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Motion Simulation of Autonomous Guided Vehicles

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Abstract

Autonomous Guided Vehicles (AGVs) using omnidirectional wheels can change their moving direction flexibly without the use of steering wheel. Is it possible that a vehicle with standard pneumatic wheels (as in a normal vehicle) change its moving direction flexibly by the technique of regulating the driving torque supplied to each wheel? In this article, the simulated motion trajectories of the two types of vehicles were presented, that are the vehicle using Mecanum wheels and the vehicle using standard pneumatic wheels (normal wheels). For vehicles with normal wheels, the simulation was carried out in two cases of motion direction control: with and without using a steering wheel. Further, the main loop of the motion direction control algorithm by regulating the driving torque to the wheels was also presented for a prototype of a vehicle with normal wheel, which was used to simulate the motion direction control experimentally. The topic will focus on motion simulation and the comparison of simulation results to evaluate the application ability of the mentioned technique in AGVs as well as in passenger cars.

Keywords: Autonomous guided vehicle (AGV), mecanum wheel, motion direction control, steering wheel.

1. Introduction

Moving directional instability of a vehicle is the most common cause of road traffic accidents and accidents in working sites. Therefore, the development of techniques for controlling the motion direction of a vehicle is a question concerned by many researchers recently not only in order to improve the technical quality of passenger cars and reduce the number of road accidents but also to reduce accidents in working sites of AGVs.

AGVs can move flexibly because they have the ability to change their moving directions without using a steering wheel. Instead, AGVs adjust their moving direction by supplying and regulating the driving torque applied to each of their wheels.

The operation and the safety of a car are affected greatly by its ability to change its moving direction. The movement of a 4-wheel steering (4WS) car in general and a self-driving car in particular has been published in various domestic as well as foreign scientific works as infollowing:

In [1], Hamid Taheri *et al*. studied autonomous vehicles using Mecanum wheels that can move in 8 different directions by applying a corresponding value of driving torque to each wheel without changing the steering angle of each steered wheel. The authors then presented the maneuverability and working productivity of this kind of autonomous vehicle.

Z. Hendzel *et al*. [2] in 2017 built the equations of motion of a robot using Mecanum multidirectional wheels by applying Lagrange equation type II. The robot model can be used in the development of control systems and movement simulation of this kind of robot.

In 2018, Yunwang *et al*. [3] simulated the dynamic properties of a vehicle using Mecanum wheels on the RecurDyn platform in specific working conditions such as moving forward, backward, left, 45-degree diagonal, or local rotation. The simulation results are similar to that of the previous studies which can serve as the basis for the evaluation of performance and design quality of autonomous vehicles using Mecanum wheels.

A. Gfrerrer in [4] presented a detailed analysis of the geometry parameters of the Mecanum wheel to find the natural parameters of the roll surface and the meridian curve of the rolls. In this work, the author formulated a differential equation that simplified the connection between the longitudinal and angular velocity of the car to give some typical geometric properties of the Mecanum wheel.

Huu Hai Ho [5] built a fuzzy controller for the steered angle of the rear wheels according to the steered angle of the front wheels. However, the topic of the paper was based on the assumption that the lateral deformation of the wheel is in the linear region. Furthermore, experimental simulation has not been presented in the paper.

Le Duc Hieu [6] analysed the forces acting on the car and other factors affecting the motion trajectory of

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the car. The thesis built equations of motion of the car. However, the topic did not consider the influence of the wheel placement angle on the forces acting on the car. The main assumption of the thesis is that the slip and lateral deflection of the wheel are negligible.

Le Ngoc Trung *et al*. [7] built mathematical models of a car based on tire characteristics that were obtained through experiment tests. From there, the parameters affecting the motion trajectory and rotation of the car were studied. The study could contribute to improving the stability of the car's motion.

Nguyen Vu Tien Linh in [8] researched on simulating the movement of cars with ABS and ASR system. The project did not consider the dynamic parameters of the car. Basically, the slippage was studied when the ABS and ASR brake systems were functional. However, in the mathematical models, the influence of lateral wind was neglected. Moreover, the topic studied the motion of the 2WS car only. Therefore, the study is not suitable for application in the 4WS car.

