A TIME OPTIMAL PATH PLANNING FOR TRAJECTORY TRACKING OF WHEELED MOBILE ROBOTS

Submitted 26th March 2010; accepted 21st February 2011.

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Abstract:

A variety of approaches for trajectory tracking control of wheeled mobile robots have been implemented. This paper presents a model for a time optimal motion control based on fuzzy logic algorithm for a three wheeled nonholonomic mobile robot with desired function. Simplified kinematic equations of a differentially driven robot are designed to follow the path with evaluated linear and angular velocities. Here, the proposed kinematic model is based on a simple geometric approach for getting the desired position and orientation. The speeds are varied depending on the variations in the path and on the posture of the robot. The robot is subjected to move in a constrained workspace. The control architecture was developed based on fuzzy logic algorithm to obtain time optimal motion control of robot trajectory tracking. The kinematic model was done on Matlab software environment and profound impact on the ability of the nonholonomic mobile robot to track the path was evaluated.

Keywords: *wheeled robot, time optimal, trajectory tracking, motion control, fuzzy logic algorithm, Matlab environment.*

1. Introduction

Autonomous mobile robots are mechanical devices capable of moving in an environment with a certain degree of autonomy. The robot is able to plan its own motion following the path as closely as possible and is usually expected to travel from its initial position to a target position located at a specified range and bearing. A wheeled robot is an autonomous robot and it can autonomously plan and control its own motion in order to accomplish specified tasks. However, these mobile robots are quite restricted in their motion by nonholonomic constraints on their wheel mechanism. In path planning, the path is completely described with geometry for the robot to move from initial to target position with orientation. In this paper, a model that describes the path of a mobile robot for given requirements is developed. The basic ability of such a robot is to reach target positions with fast and stable navigation.

Different types of kinematic model and platform designs have been studied for wheeled mobile robots. The trajectory tracking problem is highly nonlinear and several approaches have been developed to solve the problem through direct control of the robot's dynamics. Some of these approaches have mentioned the problem of motion planning under nonholonomic constraints using only a kinematic model of a mobile robot. Some kinds of dynamic models the controller can produce perfectly the same velocity that is necessary for the kinematic controller. The control design of a mobile robot with nonholonomic constraints on a reference path in trajectory tracking with determined velocity is very difficult. There are various possibilities how a target position (x_d, y_d) can be described with its orientation. The path of the robot would be satisfied with various robot constraints and the smooth requirements. Robot path planning and motion control techniques are often developed in simulation and then applied to real robot systems. Motion planning and control of autonomous vehicles involve several problems related to environment perception and representation, path planning, path tracking, velocity, motion control, etc. Nonholonomic systems have motion limitations in the kinematic model. The control of the nonholonomic systems is challenging, unlike holonomic constraints, because nonholonomic constraints involve one or more velocities and are not integrable. The nonholonomic mobile robot can reach the target with arbitrary position and orientation, but it is unable to rotate while simultaneously moving in an arbitrary direction. The control strategy of nonholonomic wheeled robot can be defined by arbitrary combinations of the following parameters (x, y, θ, υ, ω). This paper deals with concepts of the mobile robot motion control, which includes geometric path, fuzzy logic control and genetic algorithm optimization. The objective of trajectory tracking is to generate the control commands for the vehicle to follow the previously defined path by taking into account the actual position and orientation, linear and angular velocities and nonholonomic constraint imposed by the vehicle.

Many researchers have proposed various control techniques for this problem. Simple kinematic systems considered only the position of the robot and then developed simultaneously positioning and steering [1], [2], [3], [4], [5]. These techniques do not present the relation between the controller parameters and the robot real systems. Tracking a mobile robot's position and orientation precisely is a challenging task. In trajectory tracking, the actual and reference position and orientation of mobile robot are moved all the time. Hence, stabilization in tracking is a problem. Several authors adopt a simple path planning approach which identifies only the target position of the robot and passes the obstacle avoidance to the motion control using techniques such as PID, fuzzy logic, neural network and genetic algorithms. Fuzzy logic has been applied to mobile robot and autonomous vehicle control significantly [6], [11]- [15]. Genetic algorithm is useful in circumstances where it is difficult to determine an exact membership functions.

