters to determine the position of the centre and the width of the triangle membership function of FLC and three constant gain of PID control. The optimization is done through the software in the loop simulation of vehicle models represented by 10 Degree of Freedom (DOF) of the vehicle dynamics. Simulation results showed that optimization using QPSO on the parameters of the control system can guarantee the movement of the vehicle is constantly maintained at the desired trajectory with a smaller error and higher vehicle speeds compared to the control system without tuned. The results obtained will be used as the basis for testing of the hardware in the loop simulation (HILS) so it can further improve the performance of steer-by-wire system.

*Keywords;* Steering, fuzzy logic, quantum behaved particle swarm optimization,



## NOMENCLATURE

| | |
|---|---|
| $Z_s$ | sprung mass displacement at body centre of gravity |
| $\dot{Z}_s$ | sprung mass velocity at body centre of gravity |
| $\ddot{Z}_s$ | sprung mass acceleration at body centre of gravity |
| $\dot{Z}_{u,ij}$ | unsprung masses displacement |
| $\ddot{Z}_{u,ij}$ | unsprung masses velocity |
| $Z_{r,ij}$ | unsprung masses acceleration |
| $Z_{r,ij}$ | road profiles at each tyres |
| $K_{s,ij}$ | suspension spring stiffness each tyres |
| $C_{s,ij}$ | suspension damping each tyres |
| $I_{xx}$ | roll axis moment of inertia |
| $I_{yy}$ | pitch axis moment of inertia |
| $w$ | wheel base of sprung mass |
| $F_{ij}$ | suspension force each corner |
| $m_s$ | sprung mass weight |
| $m_t$ | total vehicle mass |
| $M_{zij}$ | self-aligning moments |
| $F_{pij}$ | pneumatic actuator forces at each corner |
| $F_{xij}$ | tire forces in longitudinal direction |
| $F_{yij}$ | tire forces in lateral direction |
| $i$ | indicating front or rear |
| $j$ | indicating left or right |
| $J_z$ | moment of inertia around the z-axis |
| $d$ | steering angle |
| $a$ | distance between front of vehicle and centre of gravity. |
| $b$ | distance between rear of vehicle and centre of gravity. |
| $\theta$ | pitch angle at body centre of gravity |
| $\dot{\theta}$ | pitch rate at body centre of gravity |
| $\ddot{\theta}$ | roll acceleration at body centre of gravity |
| $\varphi$ | roll angle at body centre of gravity |
| $\dot{\varphi}$ | roll rate at body centre of gravity |
| $\ddot{\varphi}$ | roll acceleration at body centre of gravity |

## 1.0 INTRODUCTION

As a part of the development of electric car technology, performance Steer by Wire system is expected to contribute to the increase in dynamic performance of the vehicle [1]. One effort to optimize the performance of the control system on the vehicle steering system is the use of Artificial Intelligence and optimization methods. Fuzzy Logic Control (FLC) is a control system that is reliable and widely applied to control steering vehicle [2,3,4], however, to obtain the values of the optimal parameters are required by an FLC is not an easy job. Weakness of tuning fuzzy parameters by on-line is the structure of the control system becomes more complex and requires a large memory so that will possibly make the process of control and convergence becomes slower [5]. Therefore the necessary process of training and learning strategy for tuning the parameters of FLC are faster. Soft computing technologies offer the combination as well as integration of more than one technique of Artificial Intelligence that aims to tune the parameters of fuzzy automatically.

The development of the control system on the Automatic Vehicle Steering Control uses FLC which is optimized using Genetic Algorithm (GA) more superior than the PD control, because Fuzzy Genetic is a nonlinear controller which is very suitable for nonlinear system [4]. The GA optimization methods require many stages in the process of computation, the method further simplified using Particle Swarm Optimization (PSO). The PSO is a kind of simple optimization method, has the ability to achieve quickest convergence, and produce high-quality solutions. The PSO-fuzzy design algorithm can move the robot (small vehicle) based on the specified behaviour and was able to coordinate in accordance with the conditions encountered effectively [2]. However, small-scale vehicles not yet represent actual vehicle dynamics, so it can be used full vehicle model [3], and one of the disadvantages contained in the regular PSO is tend to achieve convergence on local optima too fast. Therefore, it is cannot guarantee on global convergence. To solve this problem, the Quantum behaved Particle Swarm Optimization (QPSO) is used because it can guarantee the global convergence. QPSO is one of the methods of optimization based on quantum mechanics that integrates between the quantum computing and PSO in order to ensure the achievement of global convergence [6].