Most of the research topics are based on assumptions to simplify the car's model, so their contributions are limited in practice. In the following sections, the motion trajectories of two types of vehicles: AGVs with Mecanum wheels and normal vehicles will be presented.

2. Moving Trajectories of Vehicles Using Mecanum Wheels.

2.1. Mathematical Model of Mecanum Wheel

For Mecanum wheel with the inclination angle of rollers of 45° to the wheel plane, forces at the ground contact point of the wheel's rollers were shown in Fig. 1. With the driving torque M on the wheel, the longitudinal and the lateral forces are determined as following [9]:

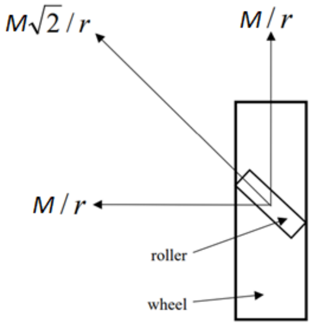


Fig. 1 Forces acting at the ground contact point of the Mecanum wheel's roller

$$F_x = \frac{M}{r} \tag{1}$$

$$F_y = \frac{M}{r} \tag{2}$$

where:

M is driving torque applying to the wheel

r is wheel radius.

2.2. The Equations of Motion of the Vehicle

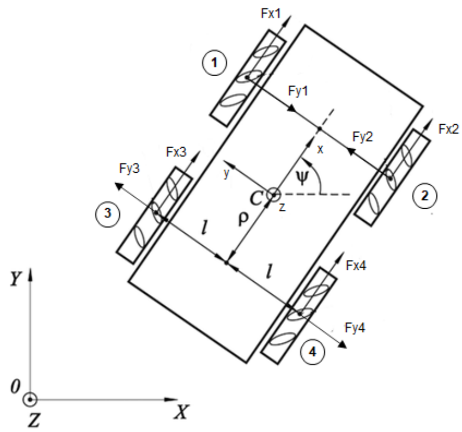


Fig. 2 Force and torque acting on the AGV using Mecanum wheel

The forces acting on the vehicle are longitudinal force F_{xi} at the contact point between the i^{th} wheel and the ground surface (i=1...4), lateral force F_{yi}, (i=1...4 is the wheel indexes) and rolling resistance F_f.

The equation of longitudinal motion of the vehicles:

$$m\ddot{x} = \sum_{i=1}^{4} F_{xi} - F_f = F_{x1} + F_{x2} + F_{x3} + F_{x4} - F_f \tag{3}$$

The equation of horizontal motion of the vehicles:

$$m\ddot{y} = \sum_{i=1}^{4} F_{yi} = -F_{y1}\sin\beta + F_{y2}.\sin\beta + F_{y3}\sin\beta - F_{y4}\sin\beta \tag{4}$$

2.3. Simulation Results

In this section the motion simulation results of a vehicle using Mecanum wheels which has 1006 kg kerb weight, wheelbase 2.31 m and track width 1.37 m will be presented for movement in straight lines and in curved lines.

2.3.1. The vehicle moving in a straight line.

In order to simulate the movement of the vehicle in a straight line, the values of driving torque applied to each wheel are chosen as in Table 1. Fig. 3 demonstrated the vehicle's motion trajectories for each simulation case.

As can be seen in Fig. 3, the vehicle can move straight in 8 different directions by applying appropriate values of driving torque to the Mecanum wheels (steering the wheels are not necessary). This is the advantage of Mecanum wheels compared to ordinary wheels

Table 1. Driving torque applied to each Mecanum wheels for straight movement of vehicle.

Driving torque (Nm)	Go forward	Turn right	Left front cross	Left rear cross
M_1	100	100	0	-100
M_2	100	-100	100	0
M_3	100	-100	100	0
M_4	100	100	0	-100

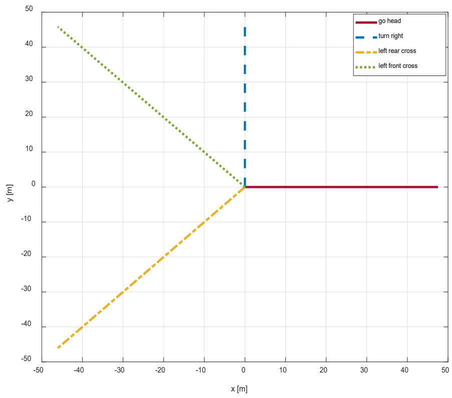


Fig. 3. Straight motion trajectory of the vehicle using Mecanum wheels

2.3.2. The vehicle moving in a curve.

In order to simulate the movement of the vehicle in a curved line, the values of driving torque applied to each wheel are chosen as in Table 2. The vehicle's motion trajectories for each simulation case were shown in Fig. 4.