In this paper, wheeled robot motion control system is discussed and genetic algorithm, fuzzy logic controller is implemented to get optimum solution. Developed kinematic model is presented based on simple geometric approach [4], [12], 13]. The problem of path planning can be simplified by calculating intersection points to be reached subsequently. Here, the control model only needs the robot's control variables or inputs (υ, ω) to set the state variables (x, y, θ). This research work proposes a motion control strategy on fuzzy logic control to produce trajectories by following a defined path with a desired position and orientation. The simulation model has been designed in Matlab environment. Mathematical equations, simulation and results are also presented. The evolution of the genetic algorithm used to find the optimal parameters for the fuzzy controller [16], [17] allows an easy tuning of the controller parameters to find suitable velocity control inputs, which stabilize the kinematic closed loop control. The proposed fuzzy controller aims at achieving perfect velocity tracking while considering not only a kinematic model but also a dynamic model of the mobile robot.

This paper analyses the kinematic modelling of three wheeled differentially driven nonholonomic mobile robot with simple geometric approach and to get the optimum design of the fuzzy controller for mobile robot trajectory tracking. The stability of a wheeled robot is analyzed for a kinematical model using a linearized kinematical model. This analysis is done for the case of a straight line and a circle with the trajectories that can be decomposed into pieces of constant curvature.

2. Path Planning

Path planning is partitioned into geometric and kinematic components. Motion control of mobile robots has been focused only on the kinematic model, there is a perfect velocity tracking. The kinematic model of the vehicle is described in detail in this section along with three wheeled vehicle mechanics.

2.1. Kinematic model

Kinematic model of the wheeled mobile robot (WMR) assumes that the robot is placed on a plane surface. The contacts between the wheels of the robot and the rigid horizontal plane have pure rolling and non slipping conditions during the motion. This nonholonomic constraint can be written as

$$\dot{y}cos\theta - \dot{x}sin\theta = 0 \tag{1}$$

The center position of the vehicle (x, y, θ) is expressed in the inertial coordinate frame. Here x and y are position of the robot and θ is orientation of the robot with respect to inertial frame. Suppose that the robot moves on a plane with linear and angular velocities, the state vector can be expressed as $\dot{q} = (\dot{x}, \dot{y}, \dot{\theta})^T$. The differential drive mobile robot is an autonomous vehicle. It has two drive wheels, which are independently driven for getting the desired path. The robot's motion on linear trajectories is given by constant velocities of the wheels and the motion on circular trajectories is determined by the difference between the angular velocities of the two drive wheels. The state of the robot is defined by its position and orientation and by the speeds of the two drive wheels. A simple structure of differentially driven three wheeled mobile robot is shown in Fig. 1.

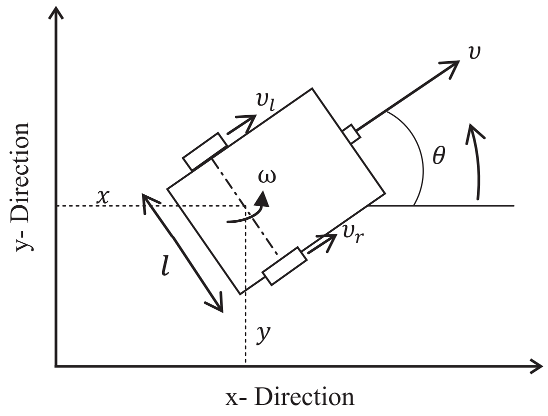

Fig.1. Three wheeled differentially driven mobile robot.

A wheeled mobile robot's motion can be expressed in terms of translational and rotational motion. The translational component is the displacement of the centre of the mobile robot and the rotational component is the rotational movement of the vehicle. For the robot's movement, the linear velocity υ and the angular velocity ω are chosen. These values are converted into the velocities of the left and right wheels. The kinematic model is formulated by using these wheel speeds and geometric constraints of the vehicle also. The kinematic behaviour of the vehicle depends on the control variables υ and ω.

$$\upsilon = \frac{(\omega_l + \omega_r)\mathrm{r}}{2} \tag{2}$$

$$\omega = \frac{(\omega_l - \omega_r)}{l} \tag{3}$$

$$\begin{bmatrix} \upsilon_l \\ \upsilon_r \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & l/2 \\ \cos\theta & \sin\theta & -l/2 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{4}$$

where ω_l and ω_r are angular velocities of left and right wheels of the mobile robot respectively. Both wheels have same radius denoted by r. These two rear driving wheels are separated by l. The linear velocities of left and right wheels are given in equation (4). Different values of ω_l and ω_r of the mobile robot trajectory are followed for the trajectory.

