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Optimized Control of Skid Steering Mobile Robot with Slip Conditions

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***Abstract*— Application of different optimization techniques for nonlinear controller parameters of a skid steering mobile robot (SSMR) with its inherited slip characteristics is crucial in saving designer's time and effort. In this paper, two computational optimization techniques, particle swarm optimization (PSO) and genetic algorithms (GA), are applied, evaluated and compared to optimize the nonlinear controller parameters of an SSMR moving in a plane. The SSMR controller is designed for tracking a reference robot with the same kinematics. For the purpose of simulation, SSMR kinematics is extended to include slip effects. Simulation programs for both optimization techniques are implemented and the optimized controller parameters are obtained. The system response is examined with the optimized parameters for tracking different trajectories in the presence of different types of disturbances and slip coefficients. Simulation results show better performance of PSO tuning based algorithm than GA one, especially in terms of Mean Square Error (MSE) performance index and computational time.**

I. INTRODUCTION

Skid steering mobile robots are widely used as outdoor mobile robots. They are suitable for terrain traversal such as loaders, farm machinery, mining and military applications, due to the simple and robust mechanical structure, faster response, high maneuverability, strong traction, and high mobility [1], [2]. In such type of robots, there is no steering mechanism, and changing the direction of motion is made by turning the right and left wheels at different velocities [3]. Due to complex kinematic constraints and wheel/ground interactions, considering only the kinematics model in the presence of slip conditions, the design of a proper controller for SSMR are challenging tasks.

A number of research papers have been published on the topic of modeling and control of skid steering mobile robots. Wheeled skid steering mobile robots stability has been studied by some authors using model based nonlinear control techniques by explicitly considering dynamics and drive models [4], [5], [6]. Furthermore, in some works the kinematics have been addressed as the relation of linear and angular velocities with the position of the vehicle [7], [8]. Slip plays a vital role in the stability and traction control of the skid steering mobile robots. So, considering the slip parameters during the controller design is an essential issue to obtain better traversability of the robot. In [9] and [10], a Sliding Mode Observer (SMO) is used for the estimation of the slip parameters based on the motion states estimation of a mobile robot using a visual sensor. However, the controller design is not included in such work. A nonlinear Kalman Filter (KF) is presented in [11] for simultaneous localization and slip parameters estimation based on Interial Measurement Unit (IMU) measurements. It is noted that the inclusion of the slip parameters in the system model is not considered. In [12], the skid-slip influence on a mobile robot is feed-forward compensated and a Vector Field Orientation (VFO) feedback tracking controller is introduced. Moreover, a Kalman Filter (KF) is developed for the estimates of skid-slip using measurements from a vision feedback sensor (Digital Camera) for position and velocity calculations. However, it is noted that the controller parameters are selected using trial and error method. Slip parameters were included in the kinematic model and they were estimated using a nonlinear observer of a tracked skid steering vehicle [13]. But, the controller design is not included. To the best of our knowledge, the slip parameters are not included in the system model in the most of the previous works except in [13] and the controller parameters, if the controller is developed, are selected based on trial and error.

Design of trajectory controllers based on the selection of their parameters using trial and error method is an immensely time-consuming and tedious process and also such parameters are difficult to be tuned. Moreover, the slip conditions for 4-wheeled SSMR plays a critical role in kinematics modeling and control of SSMR. Therefore, the main contribution of this research is the application, evaluation, and comparison of two computational optimization techniques, PSO and GA, to optimize the nonlinear controller parameters of an extended kinematic model with slip conditions of an SSMR moving in a plane. The proposed controller can overcome the effects of slip parameters with different values.

The main advantages of the proposed controller are the design and implementation simplicity, strong robustness, and good performance when compared to other controllers provided in the previous works especially for different operating conditions such as addition of different types of disturbances to the system and using different types of reference trajectories.