In this paper, optimal control system was developed on a vehicle steering system using FLC is tuned by QPSO and applied to the vehicle models with 10 Degree Of Freedom (DOF) [7,8]. The strategy of the developed control system consists of two stages in cascade control, namely lateral motion control to eliminate the unwanted lateral movement and the next control, namely yaw motion control as a complement control system on steering input. The control system structure is built using FLC as the main controller to control lateral motion and Proportional-Integral-Derivative controller (PID) as a further controller to control yaw motion. To obtain the parameters of the optimal control system for both FLC and PID control systems, the QPSO optimization method is used. The control system parameters that are optimized are as many as six parameters consisting of three parameters on FLC and three parameters of PID control. The FLC parameters are needed to determine the centre and the width of the Membership Function on two inputs and one output of the FLC. Whereas the PID control parameters are needed to determine the gain constants on the Proportional, Integral and Derivative control. The purpose of the optimal control system strategy in this paper is expected to significantly reduce unwanted dynamic disturbances on vehicles through testing of Software-In-the-Loop Simulations (SILS) so that it can improve the dynamic performance of the vehicle.

## 2.0 MATERIALS AND METHODS

### 2.1 Vehicle Dynamics Model

Based on the concept of vehicle dynamics, vehicle model has two major functions in controlling the movement of vehicles, i.e. control lateral and longitudinal [9]. In this paper, the model is constructed mainly focuses on lateral control for active steering control simulation using a model with a 10-DOF vehicle consisting of a 7-DOF ride models and 3-DOF handling model. The vehicle ride model represented in 7-DOF are expressed in seven mathematical equations (Equations 1-7), consisting of seven force equation of freedom of movements of the vehicle body (sprung mass single), namely: vertical movement (heaving), pitching, rolling and vertical movements of each wheel (four unsprung masses) [7, 8]. Suspensions between the sprung mass and unsprung masses are modelled as passive viscous dampers and spring elements.

The heaving of the car body ($Z_s$) is represented as

$$\begin{aligned} m_s\ddot{Z}_s = &-2(K_{s,f}+K_{s,r})Z_s - 2(C_{s,f}+C_{s,r})\dot{Z}_s \\ &+2(aK_{s,f}-bC_{s,r})\theta + 2(aC_{s,f}-bC_{s,r})\dot{\theta} \\ &+K_{sf}Z_{u,fl} + C_{s,f}\dot{Z}_{u,fl} + K_{sf}Z_{u,fr} \\ &+C_{s,f}\dot{Z}_{u,fr}K_{sr}Z_{u,rl} + C_{s,r}\dot{Z}_{u,rl} + K_{sr}Z_{u,rr} \\ &+C_{s,r}\dot{Z}_{u,rr} + F_{pfl} + F_{pfr} + F_{prl} + F_{prr} \end{aligned} \quad (1)$$

Where the Pitching of the car body ($\theta$) is as follows:

$$\begin{aligned} I_{yy}\ddot{\theta} = &\,2(aK_{s,f}-bK_{s,r})Z_s + 2(aC_{s,f}+bC_{s,r})\dot{Z}_s \\ &-2(a^2K_{s,f}-b^2K_{s,r})\theta - 2(a^2C_{s,f}-b^2C_{s,r})\dot{\theta} \\ &-aK_{sf}Z_{u,fl} - aC_{s,f}\dot{Z}_{u,fl} - aK_{sf}Z_{u,fr} - aC_{s,f}\dot{Z}_{u,fr} \\ &+bK_{sr}Z_{u,rl} + bC_{s,r}\dot{Z}_{u,rl} + bK_{sr}Z_{u,rr} + bC_{s,r}\dot{Z}_{u,fr} \\ &-(F_{pfl}+F_{pfr})l_f + (F_{prl}+F_{prr})l_r \end{aligned} \quad (2)$$

Rolling of the car body ($\varphi$) is expressed as

$$\begin{aligned} I_{xx}\ddot{\varphi} = &-0.5w^2(K_{s,f}+K_{s,r})\varphi - 0.5w^2(C_{s,f}+C_{s,r})\dot{\varphi} \\ &+0.5wK_{s,f}Z_{u,fl} + 0.5wC_{s,f}\dot{Z}_{u,fl} - 0.5wK_{s,f}Z_{u,fr} \\ &-0.5wC_{s,f}\dot{Z}_{u,fr} + 0.5wK_{s,r}Z_{u,rl} + 0.5wC_{s,r}\dot{Z}_{u,rl} \\ &-0.5wK_{s,r}Z_{u,rr} - 0.5wC_{s,r}\dot{Z}_{u,rr} + (F_{pfl}+F_{prl})\frac{w}{2} \\ &-(F_{pfr}+F_{prr})\frac{w}{2} \end{aligned} \quad (3)$$

Vertical Direction for each wheel is

$$\begin{aligned} m_u\ddot{Z}_{u,fl} = &\,K_{s,f}Z_s + C_{s,f}\dot{Z}_s - aK_{s,f}\theta - aC_{s,f}\dot{\theta} + 0.5wK_{s,f}\varphi \\ &+0.5wC_{s,f}\dot{\varphi} - (K_{s,f}+K_t)Z_{u,fl} - C_{s,f}\dot{Z}_{u,fl} \\ &+K_tZ_{r,fl} - F_{pfl} \end{aligned} \quad (4)$$

