# Sliding Mode Fuzzy Control of a Skid Steer Mobile Robot for Path Following

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# Sliding Mode Fuzzy Control of a Skid Steer Mobile Robot for Path Following

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***Abstract*—In this paper, robust sliding mode fuzzy logic control of a four-wheel differentially driven skid steer mobile robot, for path following is considered. This approach combines basic principles of Sliding Mode Control (SMC) with Fuzzy Logic Control (FLC). The path comprises a sequence of discrete waypoints. A novel approach in path extraction interpolates waypoints by means of quadratic curve to generate a continuous reference path. The positional data of waypoints are obtained using a vision system mounted on the mobile robot. Experimental study has been carried out to evaluate the performance of the proposed controller and to compare its performance with a conventional fuzzy logic controller performance. The experimental results show that the proposed controller has achieved superior performance in the presence of model uncertainties and external disturbances with minimum reaching time, minimum distance error, and smooth control actions.***

***Keywords*—sliding mode fuzzy logic control, path following, skid steer, vision-based**

## I. Introduction

Wheeled Mobile Robots (WMR) are widely used in diversity of fields such as agriculture, industry, land mining, military, space explorations, and other applications where the environment is inaccessible or perilous to human, such as in nuclear plants. When considering the problem of accurate path following, skid steer mobile robots are difficult to model. In fact, the wheels of the mobile robot need to skid laterally in order to follow a curved path. Moreover, the Instantaneous Center of Rotation (ICR) of skid steer mobile robots may move out of robot wheelbase, causing loss of motion stability. A survey of literature reveals that although a large amount of research has been performed on Ackermann-steered and differential drive WMRs, in terms of mathematical modeling and control, a few works exist on four-wheel differentially skid steer mobile robots. Several approaches have been developed to solve this problem through direct control of the robot's dynamics. In some of these approaches [1, 2], nonlinear controllers are derived based on the Lyapunov approach. Other types of controllers were designed [3-6] using nonlinear techniques and were applied to the nonlinear kinematic and dynamic model of the robot. In [7] the nonlinear dynamic model of the robot with coupled inputs is obtained in state space representation, using a nonlinear transformation the inputs are decouple, and state space trajectory is used as a reference. The controller uses the state trajectory starting from any point of state space and converges asymptotically on sliding surface towards an equilibrium position.

Figure. 1. Pioneer 2AT mobile robot

In [8] the stability of a pure pursuit path tracking algorithm is analyzed for a kinematic model using a linearized kinematic model. The analysis is done for the case of a straight line and a circle, with the reasoning that most trajectories can be decomposed into pieces of constant curvature. Irrespective of the performance of these approaches, they cannot be implemented if the robot model is inaccessible. In addition, they are difficult to tune in order to achieve an efficient performance.

The sliding mode control system is defined as the creation of a specific operating mode, the so-called sliding mode, which occurs on a predetermined sliding surface. The properties such as adaptiveness and robustness of the sliding mode control method make it a superior choice among the other control methods. The control action in a sliding mode controller is designed to force the system trajectory to reach the sliding surface (reaching or hitting phase) and to slide along it (sliding phase) or to remain in its vicinity [9–12]. The outstanding merit of the sliding mode controller is robustness against structured and unstructured uncertainties during the sliding phase [13–15]. However, during the reaching phase the system states are pushed toward the switching surfaces. During this period, the tracking error cannot be controlled directly and the system response is sensitive to parametric uncertainties and noise. Thus it is ideal to shorten the duration of the reaching phase [9, 16]. Also, the major drawback in the sliding mode controller is the occurrence of the undesired phenomenon of chattering. This phenomenon is due to high frequency switching which excites undesired dynamics. The sensitivity of the sliding mode controller before reaching the sliding surface and the presence of chattering may introduce problems to the path following control of mobile robots. One of the solutions of removing the chattering problem is to introduce a thin boundary layer in vicinity of the switching surface. However, by introducing a boundary layer, steady state errors may occur. The mentioned problems in the conventional sliding mode control theory can be compensated with fuzzy logic principles. Combining both FLC and SMC theories has the advantages of both SMC and FLC [17, 18]. Although traditional fuzzy controller lacks formal synthesis techniques and all the decision rules are experience oriented, the FSMC technique provides a simple way to design FLC systematically. To decrease the number of rules in the rule base of the fuzzy controller, several authors have suggested using a composite state to obtain a fuzzy sliding mode controller. The advantage of such controller is that the number of rules required is reduced from $m^n$ to $m^2$ [19- 21], or $nm^2$ in Kung [22]. In general, since the FSMC combines both fuzzy control and sliding mode control principles, the performance of closed-loop system is superior to that using only one control theory.