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In this paper, an extended kinematics model of the kinematics of the SSMR based on [4], [13] is used. This extended model takes into account the slip conditions which affect the performance of the motion of mobile robots. Then, a model based nonlinear controller with the PSO and GA algorithms to tune the nonlinear controller parameters is developed. Moreover, a comparison between the PSO and GA results is performed to show the benefits provided by both tuning algorithms and the enhancement obtained by using the proposed controller, especially in the case of the addition of pulse disturbances, variable disturbances, and different slip parameters to the system models. Finally, two types of reference trajectories (Circular and Infinity-like) are used to test and rate the proposed controller. The rest of the paper is organized as follows: In section II an SSMR extended kinematics model is presented in a systematic way. Section III focuses on the development of a model based PSO/GA nonlinear controller. Section IV is dedicated for extensive simulation results considering trajectory tracking problem. Section V is devoted to conclusions and ideas for future work.

II. Classical and Extended Kinematic Models

A mathematical description of the kinematics of an SSMR moving on a planar surface is reviewed in this section. The main equation that describes the kinematic subsystem of the SSMR moving on a planar surface as shown in Fig. 1 is given by [4], [5]:

$$\dot{q} = \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} cos\theta & x_{ICR} sin\theta \\ sin\theta & -x_{ICR} cos\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ w \end{bmatrix} \quad (1)$$

where v_x is the longitudinal velocity, w is the angular velocity of the robot with respect to the inertial frame $X_g Y_g$, $q = [X\, Y\, \theta]^T$ represents the generalized coordinates of the center of mass (COM) of the robot with X and Y is the COM position and θ is the orientation of the local coordinate frame with respect to the inertial frame. The coordinate of the instantaneous center of rotation (ICR) is defined as (x_{ICR}, y_{ICR}).

The kinematics model of SSMR is extended to include the slip effect [13]. The kinematics equations for an SSMR during turning, are given by the following, [14]:

$$\begin{aligned} \dot{X}_{slip} &= \frac{v_{rslip} + v_{lslip}}{2} cos\theta_{slip} + \frac{v_{rslip} - v_{lslip}}{2c} x_{ICR} sin\theta_{slip} \\ &\quad - \frac{v_{rslip} + v_{lslip}}{2} sin\theta_{slip} tan\alpha, \\ \dot{Y}_{slip} &= \frac{v_{rslip} + v_{lslip}}{2} sin\theta_{slip} - \frac{v_{rslip} - v_{lslip}}{2c} x_{ICR} cos\theta_{slip} \\ &\quad + \frac{v_{rslip} + v_{lslip}}{2} cos\theta_{slip} tan\alpha, \\ \dot{\theta}_{slip} &= \frac{v_{rslip} - v_{lslip}}{2c}. \end{aligned} \quad (2)$$

such that $v_{rslip} = r\omega_r(1 - i_r)$ and $v_{lslip} = r\omega_l(1 - i_l)$, where $2c$ is the distance between wheels centers, r is the wheel radius, v_{rslip} and v_{lslip} are the linear velocities of the right and left wheels under slip conditions, respectively. ω_r and ω_l are the angular velocities of the right and left wheels, respectively. i_r and i_l are the right and left wheels slip parameters, respectively. α is the slip angle. $[X_{slip}\ Y_{slip}\ \theta_{slip}]^T$ is the location of the real mobile robot under slip conditions. Therefore, to test the slip conditions' effects on the SSMR motion, the extended kinematic equation (2) can be used.

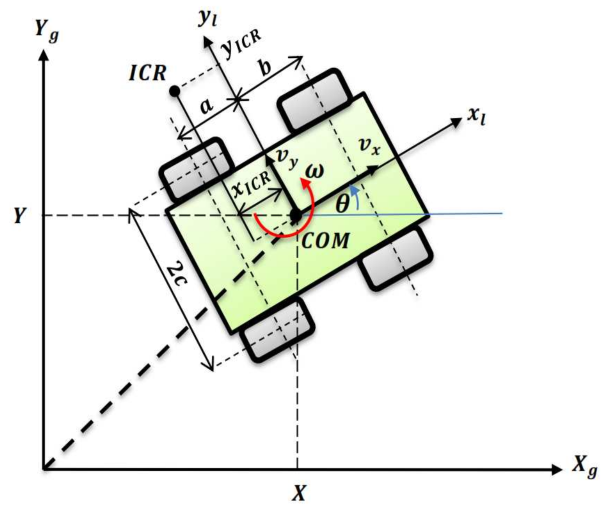

Fig. 1. Schematic diagram of SSMR

III. Controller Design

A. Model Based Nonlinear Controller Design

The problem of tracking of a reference vehicle with the same kinematics in both position and orientation [15] as shown in Fig. 2 will be considered. For an SSMR for example, this means in view of (1) that:

$$\begin{aligned} \dot{X} &= v_x cos\theta + w x_{ICR} sin\theta, \\ \dot{Y} &= v_x sin\theta - w x_{ICR} cos\theta, \\ \dot{\theta} &= w. \end{aligned} \quad (3)$$