As could be seen from Fig. 4, the vehicle can move in a curved line with a very small radius of curvature (turning radius) by regulating the driving torque to each Mecanum wheel. This is the advantage of autonomous vehicles using Mecanum wheels. Because this type of autonomous vehicle can move easily in any given trajectories, they are being used more widely in the field of production automation.

Table 2. Driving torque applied to Mecanum wheels for the movement of the vehicle in a curved line.

Driving torque (Nm)	Case 1	Case 2	Case 3	Case 4
M_1	100	100	100	100
M_2	100	150	200	250
M_3	100	100	100	100
M_4	100	150	200	250

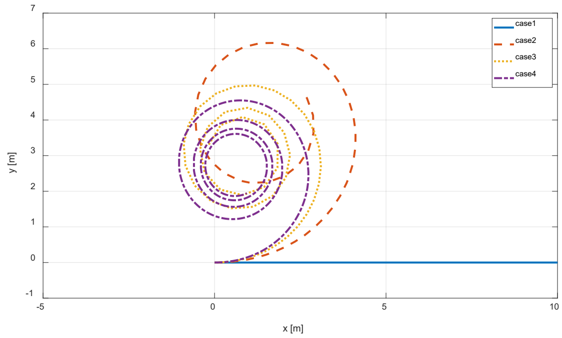


Fig. 4. Motion trajectory of the vehicle using the Mecanum wheels when moving in curved line

A further question is that, is it possible for a normal vehicle to change its moving direction by the regulation of driving torque applied to each wheel?. In the next section, the change in the moving direction of a normal vehicle with and without a steering wheel will be analysed.

3. Moving Trajectories of Normal Vehicles

3.1. Simulation Model

The simulation model of a 4WS vehicle was introduced in 2008 [7] by Le Ngoc Trung *et. al*. When the vehicle moves, forces and moments acting on the vehicle are shown in Fig. 5.

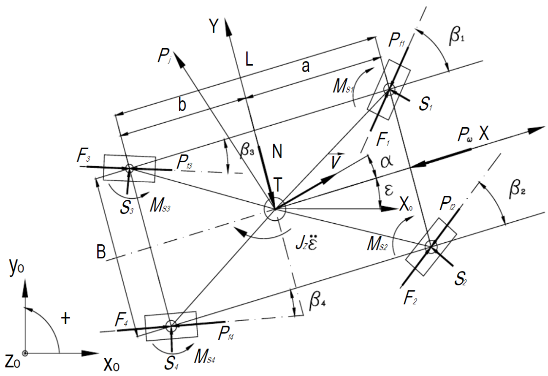


Fig. 5. Forces and moments acting on a running vehicle

In the figure, F_i is the longitudinal force, S_i is the lateral force, P_{fi} is the total rolling resistance and M_{si} is the turning moment of the wheel, where i is the index of the wheels $(i=1\div4)$. The aerodynamic forces in the longitudinal and lateral direction of the vehicle axis are P_ω and N respectively.

The inertial forces $F_a = m\ddot{X}$ (longitudinal) and $P_j = m\ddot{Y}$ (lateral) exist at the center of mass T of the vehicle. When the vehicle body turns around with angle ε, there occurs an inertial moment around the vertical axis Tz with the value of $J_z.\ddot{\varepsilon}$ (J_z is inertial moment of the vehicle).

The distance between the centre of mass of the car T to the centre of the rear axle is b and to the centre of the front axle is a.

