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Semi-automatic of steer by wire system using fuzzy logic control and swarm optimization

Fachrudin Hunaini[1], Dicky Dikananda Nafis[1], Purbo Suwandono[2], Gatot Subiyakto[2]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Widyagama Malang, Malang, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Widyagama Malang, Malang, Indonesia

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ABSTRACT

The semi-automatic steer by wire system is a vehicle steering system that does not use a mechanical link but uses an electric drive, so that the steer wheel is equipped with an angle sensor as a control system input to adjust the electric drive rotation when determining the direction of the front wheels of the vehicle. The control system uses fuzzy logic control (FLC) is optimized using swarm-based optimization. Performance testing of the optimal control system is carried out using Software in the loop simulations and hardware in the loop simulations which were then applied to the steering system prototype equipped with rack-pinion and wheel steer. The test results show that the optimal control system performance reaches a C-RMS error of 6.712. The prototype that was built has two kinds of ratios between the steering angle and the vehicle wheel angle, namely a ratio of 1:6.25 for speeds below 10 km/h making it suitable for operation when the vehicle is maneuvering in the parking area and a ratio of 1:25 for speeds above 10 km/h which is suitable for operation when the vehicle is traveling at medium or high speed.

Corresponding Author:

Fachrudin Hunaini
Department of Electrical Engineering, Faculty of Engineering, Universitas Widyagama Malang
Borobudur Road 35, Mojolangu, Lowokwaru, Malang, East Java 65142, Indonesia
Email: fachrudin_h@widyagama.ac.id

1. INTRODUCTION

The development of vehicle steering system technology using electric propulsion known as steer by wire (SbW) is divided into two types, namely fully automatic and semi-automatic of SbW systems [1]–[3]. Fully-automatic SbW is an SbW system that does not use a steer wheel to determine the direction of the wheel but uses programmatic trajectory [4], [5] global positioning system (GPS) technology [6], [7] or using line tracer [8], [9]. While the semi-automatic SbW is an SbW system that uses a steer wheel and is equipped with an angle sensor as a control system input to determine the direction of the front wheels of the vehicle [10], [11]. The advantage of using semi-automatic from SbW is that the ratio between the angle of the steer wheel to the angle of the front wheel of the vehicle can be set variably as a function of speed and technically the position or place of the steer wheel is very flexible can be changed in its placement.

In the development of SbW, the improvement of the safety system actively and to anticipate nonlinear behavior, a control system is needed with the goal is to produce fast control actions with small errors. Control systems based on artificial intelligence techniques provide discourse and inspiration to be applied because they can do work as well as those done by humans. Fuzzy logic control (FLC) is a reliable control system method for controlling nonlinear systems [12]–[14] but FLC performance can be improved to optimal by using optimization methods to optimize the value of FLC input and output parameters so that these parameters are not obtained by trial and error.

The development of behavior-based optimization methods introduces a simpler and faster optimization method to achieve convergence, namely the particle swarm optimization (PSO) method [15], [16], by simulating the social behavior of living things, such as a flock of fish or birds, that move according to a specific goal. In an effort to better ensure the achievement of global optimal, the PSO algorithm provides an innovation to the positional function of the particles dispersed in the PSO method based on quantum mechanics which is hereinafter called quantum behaved particle swarm optimization (QPSO) [17], [18]. The QPSO method further undergoes modifications to the local attractor parameter so that it better guarantees more accurate global convergence and this method is called modified-quantum particle swarm optimization (MQPSO) [19], [20].

In this paper, an optimal control system based on Artificial Intelligence was developed which was applied to the semi-automatic SbW system model. The control system strategy developed is to use the fuzzy logic controller as a control of the direction of movement of the front wheels of the vehicle which is optimized using Swarm based optimization method so that the determination of the membership function parameter is not carried out by trial and error. Testing was carried out through software in the loop simulations (SILS) to obtain an optimal control system then in real time was tested hardware in the loop simulations (HILS) using a prototype steer by wire rig consisting of: inner loop control in the form of an actuator as a rack-pinion steer drive and a rotary encoder as a wheel angle position sensor; and a steer wheel that is in the axis of a rotary encoder as the input for the steer by wire rig.