$$\begin{aligned} m_u\ddot{Z}_{u,fr} = &\,K_{s,f}Z_s + C_{s,f}\dot{Z}_s - aK_{s,f}\theta - aC_{s,f}\dot{\theta} - 0.5wK_{s,f}\varphi \\ &-0.5wC_{s,f}\dot{\varphi} - (K_{s,f}+K_t)Z_{u,fr} - C_{s,f}\dot{Z}_{u,fr} \\ &+K_tZ_{r,fr} - F_{pfr} \end{aligned} \quad (5)$$

$$\begin{aligned} m_u\ddot{Z}_{u,rl} = &\,K_{s,r}Z_s + C_{s,r}\dot{Z}_s + bK_{s,r}\theta + bC_{s,r}\dot{\theta} + 0.5wK_{s,r}\varphi \\ &+0.5wC_{s,r}\dot{\varphi} - (K_{s,r}+K_t)Z_{u,rl} - C_{s,r}\dot{Z}_{u,rl} \\ &+K_tZ_{r,rl} - F_{prl} \end{aligned} \quad (6)$$

$$\begin{aligned} m_u\ddot{Z}_{u,rr} = &\,K_{s,r}Z_s + C_{s,r}\dot{Z}_s + bK_{s,r}\theta + bC_{s,r}\dot{\theta} - 0.5wK_{s,r}\varphi \\ &-0.5wC_{s,r}\dot{\varphi} - (K_{s,r}+K_t)Z_{u,rr} - C_{s,r}\dot{Z}_{u,rr} \\ &+K_tZ_{r,rr} - F_{prr} \end{aligned} \quad (7)$$

While the tire is modeled as a simple linear spring without damping as shown in Fig.1.

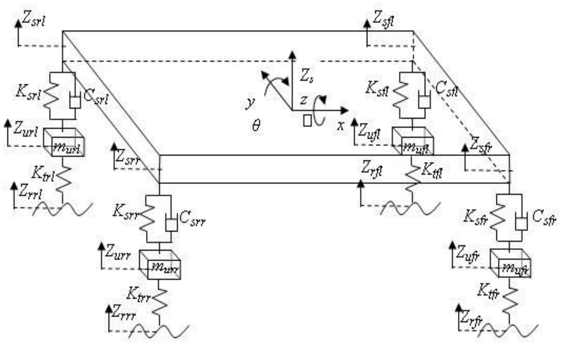

**Figure 1** Vehicle Ride Models

Vehicle handling models represented as a 3-DOF system which means having three mathematical equations consisting of three equations of force movements of the car body laterally, longitudinally and yaw motion [9,10], as shown in Fig. 2. Lateral motion and longitudinal motion are the movement of vehicles along the x-axis and y-axis are expressed in lateral acceleration ($a_y$) and longitudinal acceleration ($a_x$). Thus, the lateral motion and longitudinal motion can be obtained by double integration of lateral and longitudinal acceleration.

Lateral and longitudinal acceleration are expressed as follows:

$$a_y = \begin{pmatrix} F_{yfl}cos\delta - F_{xfl}sin\delta + F_{yfr}cos\delta \\ -F_{xfr}sin\delta + F_{yrl} + F_{yrr} \end{pmatrix} \Big/ m_t \tag{8}$$

$$a_x = \begin{pmatrix} F_{xfl}cos\delta - F_{yfl}sin\delta + F_{xfr}cos\delta \\ -F_{yfr}sin\delta + F_{xrl} + F_{xrr} \end{pmatrix} \Big/ m_t \tag{9}$$

An angular movement of the vehicle, which is based on the vertical axis is called a yaw motion ($r$) [11], which can be obtained by the integration of $\dot{r}$ and $\ddot{r}$

$$\begin{aligned} \ddot{r} = \frac{1}{J_z}\Big[&\frac{w}{2}F_{xfl}cos\delta - \frac{w}{2}F_{xfr}cos\delta + \frac{w}{2}F_{xrl} - \frac{w}{2}F_{xrr} \\ &+ \frac{w}{2}F_{yfl}sin\delta - \frac{w}{2}F_{yfr}sin\delta - l_r F_{yrl} \\ &- l_r F_{yrr} + l_f F_{yfl}cos\delta + l_f F_{yfr}cos\delta - l_f F_{xfl}sin\delta \\ &- l_f F_{xfr}sin\delta + M_{zfl} + M_{zfr} + M_{zrl} + M_{zrr}\Big] \end{aligned} \tag{10}$$

Based on equations 1-10, the models of vehicle steering systems were built using MATLAB-SIMULINK software applications. The design of the vehicle models with 10 - DOF focuses on vehicle front wheel alignment as the plant output and the plant input in the form of variety of steer angle ($\delta$) of the steering wheel (equations 8,9,10). Plant output is expressed in yaw rate (equation 10) and slip angle, where the slip angle is a characteristic of the relationship between the lateral motion (equation 8) and longitudinal motion (equation 9).