The equation of motion of the vehicle in the longitudinal direction is written as:

$$m\ddot{X} = \sum_{i=1}^{4}(F_i - P_{fi}).cos\beta_i - S_1.sin\beta_1 - S_2.sin\beta_2 + S_3.sin\beta_3 + S_4.sin\beta_4 - P_\omega \quad (5)$$

The equation of motion of the vehicle in the lateral direction is written as:

$$m\ddot{Y} = \sum_{i=1}^{4} S_i.cos\beta_i + (F_1 - P_{f1}).sin\beta_1 + (F_2 - P_{f2}).sin\beta_2 - (F_3 - P_{f3}).sin\beta_3 - (F_4 - P_{f4}).sin\beta_4 + N \quad (6)$$

The equation of rotation of the vehicle body around the vertical axis at the centre of mass *Tz* is written as:

$$J_z\ddot{\varepsilon} = ((F_1 - P_{f1}).sin\beta_1 + (F_2 - P_{f2}).sin\beta_2)a + \left((F_3 - P_{f3}).sin\beta_3 + (F_4 - P_{f4}).sin\beta_4\right)b + (S_1.cos\beta_1 + S_2.cos\beta_2)a - (S_3.cos\beta_3 + S_4.cos\beta_4)b + (S_1.sin\beta_1 - S_2.sin\beta_2).\frac{B}{2} - (S_3.sin\beta_3 - S_4.sin\beta_4).\frac{B}{2} - ((F_1 - P_{f1}).cos\beta_1 - (F_2 - P_{f2}).cos\beta_2).\frac{B}{2} - ((F_3 - P_{f3}).cos\beta_3 - (F_4 - P_{f4}).cos\beta_4).\frac{B}{2} \quad (7)$$

where:

m is the vehicle's mass.

β_i is the steering angle of the i^{th} wheel.

B is the track width.

The sign of the quantities F_i and S_i are taken in correspondence with the direction of the chosen coordinate axis.

The sign of the quantities β_i is a convention as follows: When the rear wheels rotate in the same direction as the front wheels, β_i is positive (+) and vice versa β_i is negative (-).

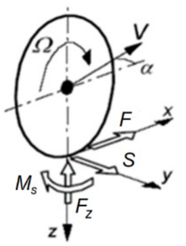


Fig. 6. Forces and torques at the contact point of the wheel with the road surface

In the spatial coordinate system, there exist at the contact point of the wheel with the road surface the following forces and torques as shown in Fig. 6.

The normal reacting force of the road surface is denoted by *Fz*. This force is balanced to the load *(Z)* distributed on the wheel.

The tangent reacting force (longitudinal force) in the wheel plane denoted by *F*, is a function of the longitudinal slip of the wheel *s*, the side (lateral) slip of the wheel *α,* and the load *(Z)* distributed on the wheel [10]:

$$F = f(\alpha,Z,s) \quad (8)$$

The lateral force located in the plane of the road and perpendicular to the plane of the wheel, is denoted by *S*. Like the longitudinal force, the value of this force is another function of the longitudinal slip *s*, the side slip *α* and the load *(Z)* distributed on the wheel [10]:

$$S = f(\alpha,Z,s) \quad (9)$$

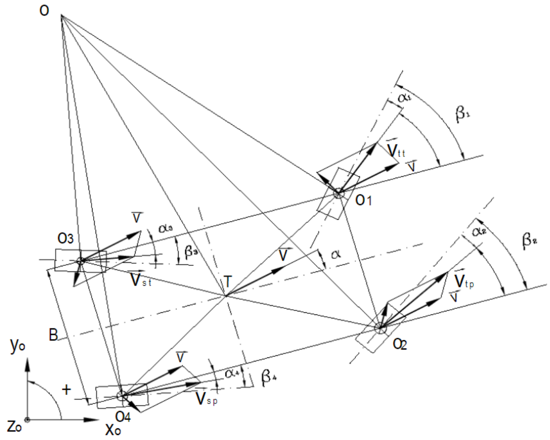


Fig. 7. Side deflection angle of tire

The longitudinal slip of the i^{th} wheel is defined as:

$$s_i = \frac{\omega_i r - V}{\omega_i r} \quad (10)$$

The lateral slip *α* of the first (front left) wheel is the side deflection angle of tire and can be defined as:

$$\alpha_1 = \beta_1 - \alpha_1' \quad (11)$$

where α_1' is the angle of deviation between the direction of the velocity of the first wheel and the longitudinal axis of the vehicle. This angle can be expressed by the following equation:

$$\alpha_1' = artg\left(\frac{-\dot{x}.sin\varepsilon + \dot{y}.cos\varepsilon + \Delta V_t.\cos\left(artg\left(\frac{B}{2a}\right)\right)}{\dot{x}.cos\varepsilon + \dot{y}.sin\varepsilon - \Delta V_t.sin\left(artg\left(\frac{B}{2a}\right)\right)}\right)$$