2.2. Geometric Model

The path planning under kinematic constraints is transformed into a pure geometric problem. There are many possible ways to describe the path. The resulting shortest path is composed of circular arcs and straight lines. The robot motion control can be done providing wheel velocities $\upsilon(t)$, $\omega(t)$ called control variables. The mathematical model of this kinematic problem considers these two control variables and three state variables $(x(t), y(t), \theta(t))$.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \upsilon \\ \omega \end{bmatrix} \tag{5}$$

The tangential velocity in x direction is $\upsilon_x = \upsilon.\cos\theta$, the tangential velocity in y direction is $\upsilon_y = \upsilon.\sin\theta$ and the angular velocity of the vehicle is $\omega = \dot{\theta}$. An appropriate approach is implemented to produce the desired trajectory described by a sequence of coordinates. An arbitrary configuration (x, y, θ), is defined by the robot path planner and the robot is placed on the path. The location of the target is known for all t, and its state transition equation simplifying to $q(t) = f(\upsilon,\omega)$. The velocities of left and right are different from each other and the robot does not move in a straight line but follows a curved trajectory around a point located at a distance r from its centre of radius, continuously changing both the robot's position and orientation. The path tracking controller has to ensure a geometrical convergence towards the path to be followed. The motion of the robot could be described with two modes, either pure rotation or pure translation. The path consists of circular arcs with a specified radius and turning angle and a straight tangent line. These circular arc and straight tangent line are used to avoid stoppage and provide continuity for the robot. To achieve controlled trajectory, the linear and angular velocities υ and ω are calculated by the equations (6) and (7) through fuzzy logic controller. For circular motion, equation (6) is used and the path is described by the function of the angle only and for linear motion, equation (7) is used and the straight line path is described by calculating the tangent length of the circles.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \qquad (6)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \upsilon.cos\theta \\ \upsilon.sin\theta \\ 0 \end{bmatrix} \qquad (7)$$

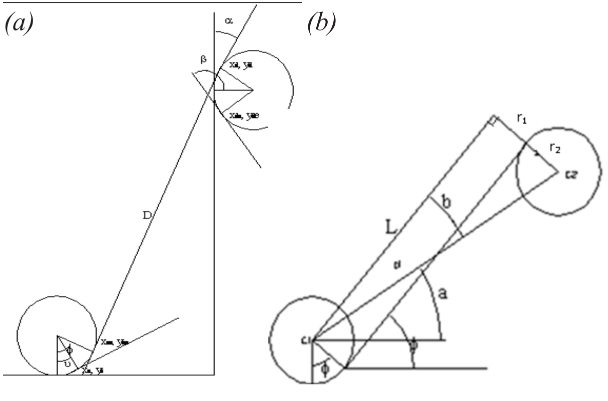

Fig. 2. (a) Trajectory of the vehicle (b) Relationship of circles and tangent line.

In order to reach a target position with a specified orientation, a trajectory consisting of a straight line and a circular arc with a fixed radius is calculated as shown in Fig. 2. The radius depends on the robot's velocity and its position. The algorithm first calculates a suitable intersection point to be reached and then calculates a circular arc through the target position. The target position can then be reached with the desired orientation. So the trajectory is calculated out of the target parameters and the present position. It consists of straight lines, circular arcs, the linear and angular velocities. The planned path consists of an arc of a circle followed by a tangent straight line segment. The discontinuity of the curvature of the path at the tangent point would be overcome by smoothening the path before computing the trajectory. The following parameters are obtained from the geometry of Fig. 2.

