



Dynamic virtual target guidance algorithm for path following control of a 4WD4WS mobile robot

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Abstract

This paper presents a method of applying a combination of the dynamic virtual target guidance algorithm and sliding mode control (SMC) to control a four-wheel-drive/four-wheel-steer mobile robot (4WD4WS) to follow the trajectory with small curvature, based on visual information captured by a single camera. A kinematic model of four-wheel-drive/four-wheel-steer mobile robot were also present, the proposed controller ensure stability and robustness when operating under uncertainties and disturbances. The process of synthesizing control laws is strictly mathematically guaranteed. The simulation in Matlab shows the research results visually.

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Keywords: virtual target guidance algorithm, sliding mode control, SMC, 4WD4WS, 4WS4WD, mobile robot

Introduction

The path following control problem of mobile robots is one of the most interested problems in robotic technology. The current trend of using more electric vehicles also creates more chances for applying mobile robots in real life. Four wheel drive/four wheel steer mobile robot, with very high mobility and maneuverability, is chosen to be studied widely including path following control problem. Many of the researchers have used sliding mode control to control a 4WD4WS mobile robot ^[1, 2]. Those controllers were often based on a kinematic model and with an assumption of highly accurate measurements when returned the exact absolute positions of the vehicle which is even a harder problem than to create a controller itself based on that.

There are many researches ^[4, 5] that often used a vision based algorithm to guide a vehicle to follow a reference path or a target, including virtual target guidance algorithms. In this study a proposed dynamic virtual target guidance algorithm is combined with a robust sliding mode control to guide a 4WD4WS mobile robot to follow a reference path based on a single camera vision can be a more effective and feasible solution.

Methodology

A. The dynamic virtual target algorithm

Virtual target guidance algorithm was a classic method for trajectory tracking, but in some cases was not applicable. The proposed guidance algorithm was named “dynamic” because the distance from the vehicle to the desire trajectory is unknown and the virtual target that is assumed to strictly follow the desire path is moving in a uncertain manner.

First, assuming that there is only one camera that was fixed on the vehicle, which was under a high quality image processing can identify the distance from the line to the center point of the camera monitor in real time. Second, the velocity of the vehicle is stable and the slipping phenomenon is not occurred. Then based on the information from camera the path following control of the 4WD4WS mobile robot can be present as in Fig 1.

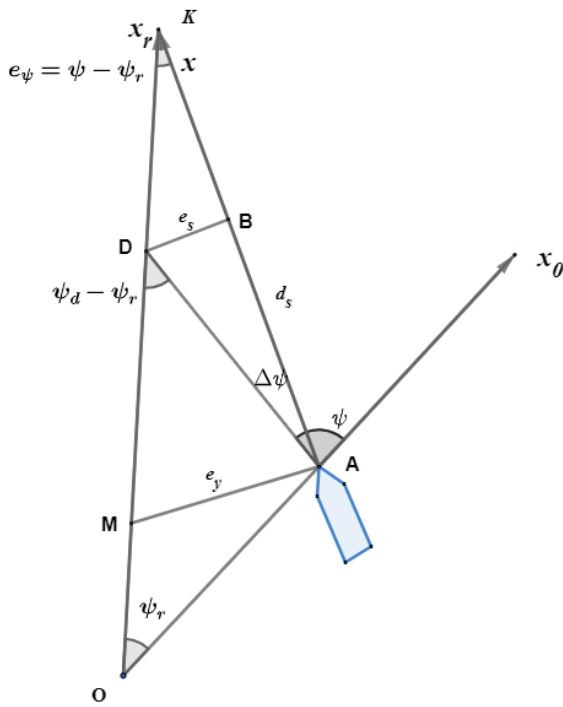


Fig 1: The dynamic virtual target algorithm in path following control

Where Ox_0y_0 is the fixed coordinate system on the ground, Axy is the body coordinate of the vehicle, and x_r is the tangential vector of the reference path which is very close to reference path due to the small value of the curvature.

Point A is the center of gravity of the vehicle and also the position of the camera. B is the center point on the camera monitor which is always straight forward a constant distance d_s from A. D is the position that the image processing software can identify based on the interception between the reference path and the horizontal line that passes through B. So the position of D is unknown and can be vary. From the current actual position A and the direction angle ψ , the vehicle needs to direct to point D with a deviation angle $\Delta\psi = \psi - \psi_d$. The process of guiding the vehicle to point D (dynamic virtual target) or eliminating the value of $\Delta\psi$ will also makes the vehicle to follow the reference path (or the lateral error will be zero).