The main concern here is to determine a feedback control which asymptotically stabilizes the tracking error $(X - X_r, Y - Y_r, \theta - \theta_r)$ at zero, with (X_r, Y_r) being the coordinates of P_r in the global frame OX_gY_g, and θ_r the oriented

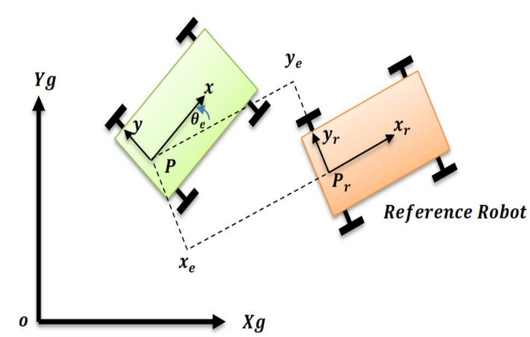

Fig. 2. Reference vehicle and error coordinates.

angle between X_g and x_r. By derivation of the tracking error in position and orientation $(X - X_r, Y - Y_r, \theta - \theta_r)$ with respect to the reference robot frame gives the vector:

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} cos\theta_r & sin\theta_r & 0 \\ -sin\theta_r & cos\theta_r & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X - X_r \\ Y - Y_r \\ \theta - \theta_r \end{bmatrix} \quad (4)$$

Now by considering the following change of coordinates and control variables in order to determine a control (u_1, u_2) which asymptotically stabilizes the error (x_e, y_e, θ_e) at zero:

$$(x_e, y_e, \theta_e, u_1, u_2) \longmapsto (q_1, q_2, q_3, R_1, R_2) \quad (5)$$

which are defined by:

$$\begin{aligned} &q_1 = x_e, \quad q_2 = y_e, \quad q_3 = tan\theta_e, \\ &R_1 = u_1 cos\theta_e - u_{1r}, \;\; R_2 = \frac{u_2 - u_{2r}}{cos^2\theta_e}. \end{aligned} \quad (6)$$

It is noted that this mapping is only defined when $\theta_e \in (-\pi/2, \pi/2)$. In other words, the orientation error between the physical robot and the reference robot has to be smaller than $\pi/2$.

By assuming the following control laws:

$$\begin{aligned} &R_1 = -K_1|u_{1r}|(q_1 + q_2 q_3) \qquad (K_1 > 0), \\ &R_2 = -K_2 u_{1r} q_2 - K_3|u_{1r}|q_3 \qquad (K_2, K_3 > 0). \end{aligned} \quad (7)$$

Finally, the control signals to the SSMR system (u_1, u_2) which represent the linear velocity v_x and angular velocity w defined in (3) are as follows:

$$u_1 = \frac{R_1 + u_{1r}}{cos\theta_e}, \qquad u_2 = R_2 cos^2\theta_e + u_{2r}. \quad (8)$$

A stability analysis based on the Lyapunov's second method was performed to prove the global asymptotic stability of the system of (7), [15].

B. Tuning of Nonlinear Controller

1) PSO Algorithm Overview: PSO was originally developed and introduced by Kennedy and Eberhart in 1995 through the bird flocking and fish schooling simulation in 2-dimensional space. PSO is a population based search algorithm in which each particle in the swarm is represented by a position and a velocity. The PSO algorithm determines how to update the velocity of a particle. Each particle updates its velocity based on current velocity, the best position it has explored so far; and also based on the global best position explored by swarm [16][17].