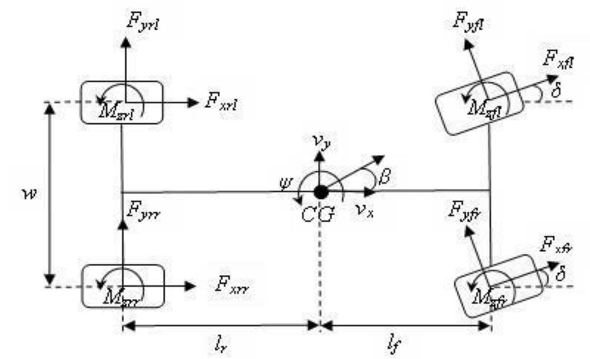

**Figure 2** Vehicle Handling Model

## 2.2 Control Systems and Optimization Strategy

Steering control system (active steer) of vehicle that was built in this paper uses two controllers in cascade [12]. The main controller is the FLC and the second is a PID controller [13], where the setting is done on the vehicle front wheel alignment as plant output of vehicle models to fit the reference input of the plant, the lookup table *x* - *y* trajectory in the form of a double line change.

Plant output is expressed in yaw, lateral and longitudinal motion, so that the function of both the above controls system are;

- FLC is used to suppress the error between the lateral motion (*y*) associated with longitudinal motion (*x*) of the desired trajectory
- PID control is used accelerating rise time, minimizes errors and reduces the overshot / undershot the yaw motion of the setting point which is the output of FLC.

An ideal condition on FLC output means that, vehicle no longer has a lateral motion (y), so that the FLC output is used as the setting point on yaw motion control. To get the optimal control is highly dependent on the composition of the design parameters of the control system [14]. In this paper, the determination of parameter values both on FLC as well as PID control is done by tuning the parameter values until the optimal value is achieved by using QPSO. Block diagram of the control structure that is used in active steering control simulation is shown in Fig. 3.

### *2.2.1 Fuzzy Logic Controller (FLC)*

FLC is the main control that is used to minimize the lateral motion error between the input and output of the plant. The main structure of the FLC, among others, fuzzyfication, crisp variable (converting error value, delta error and control output into fuzzy variables), a set of fuzzy rules consist of several fuzzy rules are grouped into rule base.

Membership Function (MF) is a function to express the degree of membership fuzzy. MF forms that is used in this paper is a triangular shape (Triangular Function), every MF at the control input (error and error delta) as well as the control output consists of seven MF. Thus, the required number of rule base is 49 rules as shown in Table 1. Each MF has language terms, respectively, Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB).

**Table 1** Rule base set

| Delta Error | Error | | | | | | |
|---|---|---|---|---|---|---|---|
| | NB | NM | NS | Z | PS | PM | PB |
| NB | NB | NB | NB | NB | NM | NS | Z |
| NM | NB | NB | NB | NM | NS | Z | PS |
| NS | NB | NB | NM | NS | Z | PS | PM |
| Z | NB | NM | NS | Z | PS | PM | PB |
| PS | NM | NS | Z | PS | PM | PB | PB |
| PM | NS | Z | PS | PM | PB | PB | PB |
| PB | Z | PS | PM | PB | PB | PB | PB |

FLC used has the ability to be tuned simultaneously on the input and output parameters of the FLC. This is due to the triangular shape of each MF is designed such that it can be changed based on the width and position of the middle point of the triangle depends on the multiplier variable. Then, the factors of change are called the multiplier factor function ($\Delta_i$). This is means all parameters of each MF are a function of $\Delta$. Therefore, when the $\Delta$ value changes, the parameters of each MF will change include changes in the position of the midpoint of the triangle ($C_n$) and the width of the triangle ($W_n$) of MF.

Value of $\Delta_i$ consists of $\Delta_{ER}$, $\Delta_{DE}$, and $\Delta_{OT}$; $\Delta_{ER}$ as a multiplying factor for the MF error input; $\Delta_{DE}$ as a multiplying factor for the MF delta error input, and $\Delta_{OT}$ as a multiplying factor for the MF on the FLC output.

Determination of the width and the position of midpoint on each MF are described in Fig. 4 and are expressed as the following equation:

Changes in the midpoints of the triangle of MF are:

$$C_n = C_{n-1} \times \Delta \tag{11}$$

Changes in the width of the triangle of MF are:

