

SIMPLE FUZZY LOGIC BASED PATH TRACKING CONTROLLER FOR A MOBILE ROBOT

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Abstract: *In this paper, a path tracking controller for differential drive mobile robots based on fuzzy logic to emulate a human driver experience is presented.*

The controller drives the robot smoothly and continuously to reach its goal through a sequence of discrete waypoints at a high speed with a high precision, by varying the linear velocity according to the robot situation on the path and by adjusting the angular velocity to appropriate the curvature of the bends.

A new measure of the look-ahead curvature is introduced and a reduced number of control variables are used to make the controller design simpler.

Simulations conducted in a high fidelity visual simulation environment show the effectiveness of the proposed controller.

Key words: *fuzzy logic, look-ahead curvature, mobile robot, path tracking.*

1. Introduction

Wheeled mobile robots are increasingly present in industrial and service robotics, particularly when flexible motion capabilities are required on reasonably smooth grounds and surfaces [1]. Several mobility configurations can be found in the applications [2].

In the absence of workspace obstacles, the basic motion tasks assigned to a mobile robot may be reduced to moving between two robot postures and tracking a given trajectory. One of the most important issues in the field of mobile robotics and autonomous navigation is to build physical systems that can move purposefully and without human intervention in real world environments and the design of control algorithms for path tracking. The main objective of such algorithms is to assure that the mobile robot will follow a predetermined path.

The problem of path tracking by a wheeled mobile robot has been gaining in popularity over recent decades and has been extensively studied in mobile robotics literature; various control strategies have been proposed to drive the robot efficiently to execute a given trajectory. These approaches can be divided into three main categories: 1) considering only the kinematic model [3 - 22], 2) considering only the dynamic model [23 - 35], and 3) considering both kinematic and dynamic model [36 - 44].

The major topic of the present study is the design of a simple path tracking controller; this is why the interest is focused on the first category. Another reason is that the computation of the algorithms of the two other categories must be made by demanding computer operations and that most market available robots come with built-in low level PID velocity controllers to track input reference velocities and do not allow the motor voltage to be driven directly.

The trajectory tracking methods adopted for kinematic control include different strategies and techniques. In [3], a combined closed-loop observer controller is developed to assure the K-exponential convergence of the tracking error. The robust PI controller proposed in [4] has a good compromise between performance and robustness. It can successfully remove the disturbance due to the robot load. Reference [5] proposes a controller which includes velocity and acceleration constraints to prevent the mobile robot from slipping and Smith predictor is used to compensate for the vision system dead time. In [6], the conditions for zero tracking error are established under the kinematic framework. The reference characterization is based on the classical decoupled robot control and the inverse kinematics of fixed, centered orientable, castor and Swedish wheels. Reference [7] deals with discrete trajectory tracking based on velocity control laws and backstepping. From a kinematic model, a robust adaptive controller is designed based on backstepping methods [8]. In addition, a reduced adaptive controller with projection mapping is proposed for the purpose of smooth vehicle movements. Geometrical mobile robot path tracking is considered in [9]. The so called Accumulated Effect method for parameter tuning for three algorithms is proposed. It is shown that the tuned parameters correspond to the optimal path tracking performance for geometrical methods. Reference [10] deals with one of the geometric path tracking methods: the Vector Pursuit. The proposed controller can determine the look-ahead distance, the reference velocity, and the limit on the angular velocity with the given constraints. A nonlinear model predictive tracking controller is presented in [11]. The controller minimizes the total tracking error

and can deviate from obstacles by incorporating into the optimization the obstacle-distance information. In [12], a computationally simple and model parameters insensitive biologically inspired tracking controller is proposed. The controller resolves the speed jump problem and removes the impractical assumptions of perfect velocity tracking by taking into consideration the acceleration constraints. The speed jump problem is resolved in [13] by incorporating a biologically inspired shunting model with the conventional nonlinear feedback control. This model is capable of generating smooth continuous velocity control commands. A neural based approach for real time path planning and tracking is proposed in [14]. The tracking controller generates a smooth path and velocity without suffering from the speed jump problem.