The advantage of HILS testing using the steer by wire rig prototype is it more economical, does not require a real vehicle, does not risk accidents even though it is done repeatedly and the data obtained is real [21], [22]. Optimal control system at the steer by wire rig prototype that was built is included in the semi-automatic category because it still uses the steer wheel as a control system input to determine the direction of the front wheels of the vehicle with the ratio between the steering angle to the vehicle wheel angle can be adjusted depending on the speed of the vehicle so that it is useful to control the steer wheel actively, improves the stability of vehicle dynamics and maneuvers, and can be applied as steering control to help the driver to have better perceptive ability to control the vehicle and respond more quickly with subtle compensation measures. This present paper consists of the following sections: i) The introduction and the review of some of the research that has been done; ii) Research method consisting of: transfer function modeling, control system strategy, and optimization methode; iii) Results and discussion consisting of test results: software in the loop simulation, hardware in the loop simulation, and steer by wire rig testing; and iv) Conclusion.

2. RESEARCH METHOD

2.1. Transfer function modeling

In the planning process of the control system, it is necessary to know the characteristics of the plant to be controlled. In this paper, the plant used is a stepper motor which is in axis with a rotary encoder. Plant characteristics are expressed in the form of a transfer function obtained through the plant identification process using MATLAB [19]. By taking input and output variable data from the stepper motors used in this research, then estimation of the transfer function modeling using the toolbox identification system on MATLAB in the form of 3-pole and 3-zero polynomials, the transfer function of the stepper motor is obtained as in the (1) with a fit to estimation (FTE) value of 97.84%.

$$F(s) = \frac{2.206\,s+133.4}{s^2+17.77\,s+132.8} \qquad (1)$$

2.2. Control system

The control system design on FLC is a process of designing membership function (MF) parameters to manifest the degree of fuzzy membership into a variable [23]. These parameters are used to determine the variable of the shape of each MF expressed as a multiplier factor $\{XE$ FLC:MF$\}$ (Δ_{ER}, Δ_{DE} and Δ_{OT}). The MF form used is a combination of triangular and trapezoidal functions and there are three MFs used, namely two control inputs (error (ER) and delta error (DE)) and one control output (OT). Each MF has its own designation, namely: negative (N), zero (Z), positive (P) [10] and use rule base IF ER AND DE IS OT. The FLC system is designed as shown in Figure 1 which connects two control inputs on the rule base with one control output.

2.3. Optimization

Optimization is a process that is needed to get the control system parameters to be optimal. The optimization method used is swarm-based [24], namely PSO, QPSO and MQPSO. The optimization process is carried out by determining the initial random particle population and then evaluating it in the vehicle control system model. The particle population is referred to as a swarm, which expresses the three MF parameters of the FLC to be optimized namely Δ_{ER}, Δ_{DE} and Δ_{OT}, and then the particle population is evaluated on the vehicle control system model. The evaluation results are then updated and repeated to be compared with the previous evaluation up to the maximum iteration. During the repetition process, there will be a change in error until the error change value becomes constant, which means that the error selection process has reached convergence, in other words, the MF parameter has reached an optimal value and FLC can work optimally. This optimization process is carried out successively using the PSO, QPSO and MQPSO algorithms. PSO algorithm: velocity (v_i) and position vector (x_i) [25], as shown in (2) and (3).

$$v_i(t+1) = wv_t(t) + c_1r_1\big(pbest_t - x_t(t)\big) + c_2r_2\big(pbest_t - x_t(t)\big) \tag{2}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{3}$$

QPSO algorithm: position vector (x_i) and local-attractor (p_i) [26], as shown in (4) and (5).

$$x_i(t+1) = p_i \pm \alpha|mbest - x_i(\mathrm{t})| * \ln\left(1/_u\right) \; u \approx U(0,1) \tag{4}$$

$$p_i = \beta \times pbest_i + (1-\beta) \times gbest_i \tag{5}$$

MQPSO algorithm: position vector (x_i) and local-attractor (p_i) [27], as shown in (6).

$$x_i(t+1) = p_i \pm \alpha|gbest - x_i(\mathrm{t})| * \ln\left(1/_u\right) \; u \approx U(0,1) \tag{6}$$

For PSOs; determined "social constant" (c1) and "cognitive constant" (c2) = 2 and the value of “inertia weight” is 0.4 to 0.9 [25]. For QPSO and MQPSO; the value of contraction–expansion coefficient (β) is determined between 0.4 to 1.0 [26], [27]. Optimization parameters; number of particles = 30, maximum iteration = 30 iterations; the optimized variable is Δ i = (Δ ER; Δ DE, ΔOT).