The position of the particle and its velocity is being updated using the following equations which are dependent on the velocity in the previous stage, its orientation toward the best response in the group and the particle's past [17][18]:

$$\begin{aligned} v_i(k+1) = \triangle(x_i(k+1)) &= c_0 \times v_i(k) \\ &+ c_1 \times Rand() \times (Pbest_i(k) - x_i(k)) \\ &+ c_2 \times Rand() \times (Gbest_i(k) - x_i(k)) \end{aligned} \quad (9)$$

$$x_i(k+1) = x_i(k) + \triangle(x_i(k+1)) \quad (10)$$

Where c_0 indicates the inertia weight, k is the k^{th} iteration, $Rand()$ is a random function in [0 1] and $\{c_1, c_2\}$ are cognitive and social parameters.

In this paper, the PSO is implemented using MATLAB which allows the user to establish the PSO parameters (the size of the swarm, PSO parameters (c_1 and c_2), and PSO inertia c_0. A flow chart of the general scheme of the implementation of the PSO is shown on the left side of Fig. 3.

2) GA Algorithm Overview: The Genetic Algorithm, GA, is considered as a powerful optimization searching technique based on the principles of natural genetics and natural selection [19]. More details about the GA algorithm used here can be found in [14].

3) Controller Parameters Tuning: The main difficulty in the controller described by equation (7) is the selection and tuning of its parameters (K_1, K_2, K_3) especially when the system has complex nonlinearities. So to overcome the difficulty of tuning the controller parameters by trial and error method, PSO and GA may be used for such purpose. The PSO parameters that used in this paper are as follows: size of the swarm =30, the dimension of the problem = 3 (which represents the three controller parameters (K_1, K_2, K_3)), PSO parameters: $c_1 = 0.12$ and $c_2 = 1.2$, PSO inertia: $c_0 = 0.9$. The GA parameters are as follows: maximum number of generations = 200, population size = 25. The fitness function for both PSO and GA is the mean of squared errors (MSE) which is described by (11). The main objective of PSO and GA is to seek for minimum fitness value. Finally, after running the PSO, the optimal parameters obtained are: $K_1 = 3.7829$, $K_2 = 3.5566$, and $K_3 = 4.0426$. while, those parameters obtained by GA are:$K_1 = 4.0736$, $K_2 = 32.5716$, and $K_3 = 9.0248$. It is noted that the computational time elapsed to obtain these parameters (K_1, K_2, K_3) using the PSO algorithm is around two minutes only which is too small compared with that consumed by Genetic Algorithm (GA), around 12 hours.

$$MSE = \frac{1}{\tau}\int_0^{\tau} (e(t))^2 dt \quad (11)$$

IV. Simulation Results

In this simulation, the extended kinematics model which is described by (2) is considered. To demonstrate the effectiveness of the proposed controller, the controller is tested and the results of PSO and GA are compared for different scenarios. Firstly, the system model is tested without any disturbances. Secondly, an addition of pulse and variable disturbances to the system and using different slip parameters (i_r, i_l and α) to test the robustness of the controller with the same parameters. Finally, the controller is tested for two types of trajectories (circular contour, Infinity-like contour). All simulations are performed using the MATLAB/Simulink environment.

The circular and the Infinity-like reference trajectories are defined by (12) and (13), respectively.

$$\begin{aligned} &x_r(t) = 7cos(0.02\pi t), \\ &y_r(t) = 7sin(0.02\pi t). \end{aligned} \quad (12)$$