$$\phi = \angle a + \angle b \qquad (8)$$

$$\tan a = \frac{C_{2y} - C_{1y}}{C_{2x} - C_{1x}} \qquad (9)$$

$$\tan b = \frac{r_2 + r_1}{L} \qquad (10)$$

$$\tan b = \frac{r_2 + r_1}{\sqrt{C_1 C_2^2 - (r_1 + r_2)^2}} \qquad (11)$$

$$\alpha 1 = \varphi - \theta_d \qquad (12)$$

$$\alpha 2 = \beta_d - (90 - \varphi) \qquad (13)$$

3. Trajectory Planning

A trajectory is a path which is an explicit function of time. To have smooth movement, the trajectory must give continuous velocity and acceleration. The robot will be moved backward and forward based on the situation, and it will compute navigation. Here, it is assumed that the robot's motion is always directly forward and that its orientation is tangent to the circle at all points of the trajectory. To construct the circle, the value for its radius given by r is found. The value r for the radius of the circle is essentially the turn radius for the robot's motion. In trajectory planning, simplified kinematic constraints are added to plan a feasible trajectory. The minimum turning radius and the dimensions of a robot plan a trajectory. According to the geometric model, the planner is considered to switch the path.

$$\begin{array}{llll} \text{if} & y_d - y_0 \geq 0 \text{ and } y_d - y_0 > 0 & \varphi = \varphi \text{ and } a = a \\ \text{If} & y_d - y_0 \geq 0 \text{ and } y_d - y_0 < 0 & \varphi = \varphi + 90 \text{ and } a = a + 90 \\ \text{If} & y_d - y_0 \leq 0 \text{ and } y_d - y_0 > 0 & \varphi = \varphi + 180 \text{ and } a = a + 180 \\ \text{If} & y_d - y_0 \leq 0 \text{ and } y_d - y_0 < 0 & \varphi = \varphi + 270 \text{ and } a = a + 270 \end{array}$$

$$\text{If} \begin{cases} a \leq \beta \leq a + 180 & \text{anticlockwise rotation} \\ \text{otherwise clockwise rotation} \end{cases}$$

$$\text{If} \begin{cases} a + 90 \leq \beta \leq a + 270 & \text{anticlockwise rotation} \\ \text{otherwise clockwise rotation} \end{cases}$$

$$\text{If} \begin{cases} a + 180 \leq \beta \leq a + 360 & \text{anticlockwise rotation} \\ \text{otherwise clockwise rotation} \end{cases}$$

$$\text{If} \begin{cases} a + 270 \leq \beta \leq a + 90 & \text{anticlockwise rotation} \\ \text{otherwise clockwise rotation} \end{cases}$$

The variables calculated by the control law are the translational and rotational velocities, based on the position, orientation, and the current values of the translational and rotational velocities. Hence, the maximum absolute value of the path curvature is minimized by maximizing the absolute value of the angular velocity. The path planning controller generates a path by calculating robot's desired orientation θ at each position. The configuration of a robot depends usually on its position (x, y), and orientation θ is a set of parameters that uniquely determine the position of every point in the robot. Different optimality criteria may be chosen depending on the desired WMR motion smoothness. For instance, while considering the robot motion the linear and angular velocity and the path arc length are calculated, so that the robot can move to any desired path effectively.

4. Control Structure and Implementation

The objective of this paper is to obtain optimum tracking behaviour. Various control techniques have been proposed for this application and are being researched. Open loop and closed loop feedback strategies are followed for controlling robot's motion. In open loop control system, the control parameters linear and angular velocities are calculated beforehand, from the geometrical approach with its initial and end position and orientation to get the desired path between them in the case of path following. In closed loop control system, PID or fuzzy logic control (FLC) or neural network (NN) or genetic algorithm (GA) is selected to implement for a highly nonlinear robot model.

4.1. Design of Fuzzy Logic Controller

The application of fuzzy logic control in robotics is to produce an intelligent robot with the ability of autonomous behaviour and decision. In this section, the problem of how to set the control parameter values for desired robot behaviour is solved. This behaviour is analysed from the sensitivity of the robot input parameters (α_1, α_2 and D). The equations (8-13) are considered for getting φ, α_1, α_2, D and L. The maximum linear and angular velocities are obtained with the set of this optimal parameters using fuzzy logic algorithm and by maintaining the continuity while considering kinematic constraints. The membership functions are derived based on the kinematical constraints of the robot. When turning with a curvature, the speed gradually decreases and makes a smooth turn. The fuzzy logic controller is selected for getting simple and optimum results. In this trajectory tracking, the optimal control parameters are evaluated from fuzzy logic and the distance and orientation errors are taken into account from the desired path.