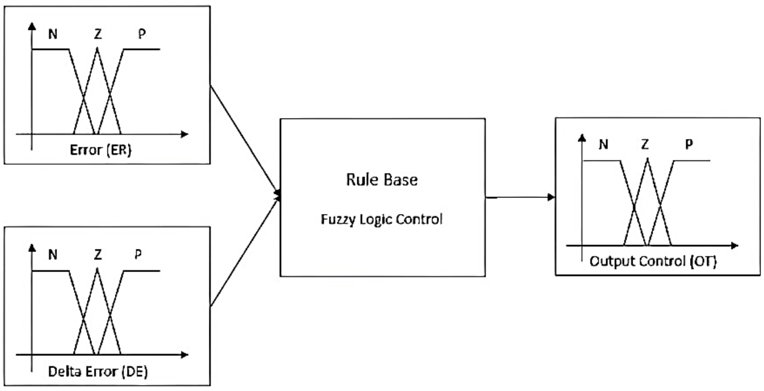

Figure 1. Fuzzy logic control system

3. RESULTS AND DISCUSSION

3.1. Software in the loop simulation (SILS)

The SILS test is a simulation to obtain FLC performance on the transfer function of a stepper motor using MATLAB/Simulink which is expressed in the C-RMS error, as shown in the picture of the outer loop control in Figure 2. The FLC is first optimized using a swarm-based optimization method, namely PSO which is compared with QPSO and MQPSO in order to obtain an optimal control system called FLC-Swarm Based. The control system model in the transfer function of the stepper motor developed hereinafter is referred to as outer loop control intended for software testing (SILS). The results of the SILS test of the optimal control system FLC-swarm based obtained convergence value, the best fitness, three optimal values of FLC parameters and C-RMS error as shown in Table 1, while the optimal control system response is as in Figure 3. The results of the SILS test showed that MQPSO achieved convergence (7th iteration) slower than PSO (2nd iteration) and QPSO (3rd iteration) but MQPSO had the smallest fitness of 4.1320 so that the optimal control system performance error expressed in C-RMS error was also the smallest at 0.06018. Therefore, the optimal control system simulation result used in HILS is FLC-MQPSO.

Table 1. Optimization results

Method Optimization	Convergent	Fitness	Parameter (Δ)			C – RMS error
			ER	DE	OT	
PSO	2	4.5572	1.4527	1.9352	1.6025	0.06636
QPSO	3	5.1585	1.1932	1.0956	1.4455	0.06823
MQPSO	7	4.1320	6.2617	3.1444	4.6833	0.06018