Despite the performance of these approaches, tedious analysis is required to design the control algorithms, in addition to the difficulty of parameters tuning. Fuzzy control using linguistic information possesses several advantages such as robustness, model free, universal approximation theorem, and rule based algorithm. It provides an algorithm which can convert the linguistic control strategy based on expert knowledge into automatic control strategy [23, 24, 25 and 26]. Thus, fuzzy control methods have attracted more attention to deal with the complex control problem of mobile robots. A fuzzy logic based navigation algorithm is presented in [15]. The fuzzy inference system exploits the information concerning the curvature of the desired path ahead the vehicle and the distance between the next bend and the vehicle to safely drive the robot. The output of the fuzzy module is the maximum value of the linear velocity; based on this, a velocities module computes the vehicle motion references that satisfy the bounds on the linear/angular velocities and accelerations. In [16], Genetic Algorithm and Differential Evolution are used to tune the membership functions of a fuzzy path tracking controller in order to improve its performance. An FPGA implementation of a digital fuzzy logic controller for path tracking is presented in [17]. In [18], a switching fuzzy logic controller for mobile robots with a bounded curvature constraint is presented. The controller tracks piece-wise linear paths, which are an approximation of the feasible smooth reference path. The controller is constructed through the use of a map, which transforms the problem to a simpler one; namely the tracking of straight lines. This allows the use of an existing fuzzy tracker deployed in a previous work, and its simplification leading to a 70% rule reduction. The dynamic Petri recurrent-fuzzy-neural-network (DPRFNN) is applied to the path tracking problem [19]. The proposed approach in [20] uses predictive control and fuzzy logic control to overcome delay and nonlinear characteristics and improve the system robustness. Robust sliding mode fuzzy logic control

of a four-wheel differentially driven skid steer mobile robot, for path following is considered in [21]. 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. In [22], a fuzzy controller for the path tracking of a mobile robot is proposed. It is based on the control of the mobile robot at a higher level since that the robot dynamics cannot be accessed. The controller showed high robustness and flexibility to follow a sequence of discrete waypoints. It is constituted of two fuzzy modules; the first one calculates the look-ahead curvature at the target waypoint and the second controls the robot linear and rotational velocities to make it moving smoothly and continuously. However, the determination of the look-ahead curvature requires the knowledge of the coordinates of four waypoints and complicated calculation to provide the inputs of look-ahead curvature fuzzy module. The second fuzzy module which is the path tracking fuzzy module has four input items and two output items, subsequently; an important number of inference rules are required.

In this paper a simple fuzzy logic controller for the path tracking problem is proposed. It is based on the experience of a human driver in car driving and has a simple architecture. The controller is composed of two fuzzy modules. The first one is a conventional fuzzy PD controller in charge of the control of the robot's angular velocity. While the second one controls the linear velocity of the robot. A new measure of the look-ahead curvature (*LAC*) is introduced in the present work to simplify the calculations. The proposed controller drives the robot through the discrete waypoints forming the trajectory in smooth and continuous manner at high speed and a high precision. To show the effectiveness of the proposed method, comparative simulation tests with the controller proposed in [22] were performed in the visual simulation environment of the Microsoft Robotics Developer Studio (MRDS).

The paper is organized as follows, in section 2; the proposed path tracking strategy is presented. The kinematic model of the differential drive mobile robot is given in section 3. The details of the path tracking controller design are presented in section 4 and the simulation results are shown and discussed in section 5. The paper is ended with a brief conclusion.

2. The Proposed Path Tracking Method

The path to track is represented by a sequence of m discrete waypoints (N_i) that can be generated offline by a global path planner in known environments, or can be calculated online by a local path planner or by an obstacle avoidance system in partially known or unknown dynamic environment (Fig. 1).

The path tracking task consists of two navigational actions; going ahead on the straight parts of the path and turning at bends. On the straight parts of the trajectory where the waypoints are well aligned, the robot can increase its linear velocity. But when approaching a bend, the robot must slow down (decreases the linear velocity) accordingly to the look-ahead curvature then increase its angular velocity to perform a sharp turn.

The robot pose in the navigation environment is given by (x_r, y_r, θ) . Where x_r and y_r represent the position of the robot and θ its orientation.

The path tracking task is performed using the following steps:

Step 1: the robot begins by tracking the first waypoint by adjusting its rotational velocity according to the heading error given by:

$$e = \theta_{d1} - \theta \quad (1)$$

Where θ_{d1} represents the desired orientation to conduct the robot to the destination (the actual waypoint), and θ is the actual orientation of the robot. θ_{d1} is given by:

$$\theta_{d1} = \text{atan2}(x_{d(i)} - x_r, y_{d(i)} - y_r) \quad (2)$$

Where $x_{d(i)}$ and $y_{d(i)}$ represent the coordinates of the actual target waypoint (N_i).