Proof

As assuming, AB and DB are perpendicular to each other:

$$DB = AB \tan(\Delta\psi) = d_s \tan(\Delta\psi) \tag{1}$$

AM and KA are also perpendicular to each other

$$\frac{DB}{AM} = \frac{KB}{KA} \tag{2}$$

Then:

$$AM = DB \frac{KA}{KB} = d_s \left(\frac{d_s}{KB} + 1 \right) \tan(\Delta\psi) \tag{3}$$

Also has:

$$KB = \frac{DB}{\tan(\psi - \psi_r)} \tag{4}$$

Then (2) can be written as

$$\frac{DB}{AM} = \frac{DB}{KA \tan(\psi - \psi_r)} \tag{5}$$

Or:

$$AM = KA \tan(\psi - \psi_r) = (KB + d_s) \tan(\psi - \psi_r) \tag{6}$$

So the lateral error between vehicle and the reference path ($e_y = AM$) can be calculated by (3) or (6), it depends on whether $KB=0$.

If KB is zero then:

$$e_y = d_s \tan(\psi - \psi_r) \tag{7}$$

And $e_y = 0 \Leftrightarrow \psi = \psi_r$ or $\Delta\psi = 0$

If $KB \neq 0$ then by (3)

$$e_y = 0 \Leftrightarrow \Delta\psi = 0 \tag{8}$$

So the lateral error (e_y) is zero if and only if the angle deviation $\Delta\psi$ is zero. That proves the algorithm to be true.

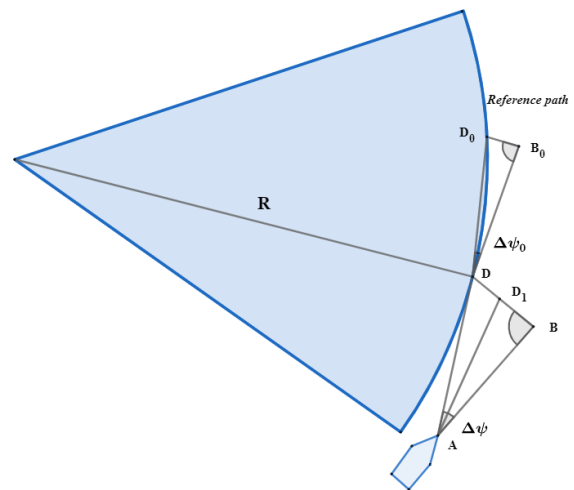


Fig 2: Applying for curve reference paths with radius R

For curve reference path the algorithm can also be applied with a compensation angle ($\Delta\psi_0$), which is the difference between a straight line and the tangential line:

$$\Delta\psi_0 = \text{atan} \left(\frac{R - \sqrt{R^2 - d_s^2}}{d_s} \right) \tag{7}$$

So when the vehicle is closed to the reference path it follows the tangential angle, not the exact point D but point D_1 as in Fig. 2. Then the steering angle of the vehicle is also keep stable at a value (target steering angle) that makes the vehicle follow the curve:

$$\delta_0 = \text{atan} \frac{\psi_{d1}}{2v} \tag{8}$$

As being shown in (7) and (8) the straight trajectory as a particular case of circular reference path when the radius of the trajectory is infinite (or its curvature is zero) then the compensation angle is zero and the target steering angle is also zero.

B. Mathematic model of the system

Many researches related to 4WD4WS mobile robot control were made by using the mathematic model which is derived from the vehicle model (car) and not really compatible with a mobile robot which is used differently with determined tasks and different parameters. In this article, a simple mathematic model is proposed based on the information that can gather by single camera and applicable for dynamic virtual target algorithm.

The model is a bicycle model, which is created under assumption that the center of gravity of the vehicle is also the geometry center. Another assumption that the movement of the virtual front and rear steering wheels are the same (in opposite direction), then the steering angle of the vehicle:

$$\delta = \delta_f = -\delta_r \quad (9)$$

Assume no slippage occurs, then as in [7] the angular velocity of the vehicle can be written as:

$$\dot{\psi} = 2 \frac{v}{l} \tan \delta \quad (10)$$

Where l is the vehicle base (length of the vehicle).