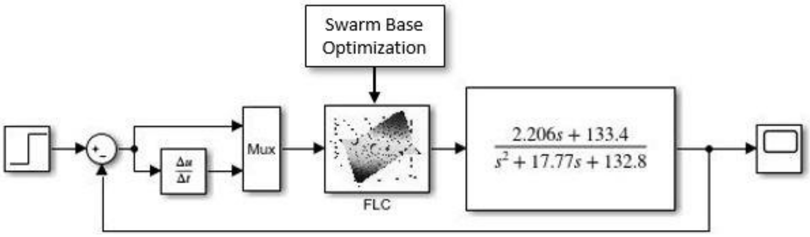

Figure 2. Outer loop control

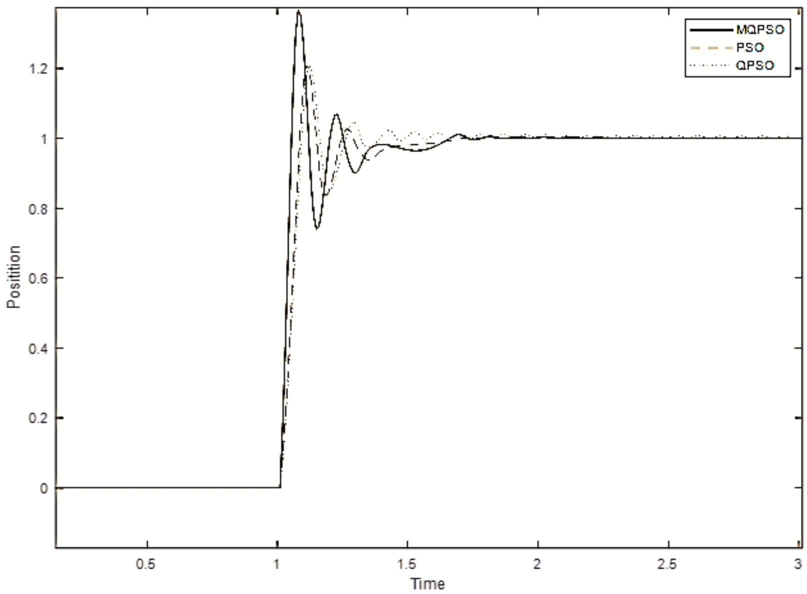

Figure 3. Optimal control system response FLC-swarm optimization

3.2. Hardware in the loop simulation (HILS)

HILS testing is a verification of SILS testing by involving hardware in the simulation. HILS testing is carried out by replacing transfer function with inner loop control in the form of hardware consisting of: stepper motor as actuator to be controlled and rotary encoder as angle sensor of stepper motor which is the output of the control system, as shown in Figure 4. The optimal control system FLC-MQPSO will detect errors between the position of the stepper motor's angle of movement against the reference in the form of double lane change and further provide control action by moving the stepper motor according to the desired position.

The HILS test results in Table 2, show that the angular movement of the stepper motor can be maintained according to the set point with a C-RMS error value of 6.712 greater than the SILS test results, as shown in the Table 2. The results of these tests indicate that there is an increase in error when implementing the optimal control system on hardware due to the characteristics of the stepper motor, namely the maximum operating time reaches 60 ms and the maximum release time reaches 15 ms, and the response characteristics are shown in Figure 5.

Table 2. SILS and HILS C-RMS error test result

No	Testing	C-RMS Error
1	SILS (MQPSO)	0.06018
2	HILS	6.71200
	Δ	6.76418

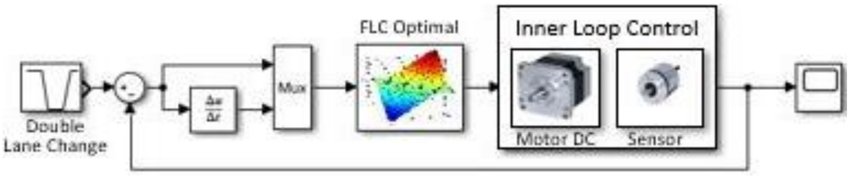

Figure 4. Inner loop control

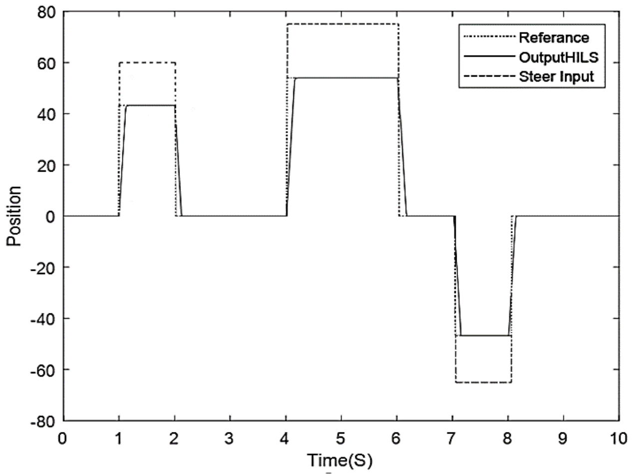

Figure 5. Comparison of reference input with hardware test output

3.3. Steer by wire rig testing

In the HILS testing is a test to determine the performance of the actuator in the form of a stepper motor controlled by FLC-MQPSO that can move according to the required reference. The HILS test results were subsequently applied to the semi-automatic steer by wire rig prototype which is built as shown in Figure 6 as the block diagram of the semi-automatic steer by wire rig and Figure 7 is the prototype of semi-automatic steer by wire rig. The optimal control system FLC-MQPSO on the semi-automatic SbW model are designed to have in the ratio changes between the steer and the front wheels which depends on the speed of the vehicle, namely at speeds below 10 km/h and above 10 km/h as shown in Table 3.