The main advantage of FSMC is that the control method achieves asymptotic stability of the system. Another attractive feature is that the number of rules required is reduced and provide robustness against model uncertainties and external disturbances. In addition, the method is capable of handling the chattering problem that takes place in the traditional sliding mode control. Although FSMC (mainly model based) has been used in robotic applications, its implementation for mobile robots is rarely reported.

In this paper, we propose a sliding mode fuzzy logic control for path following of a four-wheel differentially driven skid steer mobile robot. An approach in determination of distance error is proposed and a continuous trajectory is interpolated by means of quadratic curve. Positional data of waypoints are obtained using a CCD camera mounted on the deck of the mobile robot. Experimental studies have been carried out to evaluate the performance of the proposed controller and to verify the validity of this controller compared to traditional fuzzy logic controller.

## II. Robot Kinematic Modeling

The kinematic modeling of a four wheeled differentially driven skid steered mobile robots in two-dimensional plane is presented in this section. The posture of the robot with respect to a global reference frame-$XY$ is defined by, its center of gravity position and heading angle at any instant.

The velocity of mobile robot's Center of Gravity (CG), with respect to global frame, is given by,

$$V_{CG} = \dot{X}\,\mathrm{i} + \dot{Y}\,\mathrm{j} \tag{1}$$

Where $X$ and $Y$ are CG coordinates in the global frame of reference.

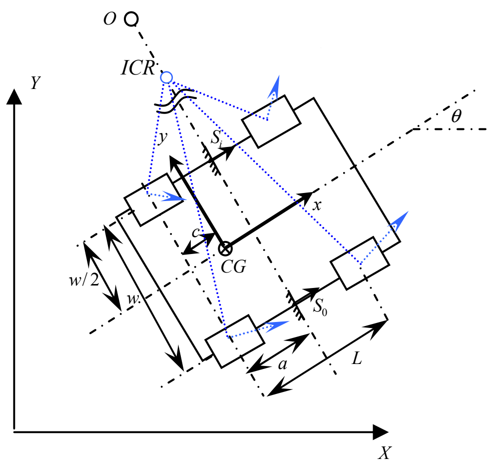


Figure. 2. Kinematic parameters of the robot

As depicted in Fig. 2, $\dot{S}_i$ ( $\dot{S}_O$ ) is introduced for the "intersection point velocity" of the line joining inner (outer) wheels centers and the orthogonal line passing through Instantaneous Center of Rotation (ICR), $a$ the distance from the orthogonal line through ICR to the rear wheels axel, $c$ the distance between CG and rear wheels axel, $\theta$ the heading angle which is positive counter-clockwise, and $w$ the width of robot. For pure rotation of the robot around ICR, the linear velocity components in local reference frame-$xy$ disappear. Also, during straight line motion, the angular velocity and the lateral velocity both vanish and ICR goes to infinity along y-axis [23]. Appling rigid body dynamics, the velocity of mass center can be expressed as

$$\boldsymbol{V}_{CG} = \dot{\boldsymbol{S}}_i + \boldsymbol{V}_{CG/S_i} \tag{2}$$

