

Implementation of drive kinematics for a self-driving car

Deriving and implementing equations for steering and electronic differential in Robot Operating System

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Abstract— The paper spells out the derivation and implementation of mathematical models which provide steering angle required and differential speed calculation for each wheel in a car-like mobile robot which gratify for both Ackermann Steering and Four-Wheel steering. The models are simulated and is validated and verified by simulation of different maneuvers for different vehicle speeds in Gazebo before testing on a real vehicle which is later found to match the precision.

Index Terms— ROS, Robot Operating System, steering angle, electronic differential, self-driving car, autonomous robots, car like mobile robot, Instantaneous Centre of Rotation, ICR.

I. INTRODUCTION

The most conventional steering arrangement is to turn the front wheels using a hand-operated steering wheel which is positioned in front of the driver, via a steering column, which may contain universal joints (which may also be part of the collapsible steering column design), to allow it to deviate somewhat from a straight line. Other arrangements are sometimes found on different types of vehicles, for example, a tiller or rear-wheel steering. Tracked vehicles such as bulldozers and tanks usually employ differential steering — that is, the tracks are made to move at different speeds or even in opposite directions, using clutches and brakes, to bring about a change of course or direction.

The basic aim of steering is to ensure that the wheels are pointing in the desired directions. This is typically achieved by a series of linkages, rods, pivots and gears. The steering linkages connecting the steering box and the wheels usually conform to a variation of Ackermann steering geometry, to account for the fact that in a turn, the inner wheel is actually travelling a path of smaller radius than the outer wheel, so that the degree of toe suitable for driving in a straight path is not suitable for turns. The angle the wheels make with the vertical plane also influences steering dynamics as do the tires.

Four-wheel steering is a system employed by some vehicles to improve steering response, increase vehicle stability while maneuvering at high speed and to decrease turning radius at low speed.

In automotive engineering, the electronic differential is a form of differential, which provides the required torque for each driving wheel and allows different wheel speeds. It is used in place of the mechanical differential in multi-drive systems. When cornering the inner and outer wheels rotate at different speeds, because the inner wheels describe a smaller turning radius. This happens because of the separation between the wheels called as wheelbase and track width. In other words, when a car is moved in a circular path, the car draws four circles in case of two-wheel steering and two circles in case of four-wheel steering. In order to stabilize the vehicle and avoid unnecessary wear and tear of the tires, the rotational speeds of the wheels are to be varied slightly with respect to each other. The electronic differential uses the steering wheel command signal and the motor speed signals to control the power to each wheel so that all wheels are supplied with the torque they need.

The navigation module considers the vehicle as an object ignoring its dynamics. The dynamics are then considered while taking action at the lower levels. With above facts said, the navigation module portrays only the linear and angular velocities at which the vehicle has to move. With these two data being delivered, steering angle is computed along with the differential speed.

II. LITERATURE REVIEW

The main purpose of literature review is to furnish background information and to emphasize the relevance of the present study. A brief review of some selected references on obstacle detection and powertrain for a self-driving car is presented below.

Powertrain

According to Shigeyuki Yoshihara et al, generally, in most electric vehicle (EV) propulsion applications, an AC motor is connected mechanically to the wheels by reduction gears and a mechanical differential, as shown in Figure 1. [1]

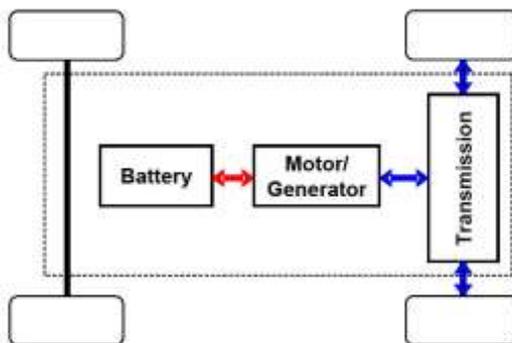


Fig 1: The above figure depicts motor connected to mechanical differential.

According to Bekheira Tabbache et al, also in some vehicle drive arrangements, high-speed, low-torque wheel motors necessitating gear reduction are employed, and in these cases, either a gear motor assembly is mounted inside the wheel, or a chassis mounted motor is connected to the wheel through gear reduction. Further simplification of the vehicle drive arrangement results in the purging of the gear being interposed between motor and wheel by employing in-wheel motors. The Figure 2 depicts in-wheel motors. The above then calls for the use of an electric differential.[2]



Fig 2: In-wheel motor

Certain Electric vehicles with independent all-wheel drive powertrain will be equipped with Variable Frequency Drives (VFD) which run on AC supply. The torque and speed of these VFDs are varied by varying the frequency in supplying the electric supply. This is on the fact that at low frequency, torque will be high and speed will be low and vice versa. In case of manually operated vehicle, devices like potmeters are used to vary the frequency, which in turn varies proportionally the torque and speed. While in case of self-driven vehicles, the frequency is varied with the help of a AC Speed Controller. In order to employ AC motors, the vehicle’s DC supply is converted to AC and pipelined to the drives as shown in Figure 3. [1]