Based on test data that the maximum radius of the front wheel angle of the vehicle is 20° which corresponds to the rotation radius of the stepper motor of 90° by using a link between the stepper motor and the front wheels of the vehicle, a rack-pinion mechanical device is used so that the ratio between the front wheels of the vehicle to the stepper motor is 1:4.5. The stepper motor movement step according to the stepper motor data sheet used by the autonics AK21-M596 W brand is 0.72° then one pulse of data is needed to drive the stepper motor per step by 0.72°. The maximum angle of the steer input required to drive the front wheels of the vehicle by a maximum of 20° is 90°×0.72° equal to 125°, thus the ratio between the maximum radius of the front wheels of the vehicle to the maximum radius of the input angle of the steer is 1:6.25 which gives the meaning that every 1° movement of the front wheels of the vehicle is equal to 6.25° the input angle of the steer. The ratio of 1:6.25 is very suitable for maneuvering vehicles at low speeds, which are below 10 km/h so that if the vehicle has to maneuver in the parking area, there is no need to turn the steering wheel for more than one turn, just a little larger than a quarter of the rotation then the front wheels have reached the maximum angle as shown in Figure 8. Meanwhile, when the vehicle has to drive at medium or high speeds, a larger ratio is needed to obtain a smoother and more stable maneuver movement, therefore at speeds above 10 km/h the ratio is increased by making each step of the stepper motor movement reduced to 25%, 0.72°/4 equals 0.18°. The maximum angle of input steer required to drive the front wheels of the vehicle by a maximum of 20° is 90°×0.18° equal to 500°. Thus, the ratio between the maximum radius of the front wheels of the vehicle to the maximum radius of the input angle of the steer is 1:25 which gives the meaning that every 1° movement of the front wheels of the vehicle is equal to 25° of the input angles of the steer as shown in Figure 9. then each step of stepper motor movement is 0.18° which corresponds to one pulse of data to drive each step of the stepper motor. The ratio of 1:25 is more suitable for maneuvering vehicles at medium and high speeds, namely above 10 km/h so that a smoother and more stable movement of vehicle maneuvers is obtained.