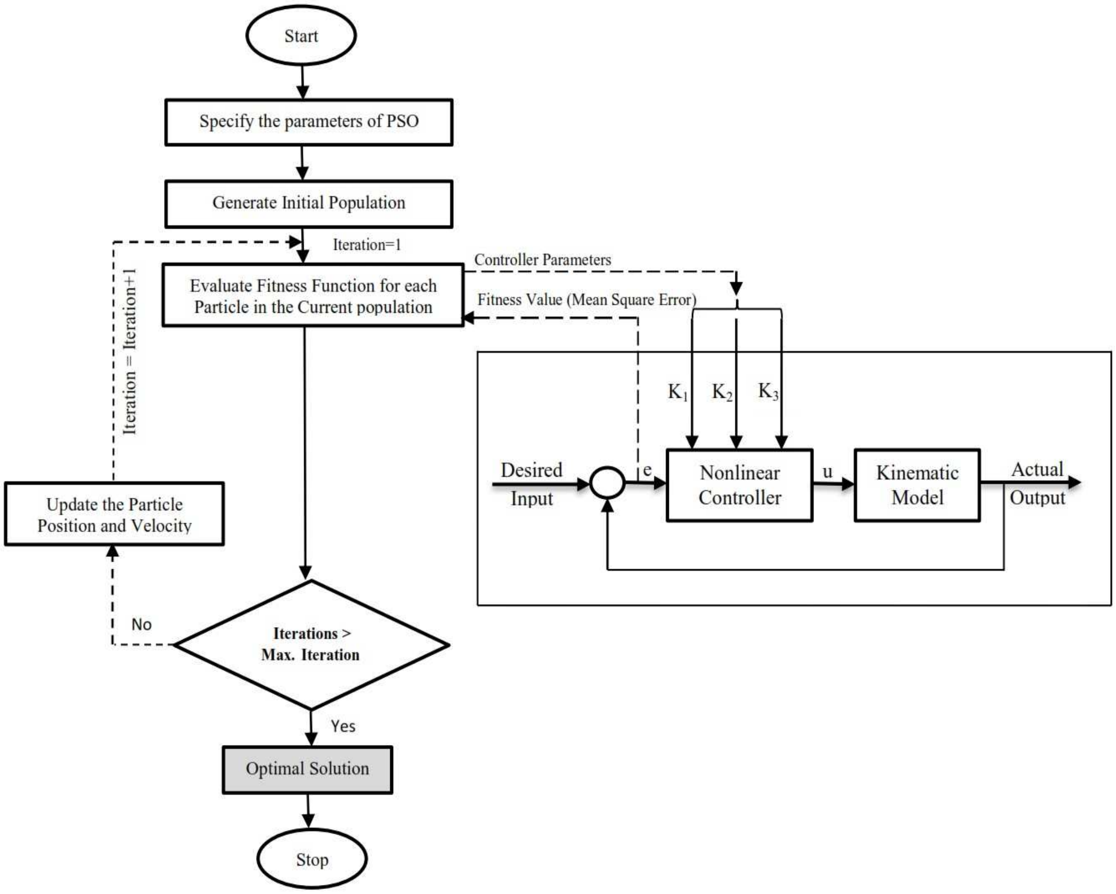

Fig. 3. PSO Algorithm tuning procedure for the controller Parameters.

$$x_r(t) = \frac{9cos(0.02t)}{1+sin^2(0.02t)},$$
$$y_r(t) = \frac{27sin(0.02t)cos(0.02t)}{1+sin^2(0.02t)}. \tag{13}$$

The system parameters applied for simulation are shown in Table I. In practice, it is difficult to measure x_{ICR} value. So it is assumed here to be [4], [5]:

$$x_{ICR} = constant = x_0 \quad x_0 \in (-a, b) \tag{14}$$

where a and b are positive kinematic parameters of the robot depicted in Fig. 1.

TABLE I
PARAMETERS OF THE MODEL

Variable	Value	Unit
$a = b$	60	cm
c	30	cm
r	20	cm
x_0	-15	cm
i_l	18 %	–
i_r	23.3 %	–
α	47	$degree$

A. Circular Contour Responses

- Scenario 1: System Without Disturbances

In this scenario, the system is tested without any addition of disturbances to assess the controller performance. Fig. 4 shows the system response to circular contour described by (12). It is clear that the system can track the desired inputs quickly and without any overshoot.

- Scenario 2: System With Disturbances and Different Slip Parameters

In this scenario, a pulse disturbance ($d = 0.2$) is added from iteration 50 to iteration 60 of the simulation period and also, a variable disturbance as a function of v_x ($d_1 = 0.1v_x$) is added to the system model as shown in Fig. 5 and here different slip parameters ($i_r = 0.38$, $i_l = 0.53$ and $\alpha = 50°$) are used to evaluate and rate the controller performance against such changes . Fig. 6 shows the system response after such disturbances addition. The tracking of the system to the desired inputs is obviously shown, but with more errors for GA response.

B. Infinity-Like Contour Responses

In order to show the effectiveness and enhancement provided by the proposed controller, an Infinity-like trajectory is used.