Block diagram (3) shows the complete process of fuzzy logic motion control. Angular velocity and linear velocity of the mobile robot are obtained as output from fuzzy controller. The fuzzy rules are defined based on the tasks. The robot motion command is dependent on the fuzzy selection that integrates and coordinates all behaviours. The initial target position is specified in a 2D space. The tangent angle and distance to the target point are calculated with respect to the robot's current position. These two values are used by the fuzzy controllers as error values. The developed fuzzy controllers for this behaviour are: angle and distance errors as inputs. During the robot movement, the robot moves whether in a straight line or in a circular arc, based on the position and orientation errors which depend on the path. Designed FLC has three inputs and two outputs. The inputs are, the linear distance in the tangent path D or L, the angle α_1 from circle for initial position and the angle α_2 from circle for target position. The outputs are, the linear and angular velocities υ and ω. The linguistic variables are defined in Table 1. Triangular and Trapezoidal membership functions are used for the input and output. The rules in Table 1 constitute a part of the knowledge base of the path tracking behaviour of mobile robot and expresses how the system has to react.

Table 1. Linguistic variables for inputs and Fuzzy rules for outputs.

Linguistic variables for inputs		Fuzzy rules for outputs			
Angle: α_1, α_2	Distance: L	Z	N	M	F
ACL: Anticlockwise Large	Z: Zero	Turn medium	Turn medium	Turn medium	Turn fast
ACM: Anticlockwise Middle	N: Near	Turn medium	Turn medium	Turn medium	Turn medium
ACS: Anticlockwise Small	M: Medium	Turn slow	Turn slow	Turn medium	Turn medium
ZE: Zero	F: Far	Zero	Straight slow	Straight medium	Straight fast
CS: Clockwise Small		Turn slow	Turn slow	Turn medium	Turn medium
CM: Clockwise Middle		Turn medium	Turn medium	Turn medium	Turn medium
CL: Clockwise Large		Turn medium	Turn medium	Turn medium	Turn fast

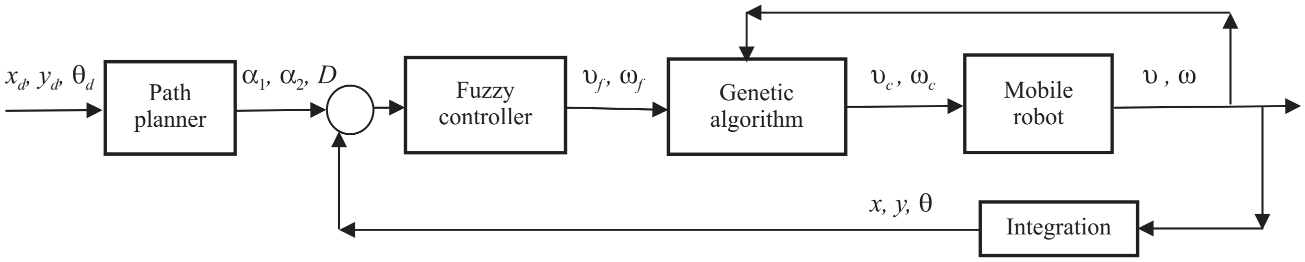

Fig. 3. General structure of motion control.