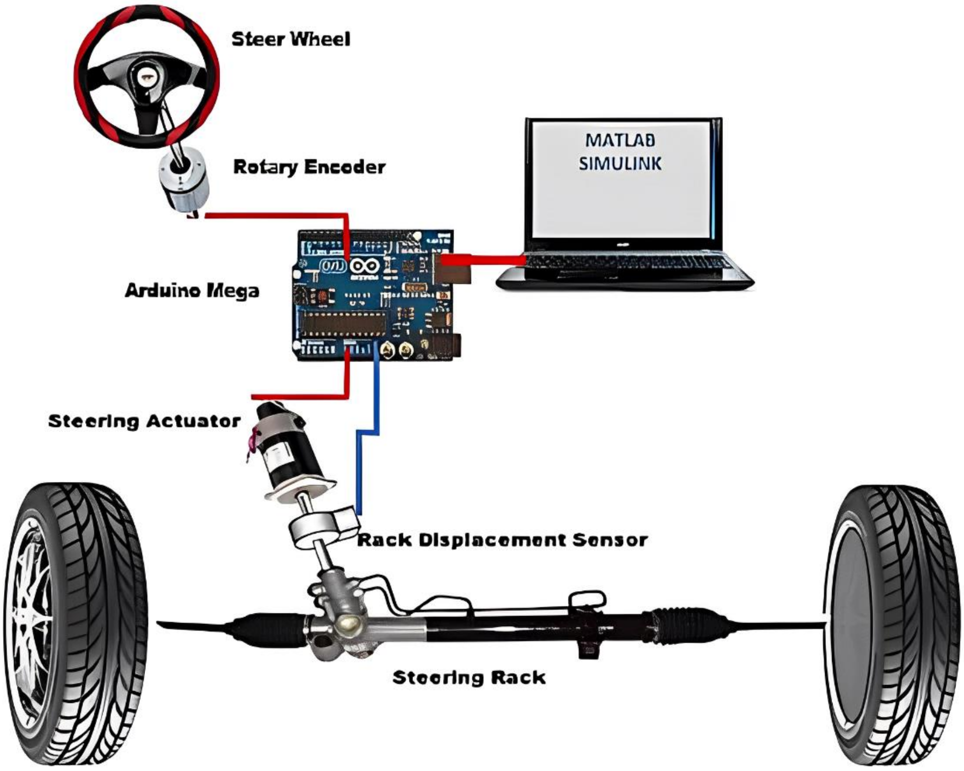

Figure 6. Steer by wire rig

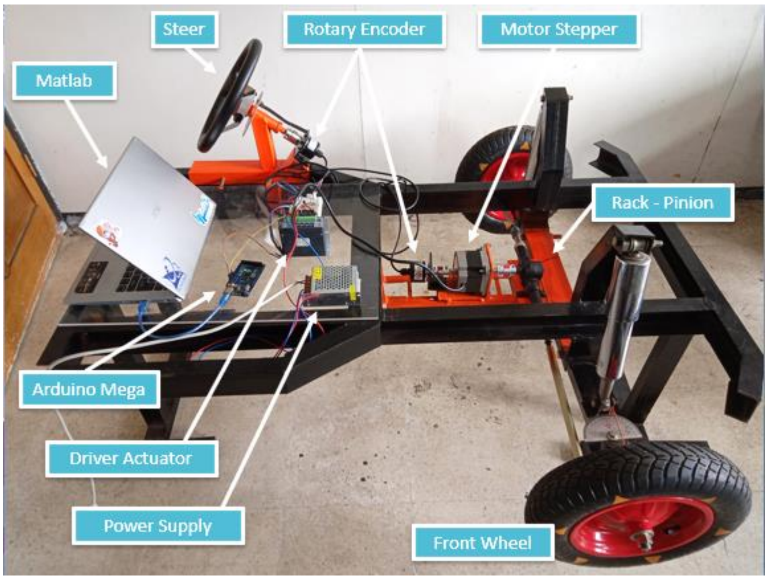

Figure 7. Prototype of semi-automatic steer-by-wire rig

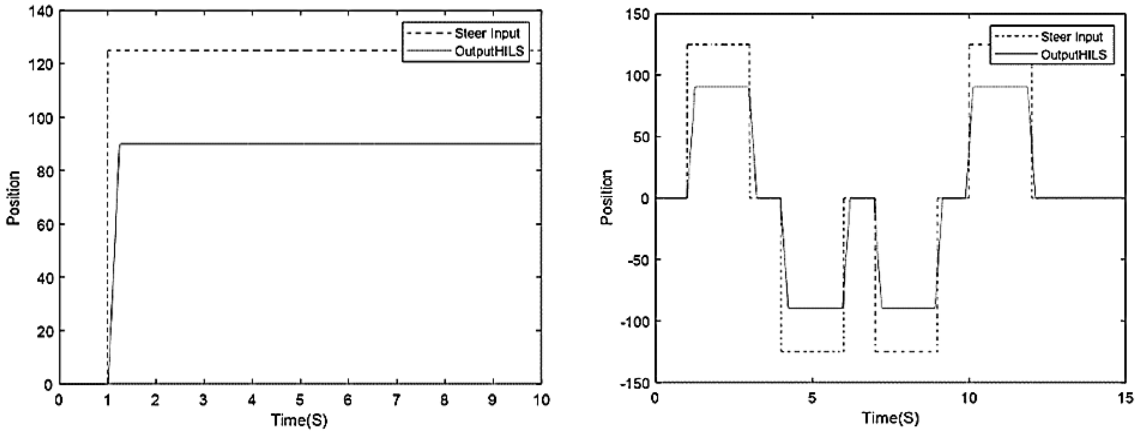

Figure 8. Control response at speeds below 10 km/h

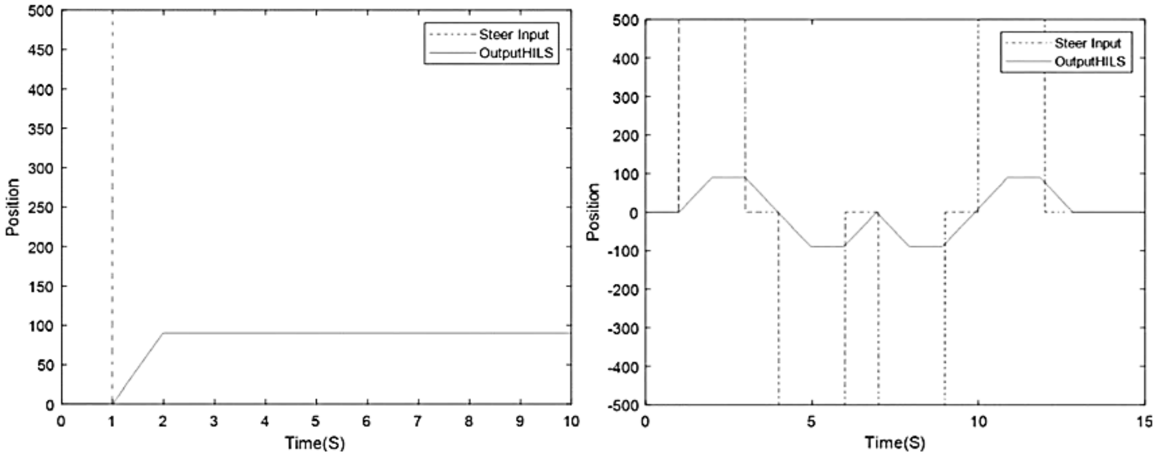

Figure 9. Control response at speeds above 10 km/h

Table 3. The ratio of the angle of the front wheels of the vehicle to the angle of the steer

Ratio	Max angle wheel (Deg)	Motor stepper			Steer max angle (Deg)	Vehicle speed
		Pulse/step	Deg/step (Deg)	Max angle (Deg)		
1:6.25	20	100%	0.72	90	125	< 10 km/h
1:25	20	25%	0.18	90	500	> 10 km/h

4. CONCLUSION

The optimal control system of the FLC-MQPSO developed on the semi-automatic SbW system model is to obtain synchronization of the steering angle to the direction of movement of the vehicle's wheels. The test results using SILS found that MQPSO can further optimize the FLC control system on the Semi-automatic SbW system model compared to PSO and QPSO with C-RMS error performance of 0.06018. The SILS test results were applied to the HILS test using the steer by wire rig prototype equipped with rack-pinion steer and wheel steer and obtained a C-RMS error performance of 6.712 which means it is greater than the SILS test results due to the characteristics of operating time and release time from the stepper motor. Optimal control system the steer-by-wire rig prototype that is built has two kinds of ratios between the steering angle to the wheel angle of the vehicle, namely a ratio of 1:6.25 for speeds below 10 km/h so that it is suitable for operation when the vehicle is maneuvering in the parking area and a ratio of 1:25 for speeds above 10 km/h which is suitable for operation when the vehicle is traveling at high speed.

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BIOGRAPHIES OF AUTHORS