Assuming that, the steering angle of the vehicle is controlled by a first order control system:

$$\dot{\delta} = \frac{K}{T} u - \frac{1}{T} \delta \quad (11)$$

Where K , T are positive constants; u is control input.

Combine (10) and (11) with the proposed guidance algorithm, mathematic model of the system can be formulated as:

$$\begin{cases} \Delta \dot{\psi} = 2 \frac{v}{l} \tan \delta - \dot{\psi}_d \\ \dot{\delta} = \frac{K}{T} u - \frac{1}{T} \delta \end{cases} \quad (12)$$

Objective of the control problem for system (12) is to make the angle deviation $\Delta \dot{\psi}$ converge to $\Delta \dot{\psi}_0$ and steering angle δ converge to δ_0 .

C. Controller design

By using sliding mode control the control problem of system (12) can be solve. First, choose a sliding variable:

$$s = \lambda * (\Delta \psi - \Delta \psi_0) + (\delta - \delta_0) \quad (13)$$

Then its derivative

$$\dot{s} = \lambda * \Delta \dot{\psi} + \dot{\delta} \quad (14)$$

Combine (12) and (14)

$$\dot{s} = \frac{K}{T} u - \frac{1}{T} \delta + 2\lambda \frac{v}{l} \tan \delta - \lambda \dot{\psi}_d \quad (15)$$

When $\dot{s} = 0$ the equivalent control is

$$u_{eq} = \frac{\delta}{K} - \frac{2\lambda v T}{K l} \tan \delta + \frac{\lambda T}{K} \dot{\psi}_d \quad (16)$$

In sliding mode control the total control input consists of two components, equivalent part and discontinuous part [8, 9]:

$$u = u_{eq} + u_d \quad (17)$$

Then from (16) and (17)

$$\dot{s} = \frac{K}{T} u_d \quad (18)$$

Choose a Lyapunov function

$$V = \frac{1}{2} s^2 \quad (19)$$

Then its derivative must be negative to ensure the system stability [8, 9]

$$\dot{V} = s \dot{s} = \frac{K}{T} u_d s \leq 0 \quad (20)$$

Then the discontinuous control input can be choose in the form of a power function to converge faster and decrease chattering effect [1, 6].

$$u_d = -K_d s^{\frac{1}{n}} \quad (21)$$

Where n is an odd constants, and K_d is a positive parameter. Then the derivative of Lyapunov function

$$\dot{V} = -\frac{K}{T} K_d s^{\frac{1}{n}} s \leq 0 \quad (22)$$

The inequation (22) is always true because the power function does not change the sign of sliding variable (n is odd) then the system is stable by Lyapunov.

Combine (16), (17) and (21) control input depends only on δ and $\Delta \psi$, while the value of $\dot{\psi}_d$ can be considered as a noise adding to the system. Assuming that

$$|\dot{\psi}_d| < M \quad (23)$$

Then the value of M can be found by experiences.

C. Simulations

Fig. 3 shows the Simulinks model of the system that uses a SMC controller that based on a dynamic virtual target algorithm. The controller only uses angle deviation and steering angle that can be measured by a single camera (and an onboard image processing unit) and 4 steering encoders to calculate the control input u , by equations (16), (17) and (21). Choose a straight line and a circular trajectory for the reference path to follow. The velocity of the vehicle is also considered to be constant at 3m/s. The distance of vision d_s is 20 m for straight line and reduce to 7 m for circular trajectory to follow a high curvature (radius of reference path is 20 m or curvature is 0.05). The initial position need to be not very far from the reference path because the camera is fixed on the vehicle and it need to be "seen" by the camera. The bounded value of noise M is 0.04.