The above kinematic relation is simply led to the following expression for the velocity of CG

$$
\boldsymbol{V_{CG}} = \boldsymbol{S}_i(\cos\theta\,\boldsymbol{i} + \sin\theta\,\boldsymbol{j}) + \theta\boldsymbol{k} \times \left\{ \left[ \frac{w}{2}\sin\theta - (a-c)\cos\theta \right]\boldsymbol{i} - \left[ \frac{w}{2}\cos\theta + (a-c)\sin\theta \right]\boldsymbol{j} \right\} + a(\cos\theta\,\boldsymbol{i} + \sin\theta\,\boldsymbol{j}) \tag{3}
$$

Using Eq. (1) and the relation between the angular velocity of the robot and the velocities of its inner and outer wheels, the kinematic model of robot is given by,

$$
\begin{aligned}
X &= S_i\cos\theta + \theta\left[\frac{w}{2}\cos\theta + (a-c)\sin\theta\right] + a\cos\theta \quad , \quad \theta = \frac{S_o - S_i}{w} \\
Y &= S_i\sin\theta + \theta\left[\frac{w}{2}\sin\theta - (a-c)\cos\theta\right] + a\sin\theta
\end{aligned} \tag{4}
$$

In this formulation, it is of primary concern to specify the parameter $a$. In order to determine this parameter, we used the simulation of the dynamical model proposed in [24]. This led us to conclude for low speeds both ICR and CG of the mobile robot are located on the $y$ axis. This indicates that the center of the gravity of the robot will be almost fixed during the motion. Therefore in low robot speeds we can say $a=c, a=0$ Letting $a=c$ in Eq. (4), the kinematic model will be reduced to

$$
\begin{cases}
X = (S_i + \theta\frac{w}{2})\cos\theta \\
Y = (S_i + \theta\frac{w}{2})\sin\theta \\
\theta = \dfrac{S_o - S_i}{w}
\end{cases}
\Rightarrow
\begin{cases}
X = (\dfrac{S_i + S_o}{2})\cos\theta \\
Y = (\dfrac{S_i + S_o}{2})\sin\theta \\
\theta = \dfrac{S_o - S_i}{w}
\end{cases} \tag{5}
$$

## III. Error Determination Algorithm

Point $B$ (Fig.3) the center of the camera field of view which is projected on the floor is chosen to be the reference point on mobile robot. The coordinates of this point are denoted by $x_0$ and $y_0$, in the local reference frame-$xy$. To obtain the error equation, distance error is defined as perpendicular distance from the reference point to the desired path. If the equation of reference in the local reference frame-$xy$ is represented by $y=f(x)$, the magnitude of distance error will be given by

$$
e = |AB| = \sqrt{(x-x_0)^2 + (y-y_0)^2} \tag{6}
$$

To determine point $A$ on the reference path which results in the minimum distance to the reference point $B$ the derivative of the distance error with respect to $x$ must be set equal to zero. This leads to the following linear algebraic equation:

$$
\begin{aligned}
&\frac{d}{dx}(e) = 0 \Rightarrow (x - x_0) + f'(x)(f(x) - y_0) = 0 \\
&\Rightarrow x + f'(x)f(x) = x_0 + f'(x)y_0
\end{aligned} \tag{7}
$$

By knowing the equation of the reference path, $y$, and the coordinates of reference point $B$ (i.e $x_0$, $y_0$), coordinates of point $A$ ($x$ and $y$) are determined and the distance error will be calculated. The equation of reference path is derive by interpolating a curve through discrete points on the floor observed by CCD camera.