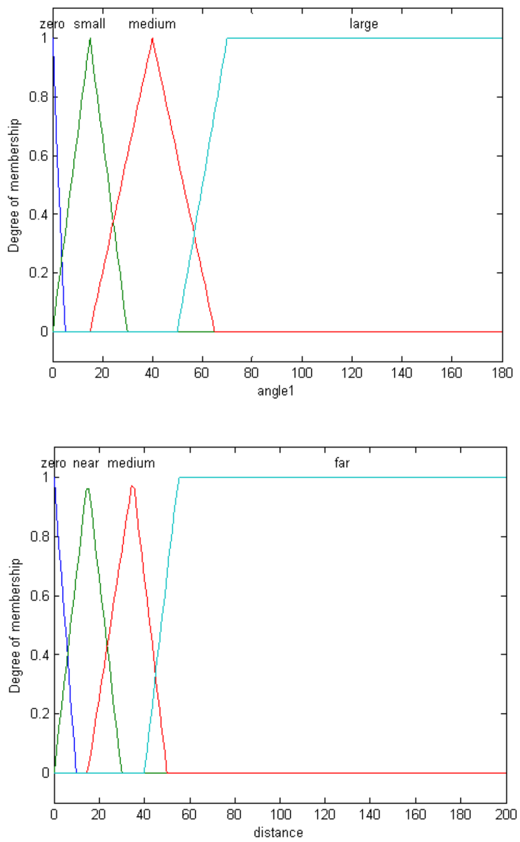

Fig.4. Representation of membership function of inputs angle errors and distance errors.

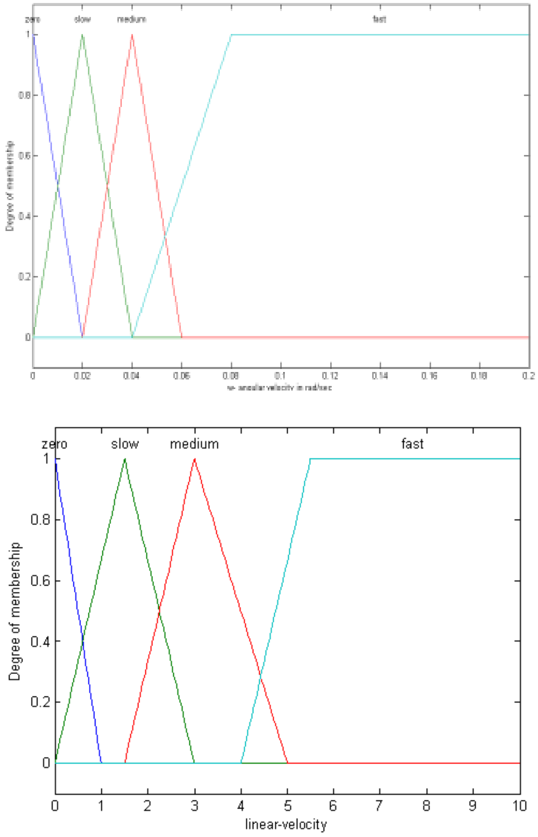

Fig. 5. Representation of membership function of outputs angular and linear velocity.

4.1.1. Membership functions of angle error

The same membership functions are described for linguistic variables α_1 and α_2 which represent orientation of the robot with respect to circle1 and circle2. The membership function of full circle is divided into two parts clockwise and anticlockwise. So the angle error interval is between 0° to 180° or 180° to 360°. The path is simplified to choose a forward moving velocity of the robot to solve trajectory tracking at every point on the curve. The path tracking controller has to ensure a geometrical convergence towards the path to be followed. If the angle α_1 is equal to zero, then the robot's front end is oriented to the direction of the tangent line L. If α_2 is equal to zero, then the robot reaches the target with its desired orientation. The fuzzy membership function D for distance error and angle errors α_1 and α_2 for circle1 and circle2 are shown in Fig. 4.

4.1.2. Membership functions of the output

Essentially, the control objective is to successfully navigate a mobile robot along a desired path in a two-dimensional environment. Designing a fuzzy controller would help in achieve this objective. Considering the situations illustrated by Fig. 2 the vehicle must be designed to follow a path against the given initial and final conditions. This step was suitably chosen to represent a monotonically decreasing function of travelling distance and to give a strong influence in the path direction. The fuzzy logic controller is used to interpret this heuristic in order to generate outputs for linear and angular velocities from the values of error distance D and error angles α_1 and α_2. When the target is far, the speed of the approach should be fast whereas when the target is near, the speed of approach should be slow. For circular motion, the centripetal acceleration is related to the angular velocity ω and the linear velocity υ by the given formula $\upsilon=r\omega$. However the simulation is accurate enough to predict the desired path.