Step 2: when the heading error approaches zero (gets small value), the robot moves toward the actual waypoint by varying its linear velocity in respect to R (the distance separating the robot and the waypoint) and the LAC .

In this study, a new measure of the look-ahead curvature (LAC) is introduced; the LAC is given by the difference of the absolute values of the desired orientation to the actual target point θ_{d1} , and the desired orientation to the next waypoint θ_{d2} (Fig. 1).

$$LAC = |\theta_{d1}| - |\theta_{d2}| \quad (3)$$

θ_{d2} is defined as follows:

$$\theta_{d2} = \text{atan2}(x_{d(i+1)} - x_r, y_{d(i+1)} - y_r) \quad (4)$$

Where $x_{d(i+1)}$ and $y_{d(i+1)}$ represent the coordinates of the next waypoint (N_{i+1}).

In the case of well aligned waypoints, the LAC will have small values. Meanwhile, in the case of a bend, the value of the LAC will increase as the distance (R) separating the robot from the bend decreases.

According to the value of the LAC two cases are considered:

Step 3: the LAC has a small value which means that the robot is moving on a straight path, and in this case the robot can increase or maintain its linear velocity at its maximum value without caring about the distance to the actual waypoint.

Step 4: if the LAC has a large value which indicates that the robot is facing a bend, the linear velocity is decreased gradually with the distance to the actual waypoint to pass the bend safely.

Step 5: a test on the distance is performed to decide when to switch from tracking the actual waypoint to tracking the next one in the sequence. In our case, we test if ($R \leq 0.3m$).

Step 6: arriving at the final destination, a virtual next point is supposed in the manner to make the value of the LAC increase as the robot approaches its target.

The tolerance at final waypoint is **1cm**, the robot stops when the condition is achieved ($R \leq 0.01m$).

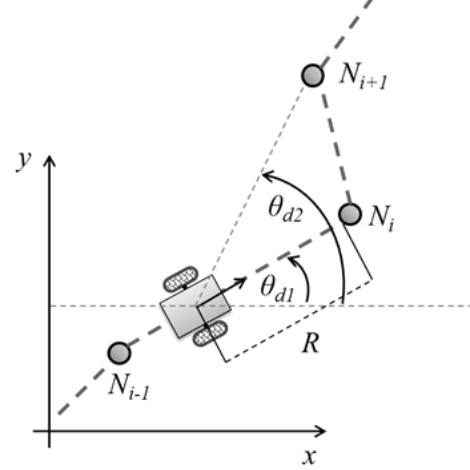


Fig. 1. Path tracking parameters.

3. Mobile Robot Kinematics

In this paper, a typical differential drive mobile robot is considered. In this design incremental encoders are mounted onto the two drive motors to count the wheel revolutions. The robot can perform calculations to determine its linear and angular velocities. The maximum linear and angular velocities of the considered mobile robot are respectively 1 m/s and 1 rad/s . The robot's wheel rotation is limited to one axis. Therefore, the navigation is controlled by the speed change on either side of the robot. The kinematical scheme of a mobile robot can be depicted as in Fig. 2, where V is the velocity of the robot centroid, V_L is the velocity of the left wheel, V_R is the velocity of the right wheel, r is the radius of each wheel, L is the distance between the two wheels, x_r and y_r represent the position of the mobile robot and θ is the orientation of the robot.

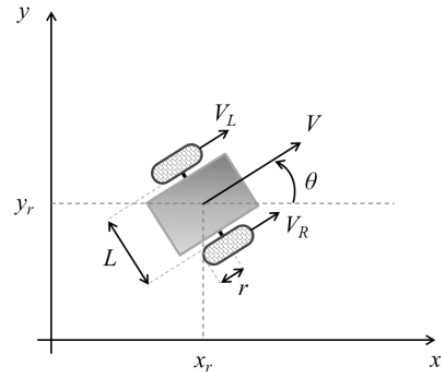


Fig. 2. The kinematical scheme of the mobile robot.