To obtain the rate of change of distance error, we introduce another local reference frame-$x_1y_1$ (Fig. 3). The velocity of the point $B$ in this frame is expressed as:

$$
\boldsymbol{V_B} = V_{x_1}\boldsymbol{i_1} + V_{y_1}\boldsymbol{j_1} \tag{8}
$$

Since the translational and rotational velocities of the mobile robot's mass center in the local reference frame are $x$ and $\theta$ respectively (assuming $a=c$), the velocity of the point $B$ can

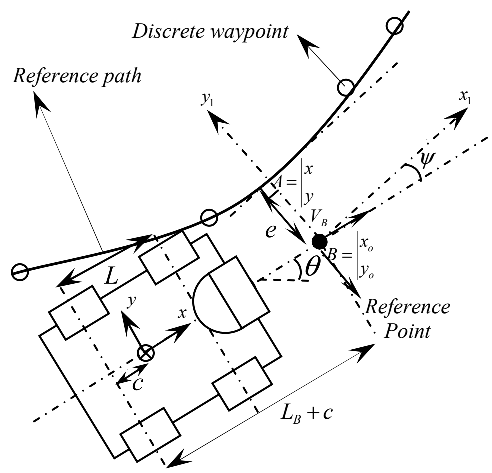


Figure 3. Error determination algorithm

be written as:

$$
\boldsymbol{V_B} = (x\cos\psi + L_B\theta\sin\psi)\,\boldsymbol{i}_1 + (L_B\theta\cos\psi - x\sin\psi)\,\boldsymbol{j}_1 \tag{9}
$$

Where $L_B$ is the distance from point $B$ to the robot's mass center. According to geometry of the followed point, the derivative of the distance error is calculated

$$
\begin{aligned}
e &= V_{A,y_1} - V_{B,y_1} = 0 - (L_B\theta\cos\psi - x\sin\psi) \\
&= x\sin\psi - L_B\theta\cos\psi
\end{aligned} \tag{10}
$$

By applying Eqs. (6)-(10), the distance error, $e$, and derivative of distance error, $e$, are calculated. In all of implementations, the extracted path and the reference point are specified in the local reference frame-$xy$ attached to mobile robot.

The reference path includes a set of sequences of waypoints. If the robot observes only one point, we expect the robot to follow that and finds more than one point. In the case that the robot finds two points, our strategy helps the robot to pass a straight line between points and runs error determination algorithm. If the observed waypoints are more than two, the proposed algorithm will interpolate a quadratic curve through waypoints and runs error determination algorithm.

## IV. Conventional Fuzzy Logic Controller

In design of fuzzy logic controller, we use Mamdani type of fuzzy control that consists of fuzzification, defuzzification and a rule base [26]. In this section we use FLC in terms of kinematic model of the robot. Inputs to the fuzzy controller are distance error, $e$, derivative of error, $\dot{e}$, and its output is rotational velocity, $\omega$. A suitable fuzzy system for rotational velocity control is implemented with seven triangular membership functions for the input variables $e$ and $\dot{e}$. Although, there is no restriction on the form of membership functions, we choose the piecewise linear description (Fig. 4). Another step in design of FLC is the fuzzy inference mechanism. The knowledge base of the system consists of 49 rules shown in table I. In this application, algebraic product is used for all the *t-norm* operators; max is used for all the *s-norm* operators, as well as individual-rule based