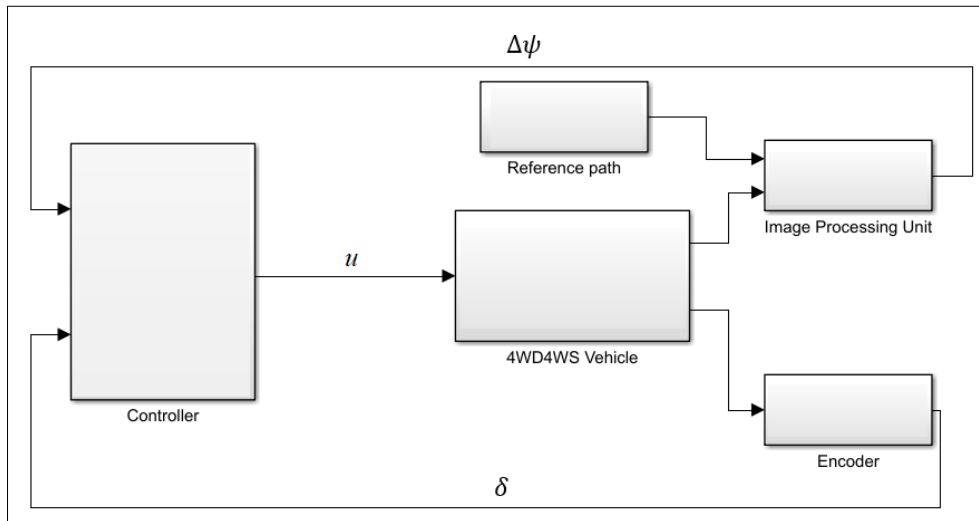


Fig 3: Block diagram of the Simulink model of the system

Results and Discussion

The figures fig. 4 and fig. 5 shows the convergence of the sliding variable in both straight and circular trajectory. Convergence time in both cases are very small, less than 0.2 s. That also make convergence time for angle deviation $\Delta\psi$ in short time, about 10 seconds (fig. 6), when the angle deviation in straight trajectory is converged to zero the convergence value in circular trajectory is nonzero value (fig. 7), though it is also a constant ($\Delta\psi_0 = 0.1788$ rad) which can be calculated by (7). The steering angle in both cases are also converged in the same manner (fig. 8 and fig. 9) when the former is converged to zero, the latter is converged to a

nonzero constant value ($\delta_0 = -0.05$ rad) can be calculated by (8). The lateral error as a results from all those is also converged to zero, after 20 seconds from a distance about 3 m the vehicle can move not further than 0.01 m in straight trajectory (fig. 10). In circular trajectory, the error is a little higher but it is not higher than 0.03 m after 15 seconds (fig. 11). The final results are shown in fig. 12 and fig. 13. The actual trajectory after some times totally overlaps the reference path in both cases.