If the controller finds both distance error and angle errors, it will apply the path to generate a decision to which direction should it go next. Before entering into fuzzy logic controller a set of feasible angle errors and distance errors are obtained to get the desired position and direction. In this way, the vehicle could run along the track and at the same time, keep its position in the path. In the simulations, to achieve controlled trajectory, the linear and angular velocities υ and ω are calculated by the given equations (6) and (7). If a different linear velocity υ is desired, the angular velocity ω would be adjusted to get smooth path in the continuity. Like that if a different angular velocity ω is desired, the linear velocity would be adjusted. The velocity profiles are generated by the fuzzy logic algorithm to follow the trajectory and choosing the control parameters for the desired behaviour. The tracked trajectory shown in Fig. 6 is very close to the desired result and the tangential and angular velocities are maintained within the limits.

4.2. Genetic Algorithm

The optimal path generation is essential for the efficient operation of a mobile robot. Recent advances in robotics and machine intelligence have led to the application of modern optimization method such as the genetic algorithm to solve the path-planning problem and motion control. In the optimization, the control parameters υ and ω evaluated from fuzzy logic controller would be changed to the desired path. The most difficult problem in motion control is to find such parameters which could match, fast speed and precise movement. A suitable fitness function can be expressed as $f = \upsilon \nabla t + r\omega \nabla t$ with constraint function of $(\upsilon_f - \upsilon_a + \omega_f - \omega_a)$. Thus, the system computes the distance between straight line and arc in the 2D space. Combining fuzzy logic and genetic algorithm reduces the time to find optimal control parameters for increasing the quality of generated paths. The simulation results demonstrate the algorithm as shown in Fig.7. Using GA the relations between linear and rotational velocities were made constant and the robot's path was lying alongside the arc of a circle.

5. Simulation Results

Trajectory generation is the problem in finding feasible solutions in the motion control. Some of the trajectory generation methods are too complicated and time consuming to produce smooth paths. A mobile robot can follow the desired reference path according to the prescribed velocity profile with a satisfactory accuracy. A motion planning optimization algorithm produces time optimal path for a given input parameter. In this paper, a simple geometric and fuzzy logic method is implemented for trajectory generation. The main idea behind the proposed design control strategy is to find a path which moves to a final position with a desired orientation.

The equation of nonholonomic constraint is not integrable. So the feasible trajectory of the robot is limited. Using the theoretical kinematic model described in section 2, the simulation can be created to get outputs under different motion trajectories and thereby to evaluate the results. In order to attend the robot's position and orientation, the control problem has been designed in such a way that the robot follows three steps with a moving reference frame. The motion of the robot could be described with two modes either pure rotation or pure translation.

The initial location is $(x\ y\ \theta) = (0\text{m}\ 0\text{m}\ 0°)$ and the target is located at $(x_d, y_d, ß)$ = (100m, 80m, 20°), (100m, 80m, 150°), (-100m, 80m, 60°), (-100m, 80m, 240°). Using a fuzzy controller as described above, the robot was able to successfully follow a smooth path towards the target. The resulting linear velocity or angular velocity is ob-

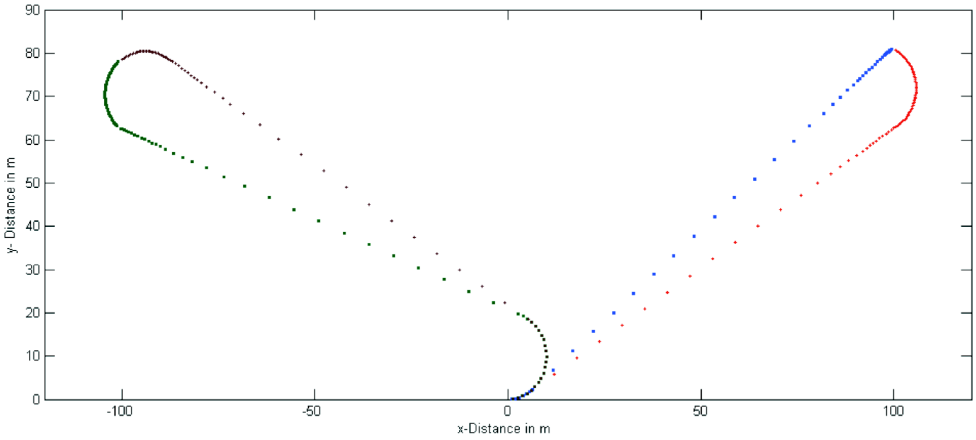

Fig. 6. State responses (x, y, θ).