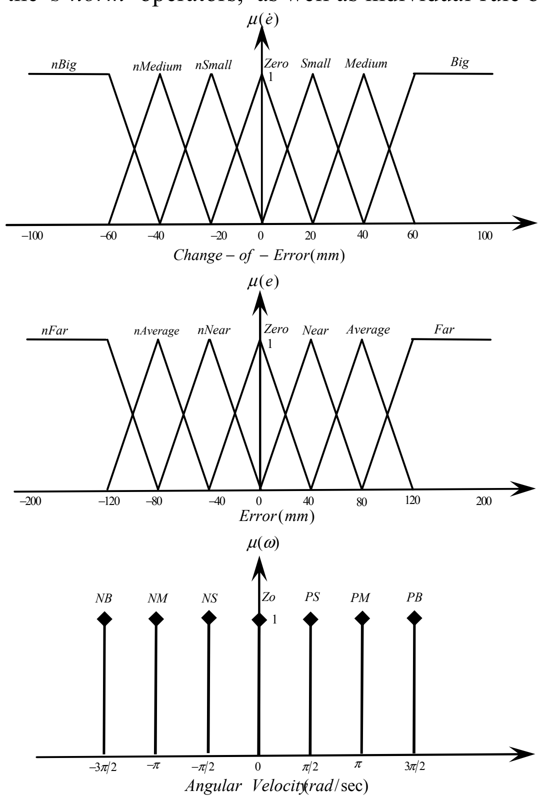

Figure. 4. Membership functions for fuzzy sets of $e$, $\dot{e}$ and $\omega$

inference with union combination and Mamdani's product implication

$$\mu_{B'}(y) = \max_{l=1}^{M}\left[\sup_{x\in U}\left(\mu_{A'}(x)\prod_{i=1}^{n}\mu_{A_i^l}(x_i)\mu_{B^l}(y)\right)\right] \quad (11)$$

There are many alternatives to perform defuzzification. The strategy adopted here is the Center Average defuzzification. This method is simple and very quick.

$$y^* = \sum_{l=1}^{M}\bar{y}^l w_l \Big/ \sum_{l=1}^{M} w_l \quad (12)$$

Where $\bar{y}^l$ is the center of $l$th of fuzzy set and $w_l$ is its height.

TABLE I. Rule base for Fuzzy Logic Controller

| $\dot{e}$ \ $e$ | nFar | nAverage | nNear | Zero | Near | Average | Far |
|---|---|---|---|---|---|---|---|
| **nBig** | NB | NB | NM | NB | NM | NS | Zo |
| **nMedium** | NB | NB | NM | NM | NS | Zo | PS |
| **nSmall** | NB | NM | NS | NS | Zo | PS | PM |
| **Zero** | NB | NM | NS | Zo | PS | PM | PB |
| **Small** | NM | NS | Zo | PS | PS | PM | PB |
| **Medium** | NS | Zo | PS | PM | PM | PB | PB |
| **Big** | Zo | PS | PM | PB | PM | PB | PB |

## V. Sliding Mode Fuzzy Logic Controller

In previous section, we used $e$ and $\dot{e}$ as fuzzy input variables, regardless of the complexity of controlled plants [27]. Such fuzzy logic controllers (FLCs) are suitable for simple second order plants. However, for more complex higher order plants, all process states can be taken as fuzzy input variables to implement state feedback FLCs. If all state variables are used to represent the content of the rule antecedent (IF part of a rule), it will require a large number of control rules and much effort to create them. Due to these facts, a simpler FLCs design is highly desirable.

In the SMFLC design, the sliding-mode principle is adopted to establish the fuzzy logic rules. First, the sliding function, denoted by $s$, is defined as:

$$s = \dot{e} + \lambda e \quad , \quad \lambda = 4 \quad (13)$$

Where $e$ is distance error, $\dot{e}$ is derivative of error, and $\lambda$ is a strictly positive constant. In this way, the SMFLC designed is capable of first converging the system dynamics to the neighborhood of the sliding surface before reaching the origin; in other words, providing the means to regulate the transient response. In experimentation, $\dot{e}$ and $\dot{s}$ are considered available by the discrete approximation of

$$\begin{aligned} \dot{e}(KT) &= \frac{1}{T}\left[e(KT) - e(K-1)T\right] \\ \dot{s}(KT) &= \frac{1}{T}\left[s(KT) - s(K-1)T\right] \end{aligned} \quad (14)$$

Where $K$ is the number of iteration and $T$ is the sampling period. The output of the SMFLC is angular velocity of the robot. The inputs to FL controller are s and $\dot{s}$ and its output is the angular velocity of the robot. The value of s and $\dot{s}$ are scaled by $G_S$ and $G_{\Delta S}$ for an optimal performance based on circumstances. Scaling gives

$$S = sG_S \qquad G_S = 0.4$$
$$\dot{S} = \dot{s}G_{\Delta S} \qquad G_{\Delta S} = 0.4 \qquad (15)$$