For the second (front right) wheel, the side deflection angle:

$$\alpha_2 = \beta_2 - \alpha_2' \quad (12)$$

where

$$\alpha_2' = artg\left(\frac{-\dot{x}.sin\varepsilon + \dot{y}.cos\varepsilon + \Delta V_t.\cos\left(artg\left(\frac{B}{2a}\right)\right)}{\dot{x}.cos\varepsilon + \dot{y}.sin\varepsilon + \Delta V_t.sin\left(artg\left(\frac{B}{2a}\right)\right)}\right)$$

The side deflection angle of the third (rear left) and the fourth (rear right) wheel are determined similarly.

3.2. Simulation Results

In this section, the motion simulation results of a small passenger vehicle which has 1006 kg kerb weight, wheelbase 2.31 m and track width 1.37 m will be presented. The simulation was carried out in two cases, when the vehicle accelerates and when the vehicle freely runs at an initial speed of 20 m/s.

3.2.1. Accelerating vehicle.

When the vehicle starts and accelerates with the constant values of turned angle of steering wheel [0° 90° 180° 360° 720°] and the value of driving torque at each wheel is 200 Nm, its simulated motion trajectories were shown in Fig. 8. The wheels' longitudinal slip was shown in Fig. 9 for the values of turned angle of steering wheel of 360° and 720° respectively.

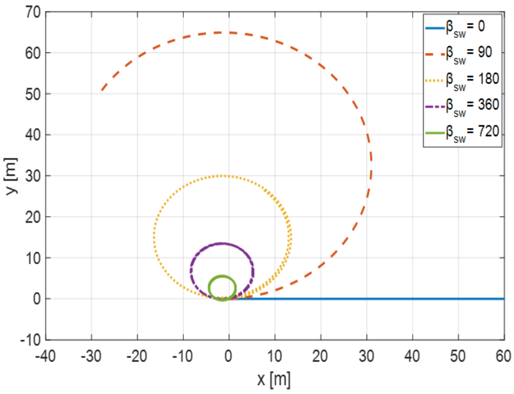


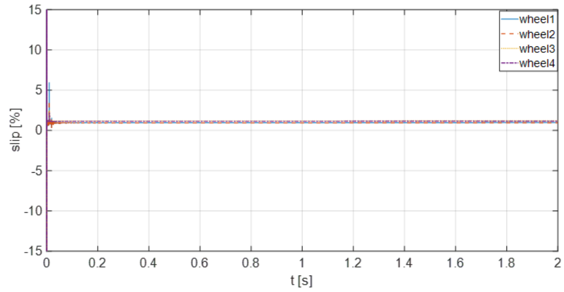
Fig. 8. The vehicle's motion trajectories with constant values of turned angle of steering wheel

The simulated trajectories correspond with practice. The vehicle moves in a straight line when the steering wheel has not been turned. With the turned angle of steering wheel increasing from 90° to 720°, the vehicle's trajectories gradually curve with the smallest turning radius of about 3 m (see Fig. 8). The values of the longitudinal slip of the wheels are almost the same, in the normal range of about 2%.

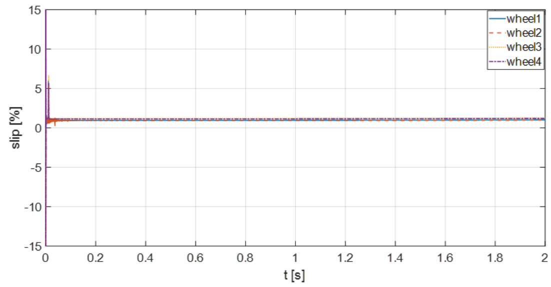
Table 3. Values of driving torque supplied to the wheels.