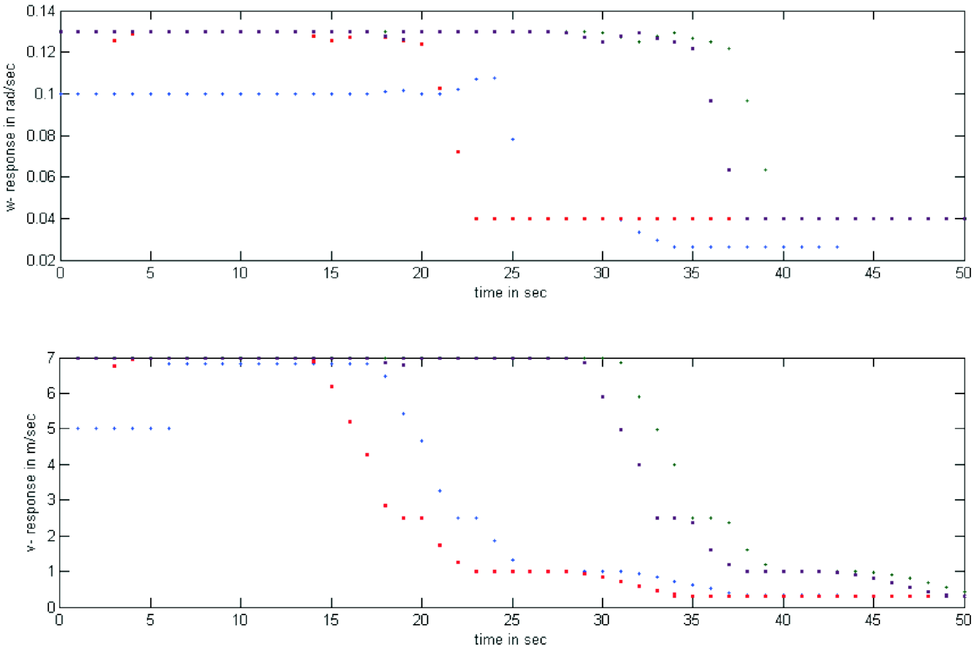

Fig.7. Fuzzy logic simulated results with genetic algorithm.

tained in all four behaviours as long as the vehicle is far away from the target. With the use of circular motion, the trajectory becomes a smooth curve and the angular and linear velocities are adjusted according to the next steps. The measure of smoothness of path is obtained by the constraint function of genetic algorithm by the given formula $\upsilon = r\omega$. The vehicle is decelerated from the maximum speed before turning a corner to adapt angular velocity and it is again accelerated after turning the corner depending on the distance. The vehicle is not stopped at this point. If the length of the straight or circular path is close to the next path, the robot would not move at minimum speed, even if it is obtained from a part of the trajectory. Robot motion control requires time optimal to drive with high speed and therefore a smooth path is necessary. Its time responses of ω and υ are shown in Fig. 7. In the intersection point of the curves the robot has to move with maximum allowed speed within radial acceleration.

This method produced trajectory characteristics which were smoother and better. The control results are analysed by the Matlab environment. These control parameters are then used to control the vehicle each time and it autonomously travels along the path as shown in Fig. 6.

6. Conclusion

Modelling and control strategy of the motion of the three wheeled differentially driven nonholonomic mobile robot is discussed. Fuzzy logic controller has been developed on Matlab software environment for addressing the problem of tracking control for a desired position and orientation. In this paper, the trajectory is used to derive the kinematic relations of the robot at the displacement, velocity and acceleration levels. The implementation of this proposed control strategy is a simple geometric approach and the simulations give satisfactory results. Suitable velocity control inputs were obtained from fuzzy logic algorithm which stabilizes the kinematic closed loop control. In future, the ability of obstacle avoidance will be added to get optimal path planning.

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