$$W_n = WR_n - WL_n \tag{12}$$

$$WR_n = WR_{n-1} \times \Delta \tag{13}$$

$$WL_n = WL_{n-1} \times \Delta \tag{14}$$

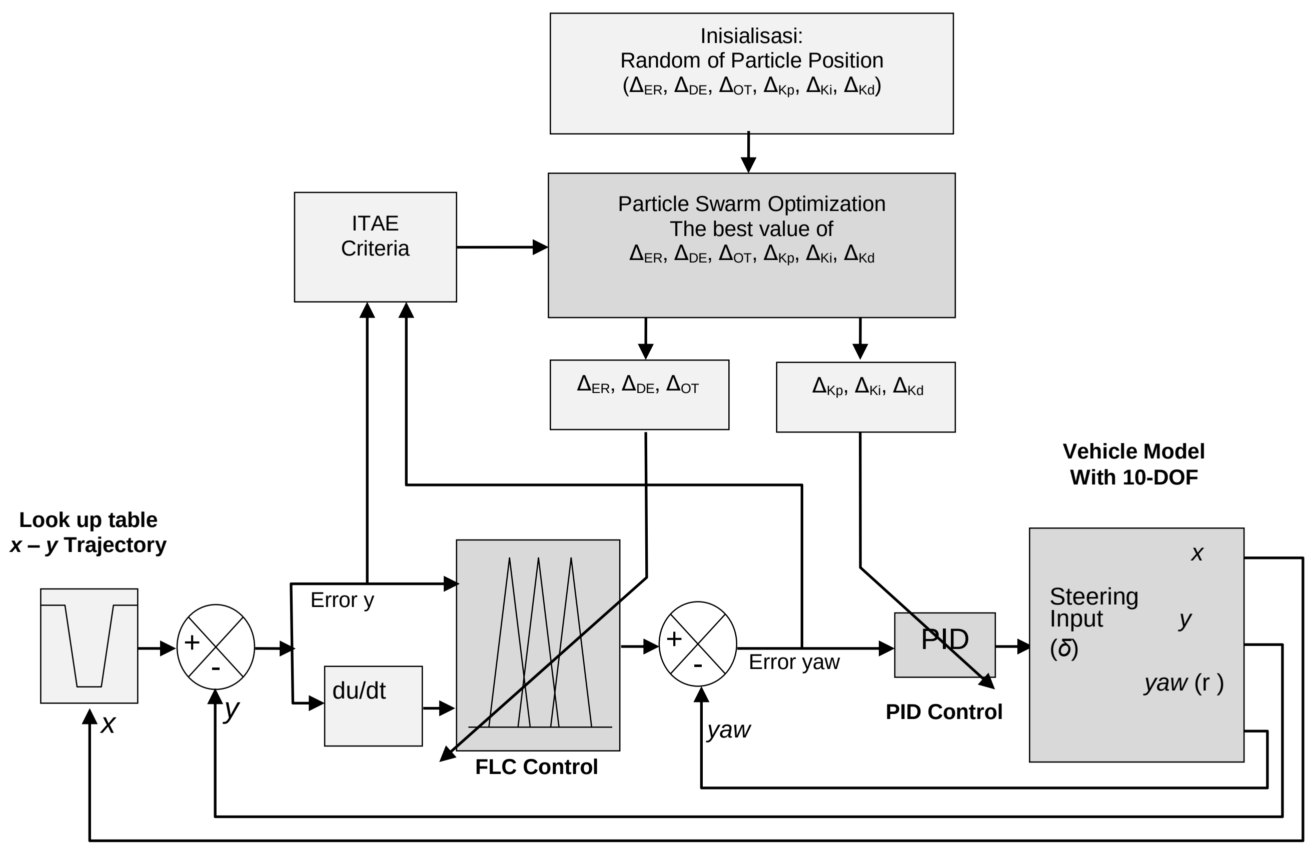


**Figure 3** The Control and Optimization Structure for active steering control on vehicle model

Actually, the value of the multiplier factor $\Delta_{ER}$, $\Delta_{DE}$, and $\Delta_{OT}$ can be determined by using the trial and error method, but in this paper the value of the multiplier factor is obtained through a learning process repeated until the optimal values obtained by using QPSO. Furthermore, the final process of the FLC is the changing variable fuzzy to crisp variable and this step is called as the defuzzification process. In this process, the centroid defuzzyfication method has been used.

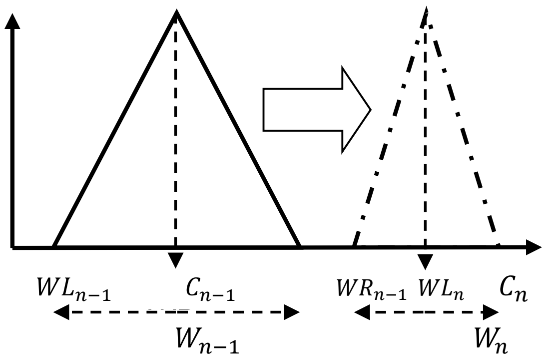


**Figure 4** Parameters of Membership Function

### 2.2.2 Proportional Integral Derivative (PID) Controller

FLC output is used as the setting point on yaw motion because ideally after elimination of error on lateral motion. It gives the sense that the vehicle has been moved without any lateral force. In other words, the yaw motion is equal to zero. PID control is used as a second control to eliminate the error between the set point of the yaw motion. Proportional control (P) is used to speed up the system response rate (rise time), Integral Control (I) is used to minimize or eliminate the steady-state error of the system and Derivative Control (D) is used to reduce the overshoot / undershoot [15]. Performance Control P, I, and D are highly dependent on the determination of the constant Kp, Ki and Kd. In this paper, PID control is used where the value of constants Kp, Ki and Kd are determined by means of learning on control system or tuning parameters Kp, Ki and Kd up to achieve the optimal composition of constants using QPSO.