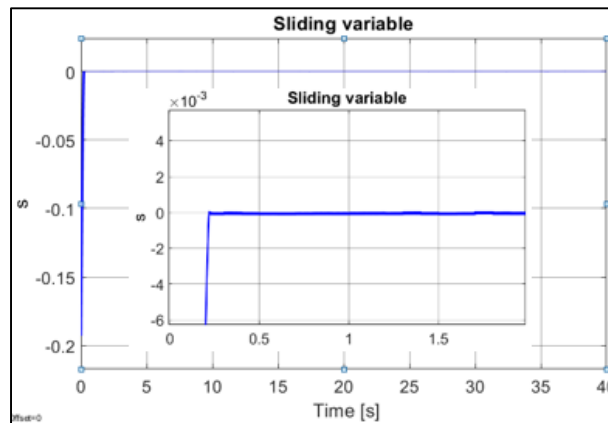


Fig 4: Sliding variable in straight reference path

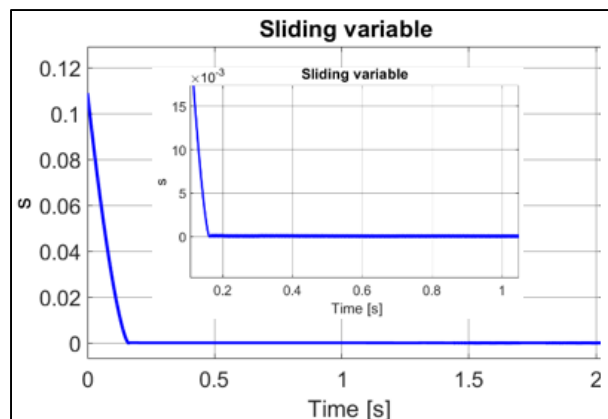


Fig 5: Sliding variable in circular reference path

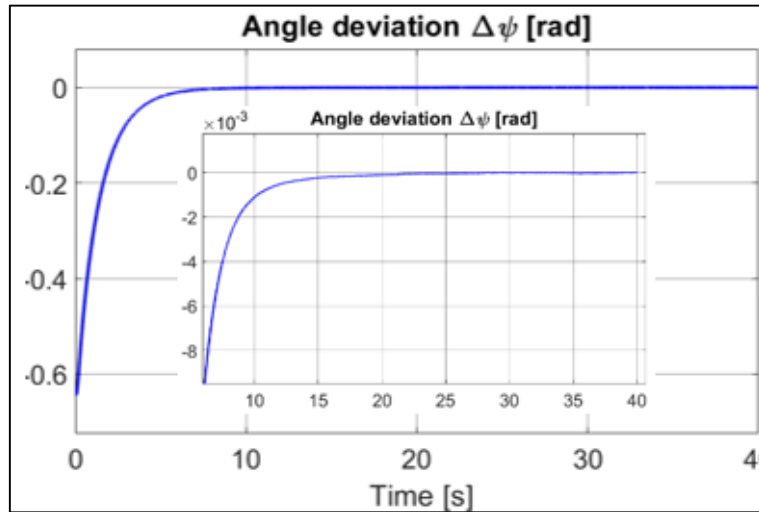


Fig 6: Angle deviation in straight reference path

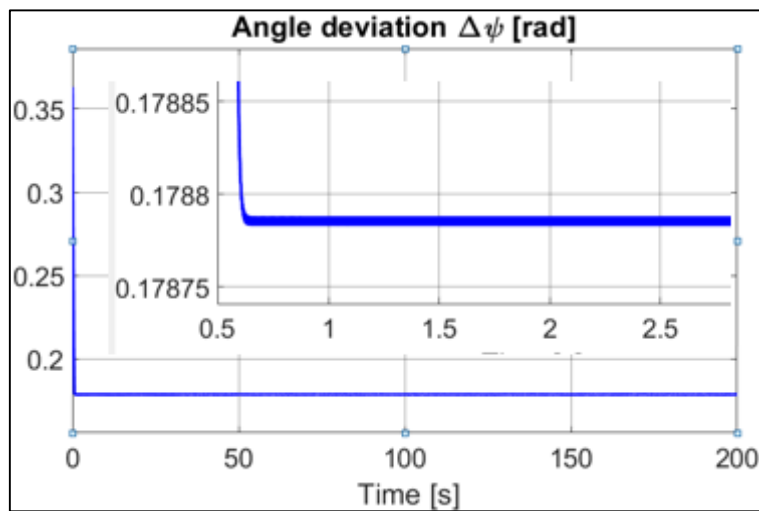


Fig 7: Angle deviation in circular reference path

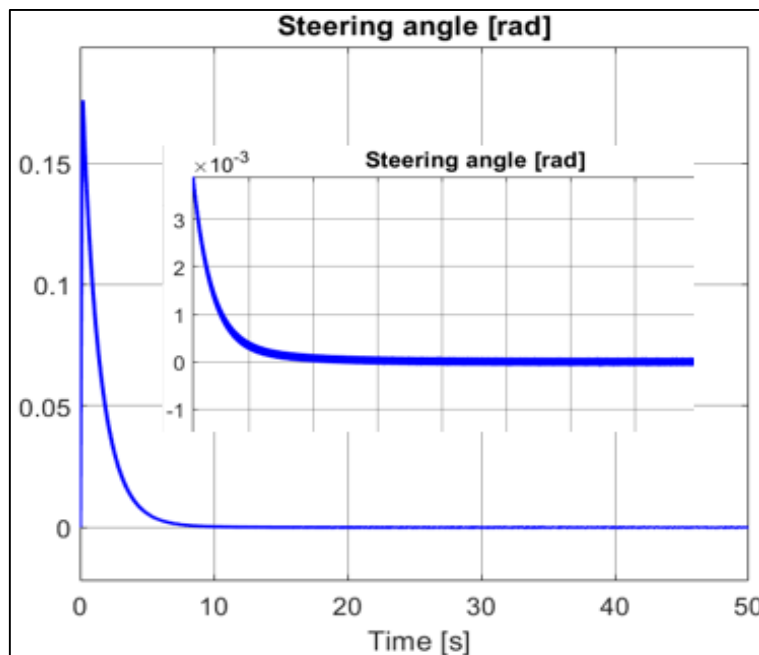


Fig 8: Steering angle in straight reference path

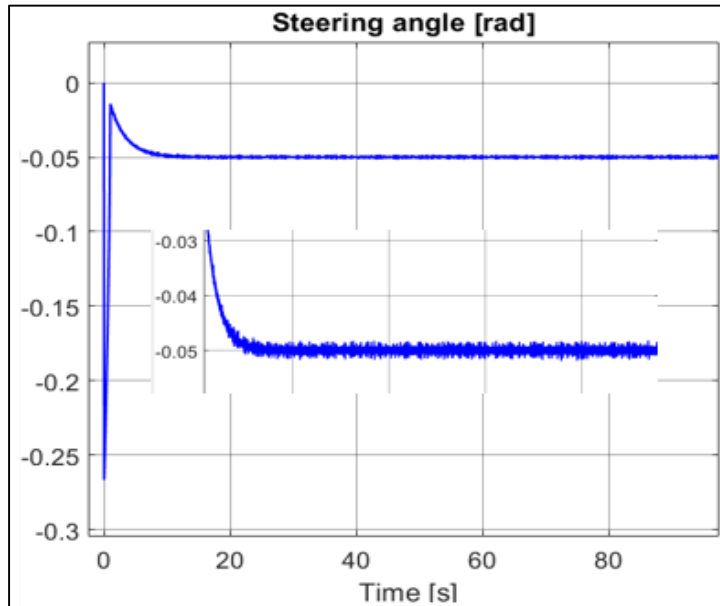


Fig 9: Steering angle in circular reference path

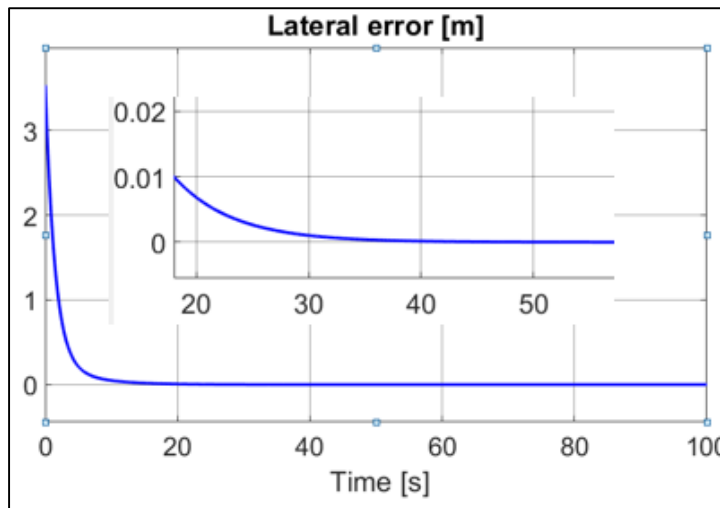


Fig 10: Lateral error in straight reference path

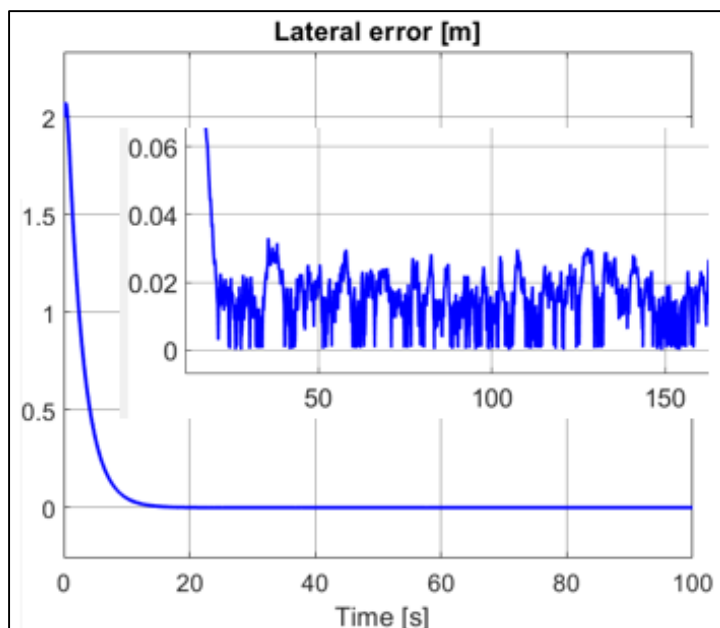


Fig 11: Lateral error in circular reference path

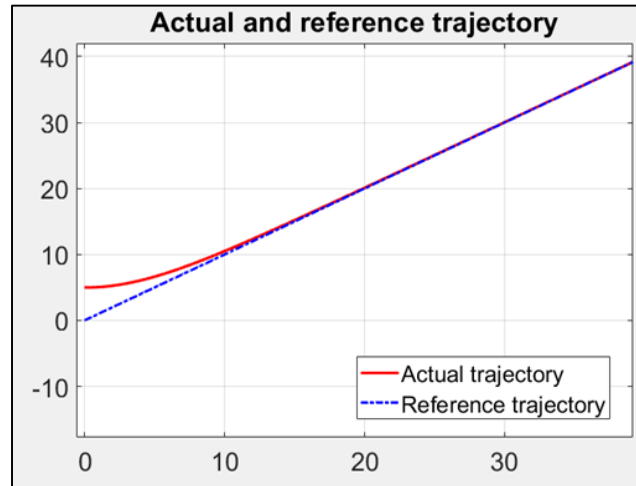


Fig 12: Actual and reference trajectory in straight reference path

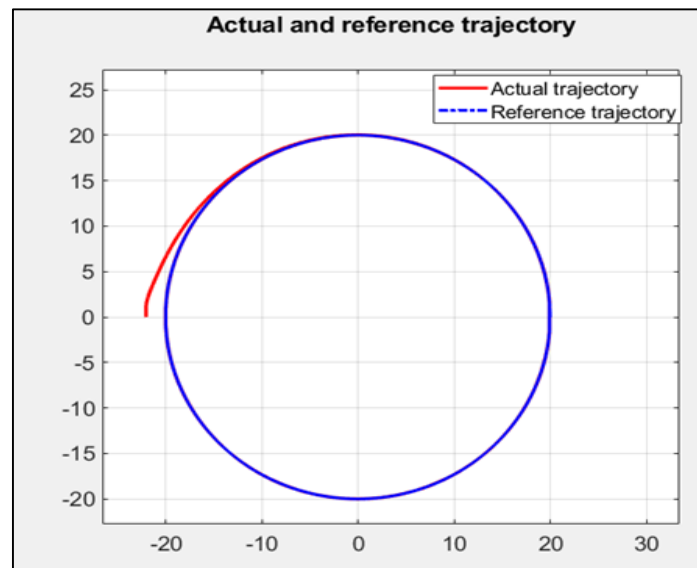


Fig 13: Actual and reference trajectory in circular reference path

Conclusions