Fachrudin Hunaini is a Lecturer in Electrical Engineering Department at the Universitas Widyagama, Malang, Indonesia. He received his B.Eng., in Department of Electrical Engineering of Universitas Widyagama, Malang, Indonesia, in 1991. And received M.Tech.and Ph.D. degrees in Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia in 1999 and 2017, respectively. He has been an Associate Professor in Universitas Widyagama, Malang, Indonesia. His research interests include the fields of power systems, electric machines, control systems and intelligence control systems. He can be contacted at email: fachrudin_h@widyagama.ac.id.

Dicky Dikananda Nafis is a student at Widyagama University Malang who is majoring in electrical engineering. The energy system is the subject of his research. He is interested in developing Artificial Intellegent, control systems, and optimization methods. He can be contacted at email: Dickydika21@gmail.com.

Purbo Suwandono is a lecturer in Mechanical Engineering Department at the Universitas Widyagama, Malang, Indonesia. with energy conversion expertise. Pursued a bachelor's degree graduated in 2011 and a master's degree graduated in 2015 in Department of Electrical Engineering of Universitas Brawijaya, Malang, Indonesia. Active teaching in 2016 until now. Research is in the field of renewable energy such as pyrolysis, Stirling machines, spirulina microalgae, and vibration. He can be contacted at email: purbo@widyagama.ac.id.

Gatot Soebiyakto is a Lecturer in the automotive engineering vocational program at Widyagama University Malang, He received his B.Eng., in Department of Mechanical Engineering of Widyagama University, Malang, Indonesia, in 1991. And received Ph.D. degrees in Mechanical Engineering from the Dept of Mechanical Engineering, Universitas Brawijaya, Malang, Indonesia, in 2006 and 2020. His research interests include Energy Conversion, automotive, fuel and combustion technology. He can be contacted at email: soebiyakto@widyagama.ac.id.