### 2.2.3 Quantum Behaved Particle Swarm Optimization (QPSO)

Over time, there was a significant development of the methods of optimization on Particle Swarm Optimization (PSO). One of the methods is the development of an innovation method that provides the function of the position of the scattered particles in PSO method. QPSO is integration between quantum computing and PSO. On classical mechanics, particles are described by the position and velocity vectors, which determine the particle trajectory. In Newtonian mechanics, the particle moves along a specified path, but this is not the case in quantum mechanics [6]. In the quantum world, the term trajectory becomes meaningless, because the position and velocity of the particle cannot be simultaneously determined in accordance with the uncertainty principle [16]. One disadvantage of PSO is unable to guarantee the global convergence, to overcome this problem, it can be used QPSO. By using the Monte Carlo method, the function of the change position (position update) of each particle in QPSO is written in Equations 15 -19 as follows [6].

$$X_{id}(t+1) = p_{id}(t) + \beta(t) * \left(mbest_d(t) - X_{id}(t)\right) * ln\left(\frac{1}{u}\right) \quad \text{if} \quad k \geq 0.5 \tag{15}$$

$$X_{id}(t+1) = p_{id}(t) - \beta(t) * \left(mbest_d(t) - X_{id}(t)\right) * ln\left(\frac{1}{u}\right) \quad \text{if} \quad k < 0.5 \tag{16}$$

$$p_{id}(t) = \varphi_d(t) * pbest_{id}(t) + \left(1 - \varphi_d(t)\right) * gbest_d(t) \tag{17}$$

$$\varphi_d(t) = \frac{c_1 * r_{1d}(t)}{(c_1 * r_{1d}(t)) + (c_2 * r_{2d}(t))} \tag{18}$$

$$mbest_d(t) = \frac{1}{N}\sum_{i=1}^{N} pbest_{id}(t) \tag{19}$$

With,
$t$ = Iteration
$X_{id}(t)$ = Position of particle *i* in dimension *d* at iteration *t*
$X_{id}(t+1)$ = Position of particle *i* in dimension *d* at iteration *t*+1
$p_{id}(t)$ = *Local attractor* of particle *i*, in dim. *d*, at iteration *t*
$c_1$ = Constant of acceleration 1 (constant of cognitive)
$c_2$ = Constant of acceleration 2 (constant of cognitive)
$r_{1d}(t)$ = Uniformly distributed random number 1
$r_{2d}(t)$ = Uniformly distributed random number 2
$N$ = Number of particles
$pbest_{id}(t)$ = Local best position, particle *i*, dim. *d*, iteration *t*
$(t)$ = Global best position particle, dim *d*, iteration *t*
$(t)$ = The mean value of the local best position, at *d & t*

Other parameters are known in the QPSO algorithm is contraction-expansion coefficient, to regulate the speed of convergence of the particle and to end the QPSO algorithm with local search better. The function of the contraction - expansion coefficient ($\beta$) is written in equation 20 [6].

$$\beta(t) = \beta_{max} - \left(\frac{\beta_{max} - \beta_{min}}{iter_{max}}\right) * iter(t) \tag{20}$$

With,
$\beta(t)$ = contraction–expansion coefficient
$\beta_{max}$ = The max value of contraction-expansion coefficient
$\beta_{min}$ = The min value of contraction-expansion coefficient
$iter_{max}$ = Maximum iteration
$(t)$ = Iteration

## 3.0 RESULTS AND DISCUSSION

Simulation of the optimal control system of lateral and yaw motion of a vehicle steering system, preceded by optimizing the parameters of FLC and PID control systems using QPSO. In this paper, QPSO optimize the six variables which consist of three variables to determine the MF on FLC parameters, namely; $\Delta_{ER}$ for input errors; $\Delta_{DE}$ delta error for input and output $\Delta_{OT}$ for FLC and 3 variables to determine the PID control parameters, namely; constants Kp, Ki and Kd.
The parameters used on QPSO;
Number of Particle = 30,
Maximum iteration = 30,
Contraction–expansion coefficient $\beta(t)$ = 0.3 - 1,

Optimization results of PSO can achieve convergence at iteration 5, while the results of QPSO optimization converged at iteration 3 as shown in Figure 5. The optimization performed using the PSO and QPSO were done repeatedly until 30 iterations on both the control systems on the model of the vehicle steering system with plant input x - y trajectory, double lane change trajectory as shown in Figure 6. This shows that in the control system learning was done with random parameters, so in the end parameter values which optimal and the lateral motion of the smallest error could be obtained. Size of the error used in the optimization process is the Integral of Time-weighted Absolute Error (ITAE) [17], while the size of error which was used in the simulation was the Continues Root Mean Square Error (C-RMS error) as shown in Table 2.