The membership functions for the fuzzy sets of $S, \dot{S}$ and $\omega$ are defined and illustrated in Fig 6. Only five fuzzy subsets, NL, NS, Z, PS, PL, are defined for $S$ and $\dot{S}$, which require

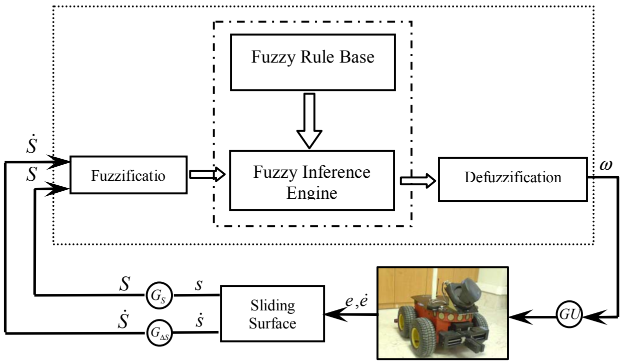

Figure. 5. Structure of the sliding mode fuzzy logic system

subsequently 25 fuzzy rules to accomplish the fuzzy control design. The resulting fuzzy sliding-mode inference rules are shown in Table II. The change of the control signal for this controller is calculated by

$$Control\ Action = SMFLC\,(S, \dot{S}) \times GU \qquad GU=3 \qquad (16)$$

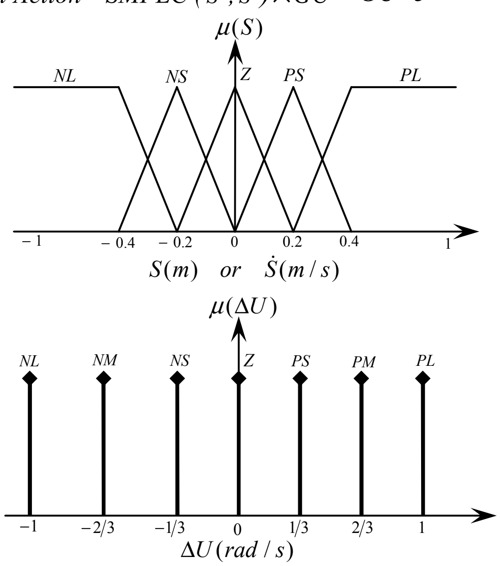

Figure 6. Membership functions for inputs and output fuzzy sets

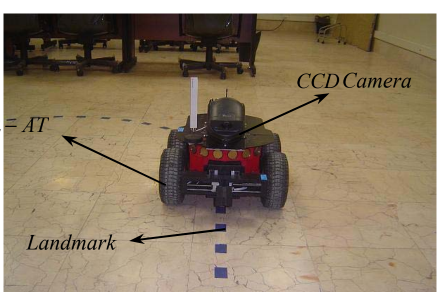

Figure. 7. .P2-AT mobile robot and its reference path

TABLE II. RULE BASE FOR SLIDING MODE FUZZY LOGIC CONTROLLER

| $\dot{S}$ \ $S$ | NL | NS | Z | PS | PL |
|---|---|---|---|---|---|
| **NL** | NL | NL | NM | NS | Z |
| **NS** | NL | NM | NS | Z | PS |
| **Z** | NM | NS | Z | PS | PM |
| **PS** | NS | Z | PS | PM | PL |
| **PL** | Z | PS | PM | PL | PL |

## VI. EXPERIMENTAL RESULTS

In this section, reliable and efficient execution of the FLC and fuzzy sliding mode control in a real application is demonstrated. The mobile robot used for this purpose is a P2-AT made by Activmedia Company (Fig.1).

Initial states of the robot as well as the distance error are shown in the plots of the path following process. The reference path includes a set of the discrete points with 20 centimeter spacing between them (Fig. 7). The robot starts moving by the initial velocity of zero. In the robot doesn't see any point, we ask the robot to turn in order to find waypoints and continue the execution of the path following.