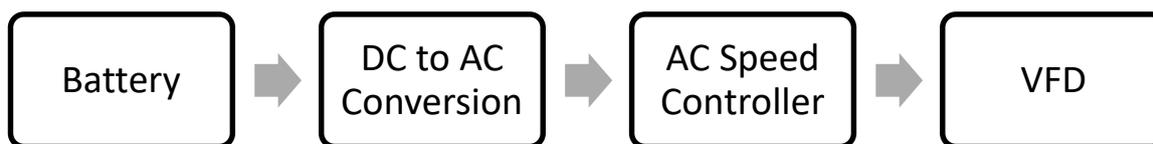


Fig 3: The above figure depicts the process flow of controlling the wheel rotation using VFD.

According to Yafei Wang et al, electric vehicles can be implemented with four in-wheel independent motors. [3] Vehicles with independent all-wheel drive powertrain, some will be equipped with DC motors which run on DC supply. The torque and

speed on these DC motors are varied by means of a H-bridge or a motor controller. The motor controller increases the current when torque is required. The decision of increasing current is made with the help of incremental encoder. Incremental encoder outputs the wheel rotation, based on its output, if the wheel is not rotating, the motor controller increases current to increase torque. To get a precise wheel rotation, PWM will be supplied from a microcontroller to motor controller. The sequence diagram is as shown in Figure 4.



Fig 4: The above figure depicts the process flow of controlling the wheel rotation using DC motors.

According to Bekheira Tabbache et al, ED-based EVs have advantages over classical EVs with a central motor. Indeed, mounting the motors directly to the wheels simplifies the mechanical layout. The ED system will reduce the drive line components, thus improving the overall reliability and efficiency. This option will also reduce the drive line weight since mechanical differential and gear reduction are not used. However, one of the main issues in the design of these EVs (without mechanical differential) is to ensure vehicle stability in particular while cornering or under slippery road conditions. This calls for a specific traction control system. [4]

Steering

According to Xiaodong Wu et al, in traditional EVs, a steering mechanism is obligatory for the turn motion. Nonetheless, by using the merit of individual wheel traction motors on the electric drive vehicles, it opens up the possibility of using a differential speed steering systems. A simple scheme is shown in Figure 5. Since gearbox, retarder, transmission and steering mechanism are called off from the four in-wheel motors independent drive vehicle or chassis mounted motors independent drive vehicle. Using four motors independently to drive vehicle, the steering of the vehicle is achieved by the differential speed controls on four wheels. The minimum turning radius of differential speed steering can be zero when a when on axis rotation is performed, which is impossible by traditional steering method.

Differential speed steering is extensively employed in the navigation of mobile robot. Due to undistinguishable steering mechanisms, wheeled and tracked skid-steered vehicles share many properties. Many of the difficulties associated with modelling and operating in these kinds of skid-steered vehicles arise from the complex contact between wheel and terrain. For Ackerman-steered vehicles as shown in Figure 5, the wheel motions may often be accurately modelled by pure rolling, while for differential-steered vehicles, in general, are modelled by curvilinear motion, the wheels roll and slide at the same time. This makes it difficult to develop kinematic and dynamic models, which accurately designate the motion characteristic. Vehicle can be steered through differential braking which is to get a speed difference in similar thought. [4]

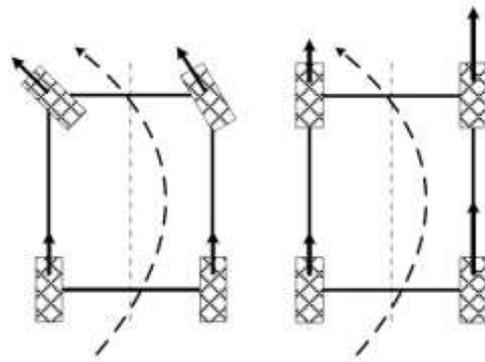


Fig 5: Two kinds of steering methods. Left depicts Ackermann steering. Right depicts differential steering.

Ackermann steering is the steering mechanism implemented in all the cars running on road. With this mechanism, the inner wheel turns more than the outer wheel towards the Instantaneous Centre of Rotation (ICR) as inner wheel covers less distance compared to the outer wheel. ICR is an imaginary point about which the car takes a turn as shown in Figure 6.

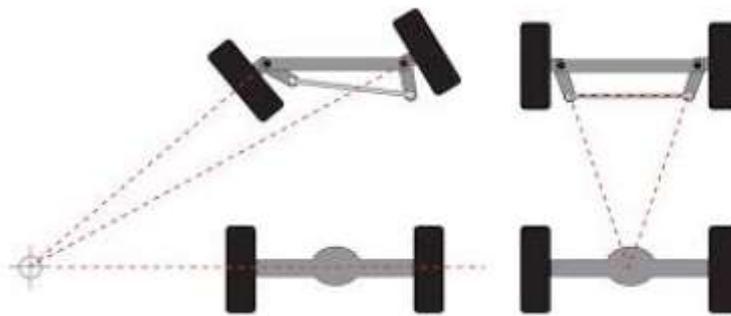


Fig 6: Figure depicts the Ackermann steering mechanism.