Fig. 7 and Fig. 8 show the system responses for the 2 scenarios described above, respectively. It is clear that the system can track the desired inputs despite of changing the reference inputs, addition of disturbance and using different slip parameters.

For a comparison between the responses of the PSO and GA tuned controllers for the two types of trajectories (circular and Infinity-like), the Mean Squared Error (MSE) described by (11) is calculated and plotted for the two controllers and the MSE numerical values for X, Y, and θ references are shown in Fig. 9. It is clear from this figure that the PSO-based controller provides lower values than the controller based on GA.

V. Conclusions

In this paper, a kinematics model based controller is considered for a tracking control problem of a 4-wheels skid steering mobile robot with inherited slip. Two optimization techniques, GA and PSO, are applied for optimizing the controller's parameters. Evaluation and comparison of GA and PSO results illustrate the enhancement and improvements provided by PSO-based controller results. The PSO superiority is clear in terms of the performance index (Mean Square Error) and computational time. In future, experimental implementation of the proposed PSO-based controller would be considered. Online optimization would also be tackled.

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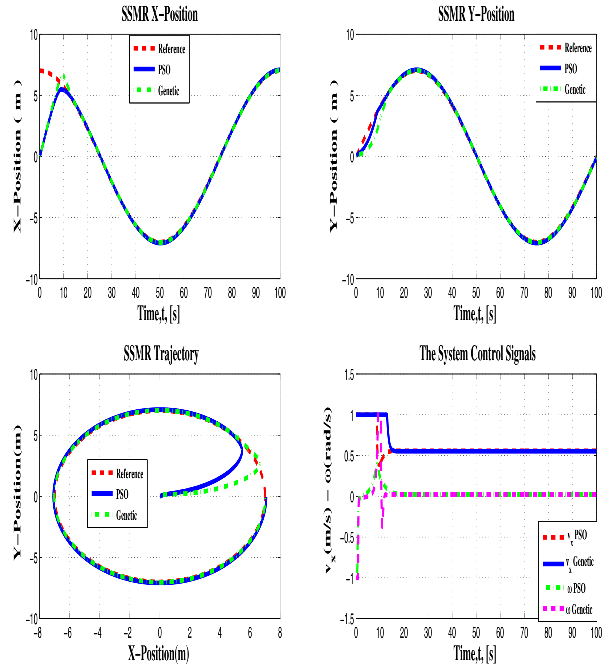

Fig. 4. Circular contour responses without disturbance

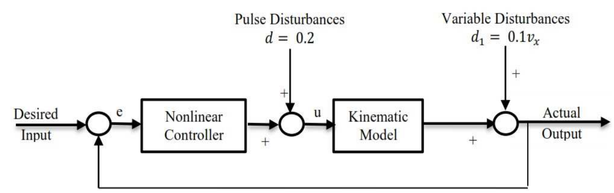

Fig. 5. System block diagram with pulse and variable disturbances

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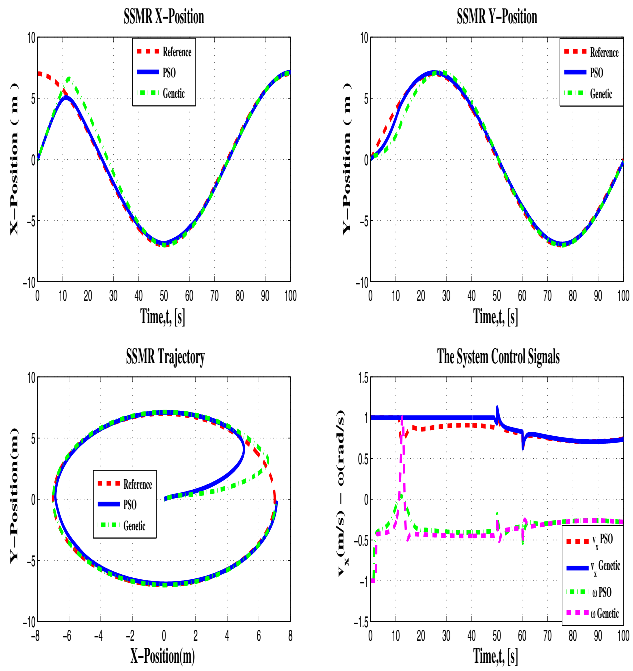