In order to compare FLC and SMFLC performances, three different scenarios have been presented. In the first scenario, the robot was directed through an uneven sandy terrain. It was preferred to create the sandy terrain in the path curvature to make the path following more difficult results are depicted in Fig. 8. In the second scenario, a 13 kg pay load was added to the robot and path following was performed. Fig. 9, shows distance error of reference point for following the desired path. Finally, the distance between discrete waypoints was increase to compare the controllers, resembleing external disturbances. Results of experimentation are shown in Fig 8-10. A summery of results are presented in Table III. Superior performance of SMFLC compared to traditional FLC was observed in all cases. Experimental results show that the proposed sliding mode fuzzy controller is robust against parameter uncertainty and external disturbance.

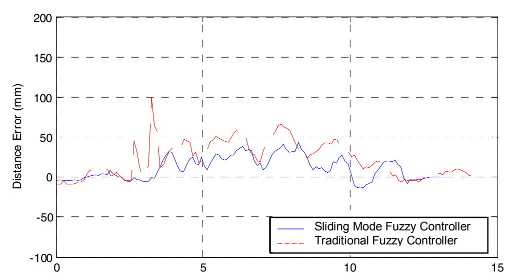

Figure. 8. Performance of controllers on an even sandy terrain (change in ground friction coefficient), V=400 (mm/sec)

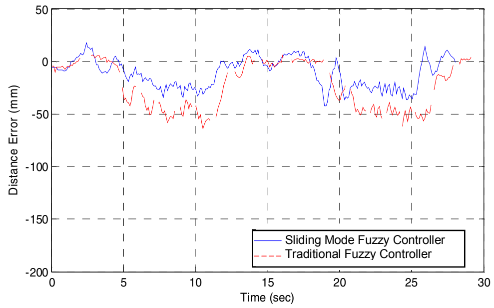


Figure. 9. Performance of controllers in presence of 13 kg pay load. (parameter uncertainty), V=400 (mm/sec)

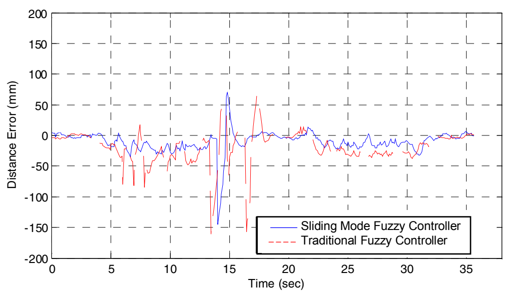


Figure. 10. Performance of controllers in presence of external disturbance (removing some of discrete waypoints) in V=400 (mm/sec)

TABLE III. PERFORMANE OF CONTROLLERS IN DIFFERENT CONDITIONS

| | Maximum value of distance error (mm) | Average of absolute value of distance error (mm) | Standard deviation of distance error (mm) |
|---|---|---|---|
| ***Performance in presence of change in the ground friction coefficient*** | | | |
| SMFLC | 43.6 | 13.9 | 14.2 |
| FLC | 98.7 | 24.6 | 22 |
| ***Performance in presence of parameter uncertainty*** | | | |
| SMFLC | 42 | 14.6 | 14.2 |
| FLC | 63.7 | 23.8 | 22.3 |
| ***Performance in presence of removing some of discrete waypoints*** | | | |
| SMFLC | 145.6 | 13 | 17.7 |
| FLC | 160.5 | 22.6 | 27.5 |

## VII. CONCLUSION

In this paper, sliding mode fuzzy logic control for path following of a skid steer mobile robot is presented. The path consists of a sequence of discrete waypoints. An approach in error determination is proposed. The sliding function is employed as fuzzy inputs to provide the capability for the designer to regulate the transient response of the system. The scheme of SMFLC offers a procedure to reduce fuzzy rules. Experimental studies have been carried out to evaluate the performance of the proposed controller. Results show better performance of this controller compared to traditional fuzzy logic controller.

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