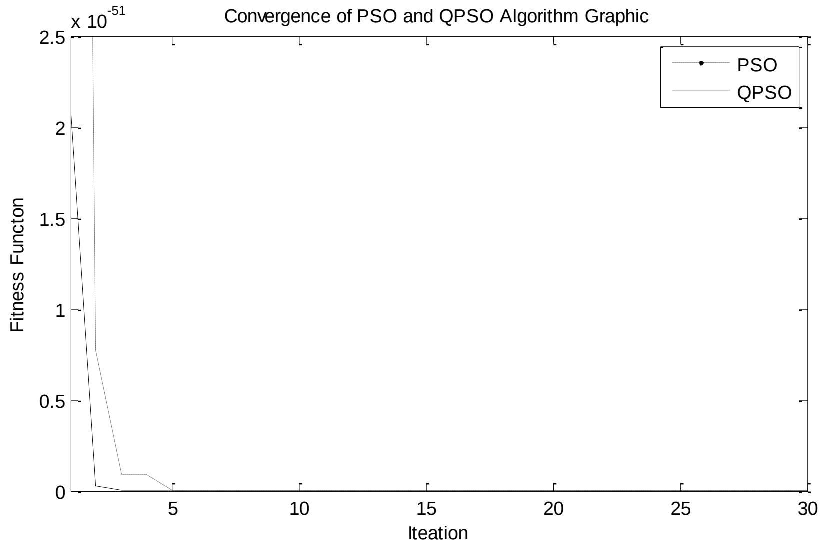


**Figure 5** Convergence of PSO and QPSO

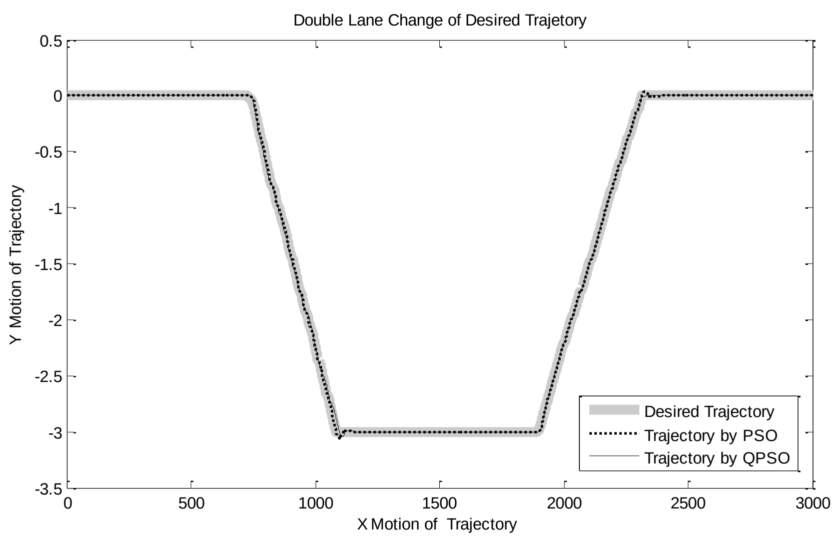


**Figure 6** Double Lane Change Trajectory

**Table 2** Optimization results of PSO and QPSO (Speed=13. 88m/s)

| | Convergence | Error | | Optimal Parameters | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ITAE | C-RMS | $\Delta_{ER}$ | $\Delta_{DE}$ | $\Delta_{OT}$ | Kp | Ki | Kd |
| PSO | 5 | 1,346757e-54 | 0.005689 | 0.2923 | 1.3776 | 3.7602 | 84.6357 | 1.0095 | 0.1923 |
| QPSO | 3 | 2.965141e-45 | 0.005298 | 0.2714 | 1.3710 | 3.7602 | 84.5333 | 2.3613 | 0.2174 |

Value of $\Delta_{ER}$, $\Delta_{DE}$, and $\Delta_{OT}$ which has been obtained is a multiplier factor to determine the width of the triangle and the midpoint position of each triangle MF where the initial value before the optimizations is one, and the value of Kp, Ki and Kd are constant value for proportional, integral and derivative control.

In the end, six parameter values have been obtained from the optimization process are the optimal parameter values used as parameters for the optimal control system simulation process. Simulation of the optimal control system on the vehicle steering system uses QPSO (FL-PID tuned by QPSO) is also compared to the optimal control system using PSO (FL-PID tuned by PSO) and a control system without optimization (called PID-PID and FL-PID) such as shown in Table 3. Figure 7 shows the response during the vehicle manoeuvre and Figure 8 shows the characteristics of the optimal control system.

The results of the optimal control system simulation of the vehicle steering system will be a recommendation for further testing using hardware in the loop simulations (HILS).