Fig. 6. Circular contour responses with disturbances and different slip parameters

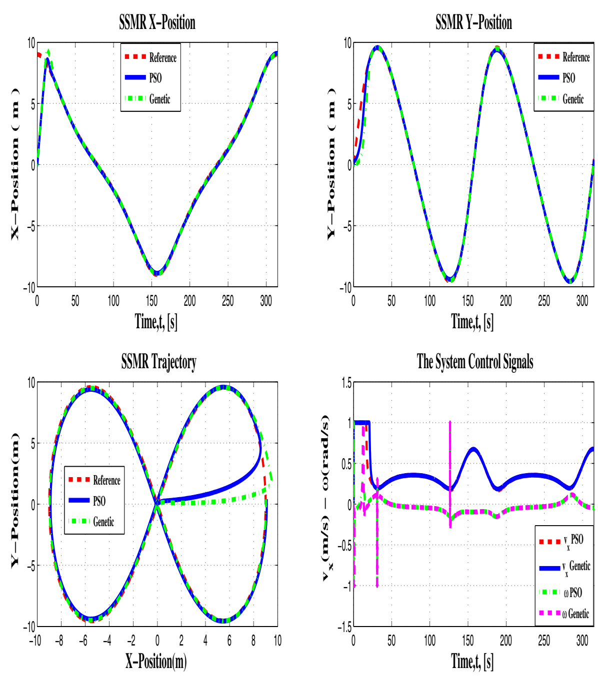

Fig. 7. Infinity-like contour responses without disturbance

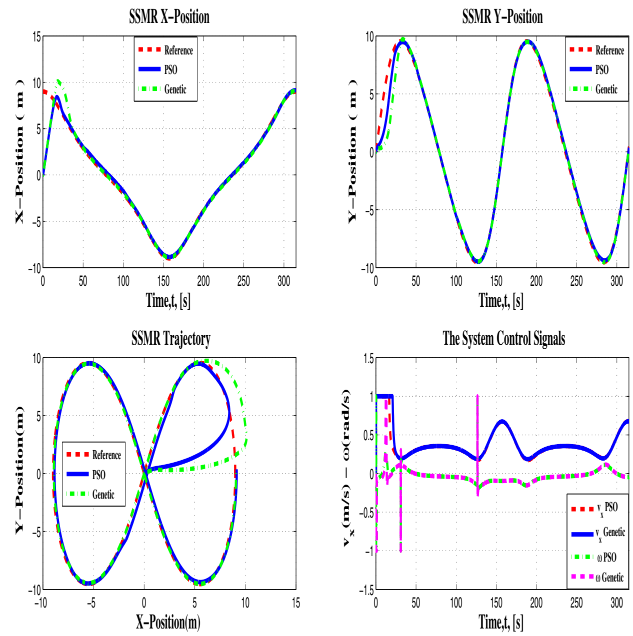

Fig. 8. Infinity-like contour responses with disturbances and different slip parameters

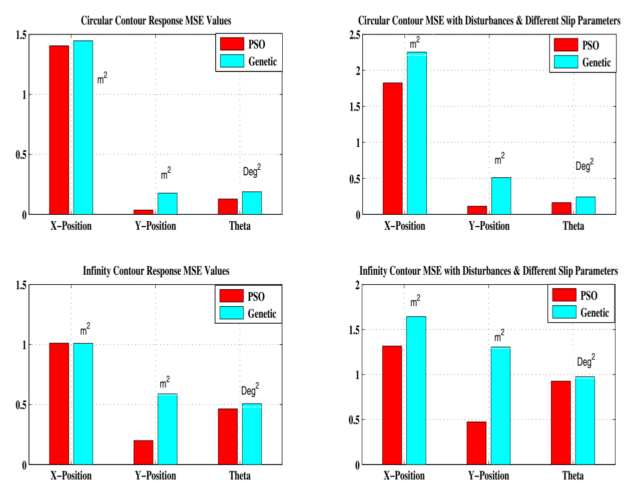

Fig. 9. Mean square error comparison for the slip case

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