According to the motion principle of rigid body kinematics, the motion of a mobile robot can be described using equations (5) and (6), where ω_L and

ω_R are angular velocities of the left and right wheels respectively, and ω is the angular velocity of the robot centroid.

$$V_R = r\omega_R, V_L = r\omega_L \quad (5)$$

$$\omega = \frac{V_R - V_L}{L}, V = \frac{V_R + V_L}{2} \quad (6)$$

Combining (5) with (6), we can obtain

$$\omega = \frac{r}{L}(\omega_R - \omega_L), V = \frac{r}{2}(\omega_R + \omega_L) \quad (7)$$

From (7), we can express the control variables as

$$\omega_R = \frac{1}{r}V + \frac{L}{2r}\omega, \omega_L = \frac{1}{r}V - \frac{L}{2r}\omega \quad (8)$$

Moreover, we can define the kinematic model of the mobile robot as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 \\ \sin \theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \omega \end{bmatrix} \quad (9)$$

4. The Fuzzy Path Tracking Controller Design

To realize the path following strategy described above, the fuzzy controller of Fig. 3 is proposed based on natural intuition. The calculation module performs some comparisons and calculations to provide the inputs of the two fuzzy modules. These modules generate the commands to drive the robot to execute the given trajectory.

The first fuzzy module (FLC 1) is a conventional fuzzy PD controller that takes as input items the heading error (e) relatively to the actual targeted waypoint and its derivative (\dot{e}).

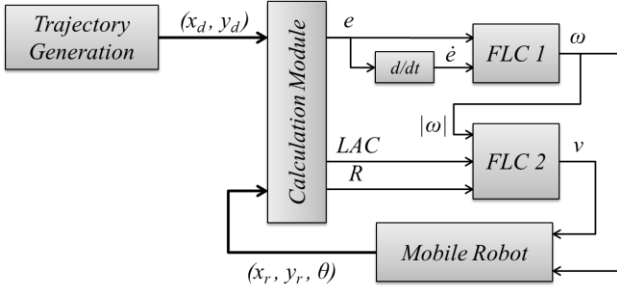


Fig. 3. The path tracking controller.

It generates the rotational velocity command to be applied to the robot wheel controllers to make the robot heading for its target waypoint. Three triangular membership functions uniformly distributed on a normalized discourse universe are used for the inputs of the controller and three singletons are used for its output (Fig. 4). The two fuzzy modules are Sugeno type zero fuzzy controllers. The FLC 1 uses the inference rules of Table 1.

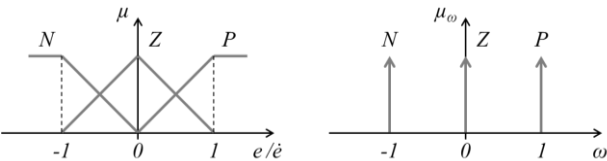


Fig. 4. Membership functions of the FLC 1.

The output crisp value of this module is given by the center of gravity for singletons (COGS) defuzzification method:

$$\omega = \frac{\sum_i \mu_{\omega}(\omega_i) \omega_i}{\sum_i \mu_{\omega}(\omega_i)} \quad (10)$$

where ω_i are singleton values of the individual rules ($i = 1, \dots, 3$), and $\mu_{\omega}(\omega_i)$ their corresponding outputs.

Table 1:

Inference rules of the FLC 1.

e / \dot{e}	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

The FLC 2 generates the robot's linear velocity reference command according to the distance to the considered waypoint (R), the LAC and the absolute value of the output of the FLC 1. The robot linear velocity has a maximum of 1 m/s, and the distance R is supposed to range in the interval $[0 \ 1] \text{ m}$. The FLC 2 module uses the fuzzy sets of Fig. 5 and the inference rules of Table 2.

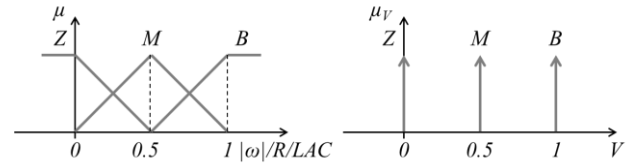


Fig. 5. Membership functions for the FLC 2.

As shown in the rule base, if the absolute value of the angular velocity reference ω (output of FLC 1) has a big (B) or a moderate (M) value (the robot is turning) then the linear velocity V should be decreased. When the absolute value of ω has a small value (Z) and the robot is going through a sequence of waypoints forming a straight path (LAC is Z) then the linear velocity should be increased without taking into account the distance between the waypoints. When the robot is heading for its final destination, a virtual next point is supposed so that the LAC increases with the decrease of the distance to the goal. The linear velocity will decrease accordingly to the distance R and the robot will stop on the final waypoint.