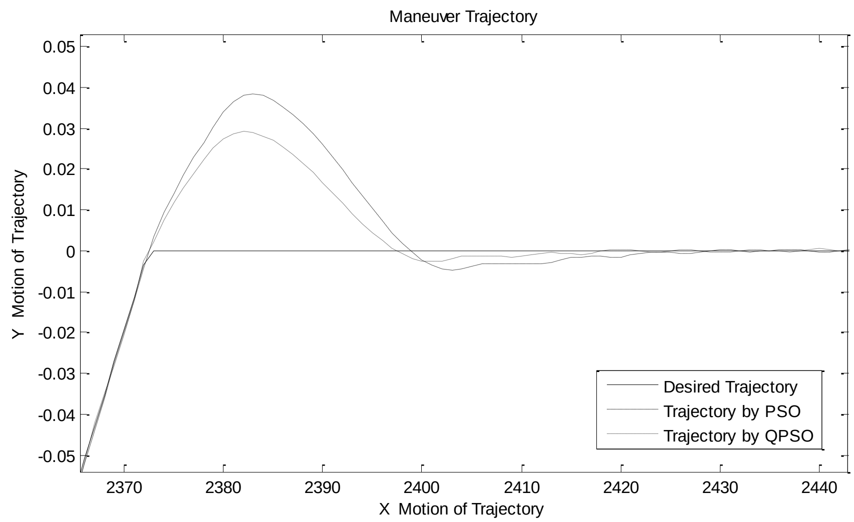


**Figure 7** Response of the vehicle manoeuver

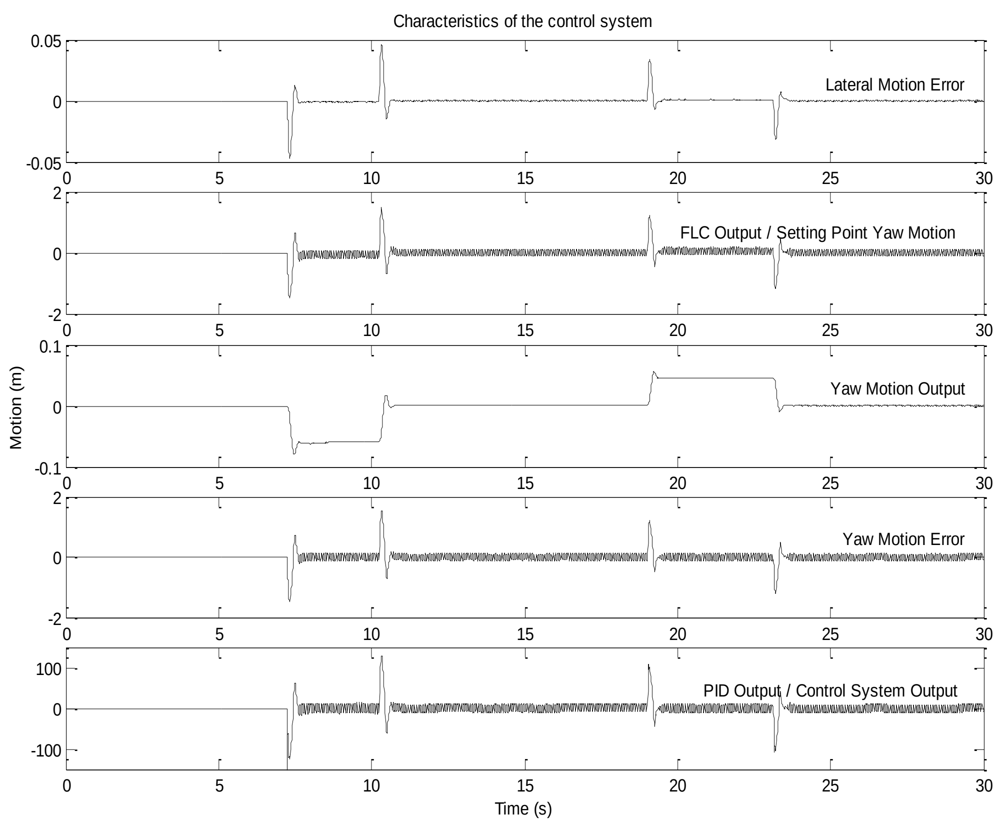


**Figure 8** Characteristics of the optimal control system

**Table 3** Benchmark of optimal control system

| No | Velocity | | C-RMS Error Double Lane Change | | | |
|---|---|---|---|---|---|---|
| | Km/h | m/s | PID – PID | FL – PID | FL – PID tuned by PSO | FL – PID tuned by QPSO |
| 1 | 10 | 2.77 | 0.30970 | 0.104200 | 0.043310 | 0.05595 |
| 2 | 20 | 5.55 | 0.64640 | 0.033450 | 0.023370 | 0.01993 |
| 3 | 30 | 8.33 | 0.02211 | 0.017260 | 0.011490 | 0.01081 |
| 4 | 40 | 11.11 | 0.01743 | 0.011800 | 0.007558 | 0.007006 |
| 5 | 50 | 13.89 | 0.01096 | 0.009131 | 0.005625 | 0.005298 |
| 6 | 60 | 16.67 | 0.01008 | 0.008129 | 0.004647 | 0.004623 |
| 7 | 70 | 19.45 | time out | 0.007949 | 0.004864 | 0.004762 |
| 8 | 80 | 22.22 | time out | 0.010050 | 0.005111 | 0.004755 |
| 9 | 90 | 24.99 | time out | time out | 0.006101 | 0.006085 |
| 10 | 100 | 27.77 | time out | time out | time out | time out |
| 11 | 110 | 30.55 | time out | time out | time out | time out |

## ■4.0 CONCLUSION

The simulation results obtained show that the used of Fuzzy Logic Control (FLC) system (on the lateral motion) and PID control system (on the yaw motion) which were tuned with QPSO (FL-PID tuned by QPSO), can maintain the movement of the vehicle in accordance to the desired trajectory with low error and good performance at the higher speed compared to the steering system controlled by the Fuzzy Logic and PID controls which were tuned with PSO.


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