	Case 1	Case 2	Case 3	Case 4
M1(N.m)	100	100	100	100
M2(N.m)	100	150	250	300
M3(N.m)	100	100	100	100
M4(N.m)	100	150	250	300

When the steering wheel has not been turned and the driving torques supplied to the wheels are chosen as in Table 3, the simulated trajectories of the vehicle are shown in Fig. 10 and the longitudinal slip of the wheel are in Fig. 11.



(a). Turned angle of steering wheel β_{sw} = 360°



(b). Turned angle of steering wheel β_{sw} = 720°

Fig. 9. The wheels' longitudinal slip of accelerating vehicle with turned steering wheel.

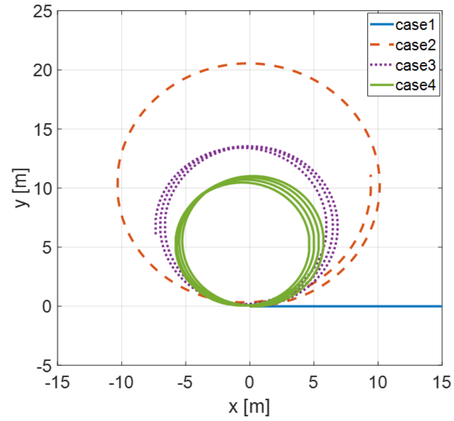
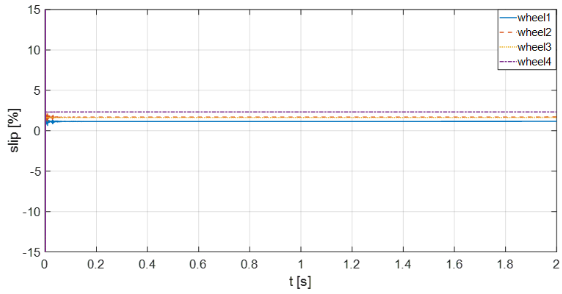


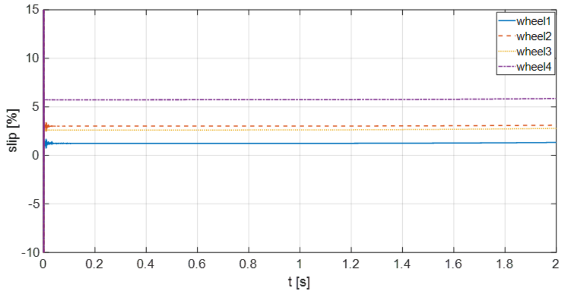
Fig. 10. The motion trajectory of vehicle with different values of driving torque supplied to the left and the right wheels

When the driving torques supplied to the wheels share the same value, the vehicle moves in a straight line. The vehicle moves in a curve line if the values of driving torque supplied to the right wheels are different from the values to the left wheels. The turning radius of the vehicle depends on that difference.

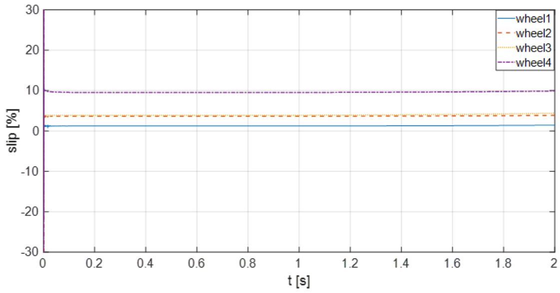
The vehicle's trajectories in two ways of change moving direction, that are turning the steering wheel and adjusting the values of driving torque supplied to the right and the left wheels, are similar and almost circular.



(a). Case 2



(b). Case 3



(c). Case 4

Fig. 11. The wheels' longitudinal slip of accelerating vehicle with the difference of driving torque supplied to the left and the right wheels

The longitudinal slip of the wheels is greater if the difference of driving torque supplied to the right and the left wheels increases. For the difference of 200 Nm (case 4), the slip value of the rear right wheel (wheel4) is the greatest (of about 15%). This value does not greatly affect the tire's wear.