The crisp value of V is given by:

$$V = \frac{\sum_i \mu_V(V_i) V_i}{\sum_i \mu_V(V_i)} \quad (11)$$

Where V_i is the position of the singleton in rule i ($i = 1, \dots, 3$), and $\mu_V(V_i)$ its membership of the resulting conclusion set.

Table 2:
Inference rules of FLC 2.

R / LAC	$/\omega/ \text{ is } Z$			$/\omega/ \text{ is } M$			$/\omega/ \text{ is } B$		
	Z	M	B	Z	M	B	Z	M	B
Z	B	M	Z	Z	Z	Z	Z	Z	Z
M	B	M	M	Z	Z	Z	Z	Z	Z
B	B	B	B	Z	Z	Z	Z	Z	Z

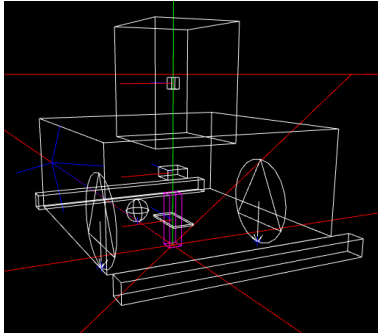
5. Simulation Results

To show the effectiveness of the proposed controller, a number of control simulations were performed in the *Microsoft Robotics Developer Studio* (MRDS). The MRDS includes a full featured 3D visual simulation environment complete with a physics engine to approximate interactions between objects within a virtual world. In all simulations, a simulated version of the Pioneer 3DX mobile robot is used (Fig. 6). It is assumed that the robot moves on a planar surface in which a reference frame is defined. It is also assumed that the global position and the orientation of the robot are known at each time.

The simulation tests consist of tracking the same sinusoidal trajectory but with the distance in x between the waypoints varied from 0.75 to 0.25 m. At the beginning of each test, the robot is located at the origin of coordinates with a zero heading.



(a)



(b)

Fig. 6. Visual (a) and physical (b) representations of the Pioneer 3DX in MRDS.

In Fig. 7 are depicted the results of the execution of a sinusoidal path with 0.75 m step on the x axis by our controller and the *Higher Level Path Tracking Controller* (HLPTC) presented in [22]. Fig. 8 shows the variation of the linear velocity during the

execution of the sine wave trajectory. From these two figures, it is clear that the proposed controller tracks the given path with a higher precision than the HLPTC; this is essentially due to the look-ahead curvature adopted in our work which varies inversely with the variation of the distance to the next bend. From the linear velocities variations, one can notice that the proposed controller finishes the trajectory execution faster than the HLPTC.

In the two next tests (Figs 9 and 10), the distance between waypoints is decreased to 0.5 and 0.25 m respectively. The precision of both controllers is ameliorated because of that bringing the waypoints closer results in the decrease of the curvature of the bends between the waypoints. Fig. 11 shows the advantage of the proposed controller to execute the trajectory in a shorter time. It is also noticeable that the variations of the linear velocity are finer than in the first example and that the controller takes less time to reach the final destination.

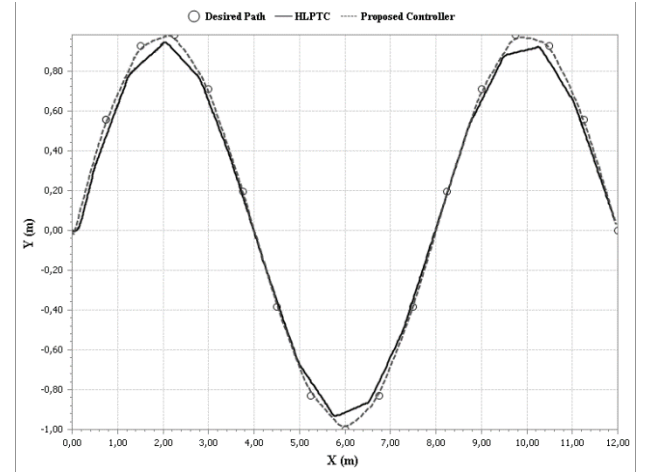


Fig. 7. Execution of a sinusoidal trajectory with 0.75 m step on the x axis.