In this study, a new dynamic virtual target guidance algorithm was proposed to control a 4WD4WS mobile robot to follow a reference path. The algorithm was combined with an effective sliding mode control proved stability and robustness against a bounded uncertainty, therefore show a very high accuracy in path following control. In this study, a mathematic model based on camera vision also was present and proved to be effective.

References

1. Solea R, Filipescu A, Manzu V, Filipescu S. Sliding-mode trajectory-tracking control for a four-wheel-steering vehicle. 8th IEEE International Conference on Control and Automation; c2010. p. 382-7.
2. Dumitrascu B, Filipescu A, Vasilache C, Minca E, Filipescu A. Discrete-time sliding-mode control of four driving/steering wheels mobile platform. In: 2011 19th Mediterranean Conference on Control & Automation (MED); Corfu, Greece, c2011. p. 1076-81. doi: 10.1109/MED.2011.5983167.
3. Lee M-H, Li T-HS. Kinematics, dynamics and control design of 4WIS4WID mobile robots. The Journal of Engineering. c2015; p. 6-16.
4. Thakar S, Ratnoo A. A tangential guidance logic for virtual target-based path following. In: AIAA Guidance, Navigation, and Control Conference; 9-13 January 2017; United States; c2017.
5. Breivik M, Fossen TI. Principles of guidance-based path following in 2D and 3D. Proceedings of the 44th IEEE Conference on Decision and Control; Seville, Spain; c2005. p. 627-34. doi: 10.1109/CDC.2005.1582226.
6. Mehrjerdi H, Zhang Y, Saad M. Adaptive exponential sliding mode control for dynamic tracking of a nonholonomic mobile robot. Intelligent Robotics and Applications; c2012; p. 643-52.
7. Dai P, Katupitiya J. Force control for path following of a 4WS4WD vehicle by the integration of PSO and SMC. Vehicle System Dynamics. 2018;56(11):1682-1716. doi: 10.1080/00423114.2018.1435888.
8. Itkis U. Control System of Variable Structure. New York: Wiley; c1976.
9. Edwards C, Spurgeon S. Sliding Mode Control: Theory and Applications. London: Taylor and Francis; c1998.