3.2.2. Vehicle running at initial speed of 20 m/s.

In this section, the motion of the vehicle at an initial speed of 20m/s is simulated in two scenarios: the steering wheel is turned, and the values of driving torque supplied to each wheel are regulated in order to change moving direction. The simulated running trajectories and longitudinal slip of the wheels will be presented and discussed.

When the vehicle runs with the constant values of turned angle β_{sw} of steering wheel [0°, 90°, 180°, 360°], its simulated running trajectories are shown in Fig. 12. The wheels' longitudinal slip when the vehicle runs with the values of turned angle of steering wheel at 180° and 360° was shown in Fig. 13. When the steering wheel has not been turned, the vehicle runs in a straight line. With non-zero value of turned angle β_{sw}, the vehicle moves in a curved line.

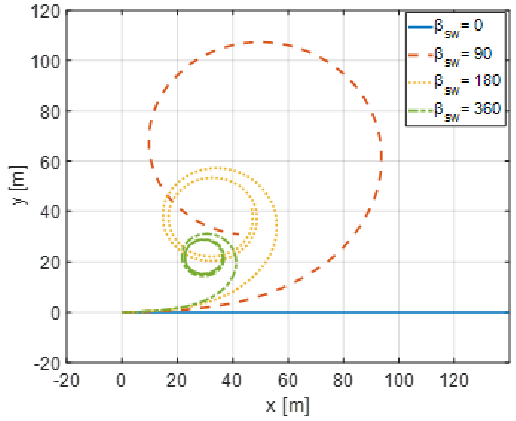
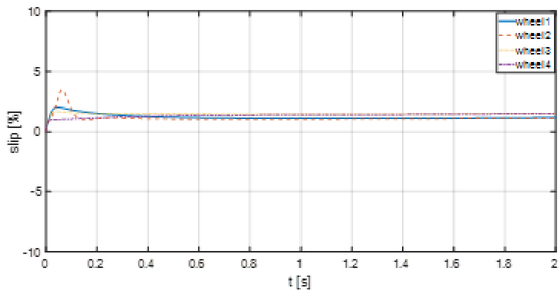
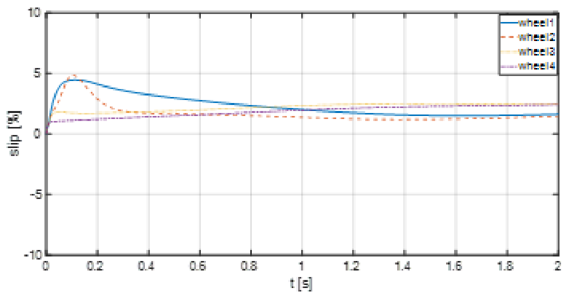


Fig. 12. Motion trajectories of free running vehicle with the steering wheel turned



(a). Turned angle of steering wheel β_{sw} = 180°



(b). Turned angle of steering wheel β_{sw} = 360°

Fig. 13. Wheel slip of free running vehicle with the steering wheel turned.

When the steering wheel has not been turned and the driving torques supplied to the wheels are chosen as in Table 4, the simulated trajectories of the vehicle were shown in Fig. 14 and the longitudinal slip of the wheels was shown in Fig. 15. If the driving torques supplied to the wheels share the same value, the vehicle moves in a straight line. If the values of the driving torque supplied to the right wheels differ from the values to the left wheels, the vehicle moves in a curved line. The value of the turning radius of the simulated trajectories depends on the difference in driving torque supplied to the left and to the right wheels of the vehicle.

In both scenarios, the trajectory of the vehicle's movement in two scenarios are similar and almost spiral. The longitudinal slip of the wheels fluctuates in a small range of about 5%, which does not affect the tires' wear or lifespan.

Table 4. Values of driving torque supplied to the wheels with vehicles running at initial speed of 20 m/s.