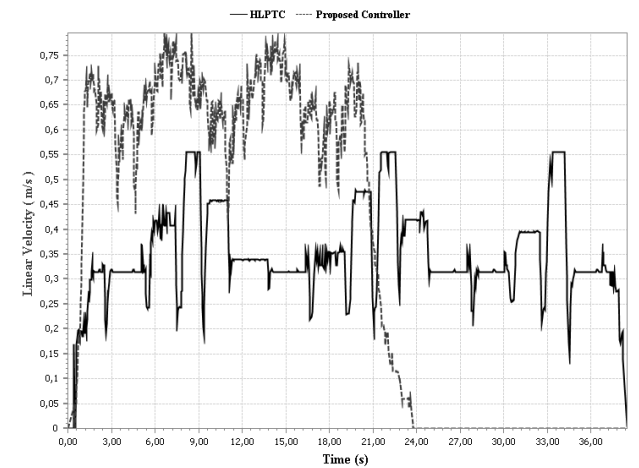


Fig. 8. Linear velocity profile (0.75 m step on the x axis).

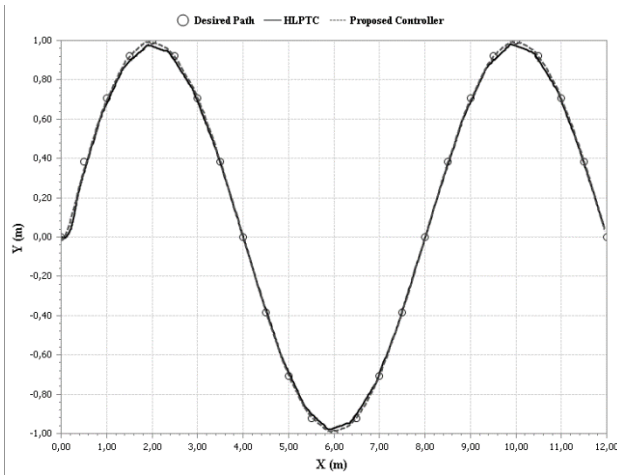


Fig. 9. Execution of a sinusoidal trajectory with 0.5 m step on the x axis.

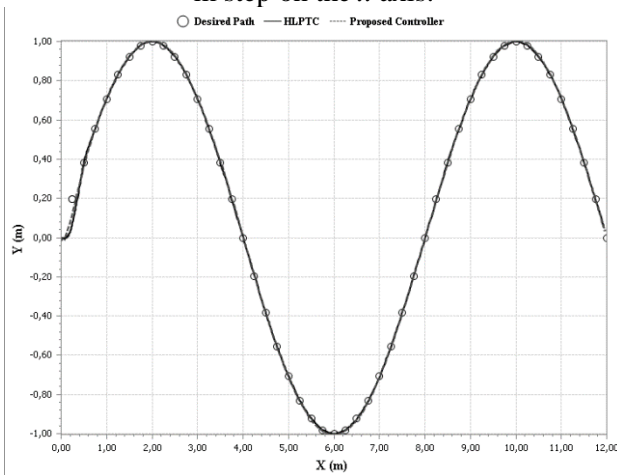


Fig. 10. Execution of a sinusoidal trajectory with 0.25 m step on the x axis.

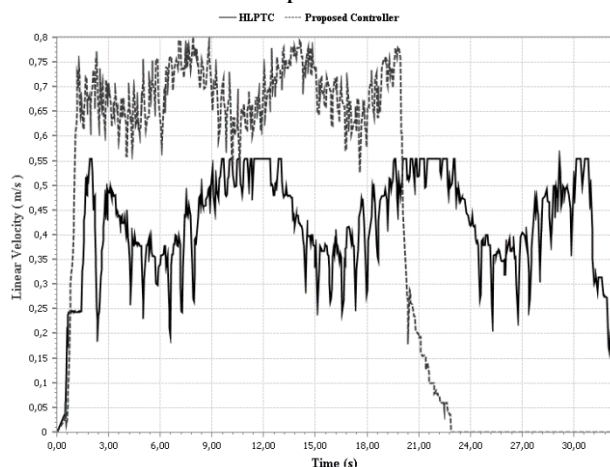


Fig. 11. Linear velocity profile (0.25 m step on the x axis).

6. Conclusion

In this paper, a simple path tracking fuzzy controller is presented. The main particularities of the controller are the simple structure and the fast decision making process. The controller drives a mobile robot to track a given path as would do a human driver. The path to track is presented in

the form of discrete waypoints; this has the advantage of that no interpolation is required to generate a continuous trajectory.

The simulation results show that the proposed controller can drive the robot to reach its destination with high precision at a high velocity.

In future works, practical implementation and the integration of the proposed path tracking controller in a complete navigation system is to be investigated.

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