	Case 1	Case 2	Case 3
M1(N.m)	100	100	100
M2(N.m)	100	150	250
M3(N.m)	100	100	100
M4(N.m)	100	150	250

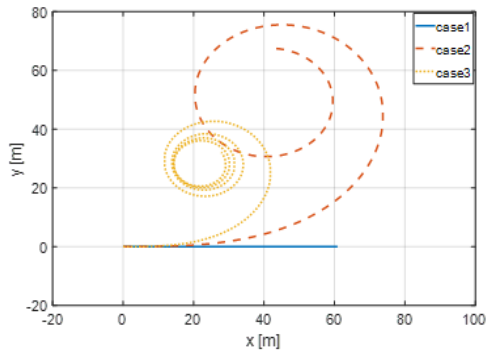
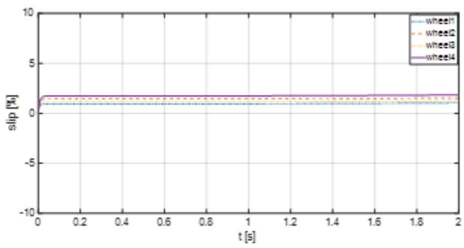
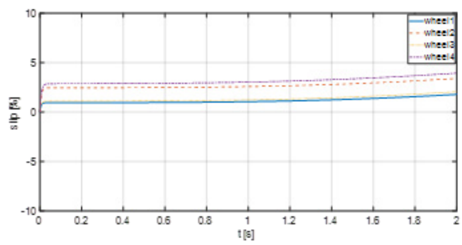


Fig. 14. The motion trajectory of vehicle with different values of driving torque supplied to the left and the right wheels (without turning of the steering wheel)



(a). Case 2



(b). Case 3

Fig. 15. Wheel slip of vehicle with different values of driving torque supplied to the left and the right wheels (without turning of the steering wheel)

From the relationship between the turning radius of trajectory and the difference of driving torque applied to the left and to the right wheels of the vehicle, a method to control the moving direction of a vehicle by regulating the driving torque applied to the left and right wheels could be proposed.

4. Experimental Simulation of Motion Direction Control

The prototype of vehicle with normal wheel was used to simulate experimentally control of motion direction. The vehicle prototype was controlled to move along a guiding line. The PID controller was used to regulate driving torque supplied to the right and the left wheels of the prototype vehicle and an infrared sensor was used to define the error of motion direction. The main loop of control algorithm was illustrated in Fig. 16 and the position of vehicle prototype moving along the guiding line was shown in Fig. 17. The experiment showed that it is possible to control the motion direction of vehicle by regulating the values of driving torque to the vehicle's wheels.

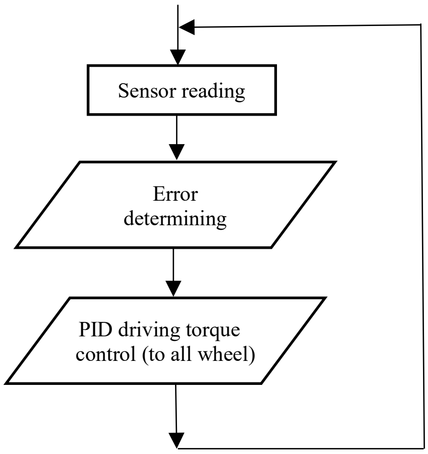


Fig. 16. Main loop of motion direction control algorithm by regulating the driving torque to the wheels

Fig. 17. Positions of vehicle prototype moving along the guiding line by regulating the driving torque to the wheels

5. Conclusion

From the simulated motion trajectories with the values of driving torque applied to each Mecanum wheel as in Table 1 and Table 2, it can be seen that a vehicle with Mecanum wheels can move in a straight line or curve line by regulating the driving torque to the wheels, therefore it is not necessary to design steering wheel on autonomous vehicles using Mecanum wheels.

On a vehicle with normal pneumatic wheel there must be a steering wheel to control its moving directions. Simulated motion trajectories of vehicle with normal pneumatic wheels with the values of driving torque applied to each wheel as in Table 3 and Table 4 show that the vehicle can move in a straight line or curved line either by regulating the turned angle of steering wheels or by regulating the driving torque to the wheels. When the vehicle runs at a low speed, it can move in a trajectory with small turning radius. The simulation showed that the value of the longitudinal wheel slip was not great enough to affect the tire's wear and lifespan.

From the previous comments, the technique of regulating driving torque supplied to the wheels for passenger cars could be suggested to improve motion direction stability as well as to develop self-driving electric cars in near future.

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