Ackermann steering can be implemented by employing either Ball-Screw mechanism, Pitman lever or Rack and Pinion mechanism as shown in Figure 7. The aforementioned mechanisms are employed to move the tie rod left and right to obtain desired steering angle which is achieved with the help of a linear actuator in case of Pitman lever or a rotary actuator in case of Rack and Pinion and Ball-Screw mechanisms.



Fig 7: Depiction of Rack and Pinion for steering

The steering mechanisms are generally implemented for front wheels only. Nevertheless, to take a sharper and shorter turn during cornering and high speed maneuvers, the same can be replicated to rear wheels to obtain four-wheel steering.

Outcome of Literature review

According to the present theories and practices, any of the aforementioned methods can be used in implementing the drivetrain. All wheel drive can be implemented with a motor for each wheel. Nevertheless, in order to avoid converting DC to AC and Controlling the frequency of AC, DC motors are employed for all wheels. Also, with the intention of research and development

of the base platform, chassis mounted motors with gear reduction mechanism is employed. Since the chosen motor is a DC motor, it is driven by open source motor controllers controlled by a Arduino Mega.

According to the present theories and practices, there are numerous ways of implementing steering mechanisms. While considering the weight of the vehicle, differential steering will not suffice. Also, due to the curvilinear motion, the odometry feedback calculation will vary. Hence, by employing Pitman lever mechanism, steering is actuated for both front as well as rear wheels. A linear actuator is employed to actuate the Pitman arm and a rotary encoder to have a feedback from steering.

III. DERIVATION

The equations below are derived as per the following assumptions,

- The value of Linear Velocity is known at a given instant.
- The value of Angular Velocity is known at a given instant.
- The value of Wheelbase is known which is a constant. Since, the length of the car cannot change.
- The value of Trackwidth is known which is a constant. Since, the width of the car cannot change.
- The value of vehicle's wheel diameter is known which is a constant.
- As per Robotics Right Hand Rule, Turning Radius is Negative for Right Turn and Positive for Left Turn. Hence, θ value is negative for Right Turn and Positive for Left Turn.

Deriving equations for Electronic Differential in Ackermann Steering

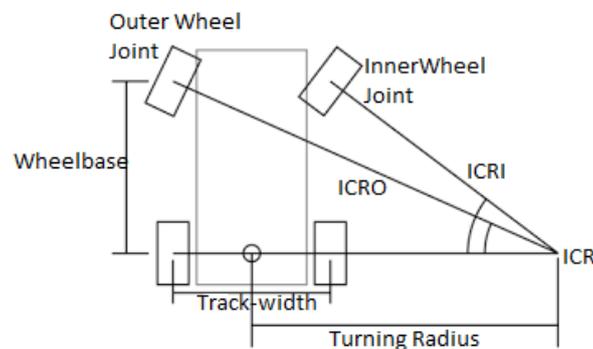


Fig 8: Parameters and variables used in derivation for Ackermann Steering.

The below equations are derived with reference to Figure 8

First, turning radius is computed from Linear and Angular velocity

$$\text{Turning Radius} = \frac{\text{Linear Velocity}}{\text{Angular Velocity}} \quad (1)$$

Where *Linear Velocity* and *Angular Velocity* are obtained from navigation stack

the displacement of rear wheel joints along the arc drawn about ICR as the center is calculated using the below equation,

$$\text{Displacement} = (\text{Turning Radius} \pm \text{trackwidth}/2) \times \text{Angular Velocity} \quad (2)$$

Where, Turning Radius is obtained from (1) in Meters

Angular Velocity is obtained from navigation stack in Radians per Second

The sign in equation (2) changes based on the position of the wheel.

From Figure 8,

$(\text{Turning Radius} + \text{trackwidth}/2)$ is used for outer wheel.

$(\text{Turning Radius} - \text{trackwidth}/2)$ is used for inner wheel.

The rotations required to cover the distance is calculated using the equation below,

$$\text{Wheel Rotations} = \frac{\text{Displacement}}{\text{Wheel Radius}} \quad (3)$$

Where, Displacement calculated from the equation (2) with unit meters

Wheel Radius is the radius of the wheel in meters
 Wheel Rotations are commanding angles for each instant in Radians

The distance between ICR and the inner wheel's joint is calculated using Pythagorean theorem as mentioned below

$$ICRI = \sqrt{\text{wheelbase}^2 + (\text{turning radius} - \frac{\text{Track-width}}{2})^2}$$
 (4)

To calculate the displacement of front inner wheel joint along the arc drawn about ICR as the center is calculated using the below equation,

$$\text{Displacement} = ICRI \times \text{Angular Velocity}$$
 (5)

Where, Turning Radius is obtained from equation (4) in Meters
 Angular Velocity is obtained from navigation stack in Radians per Second

The rotations required to cover the distance is calculated using the equation below,

$$\text{Wheel Rotations} = \frac{\text{Displacement}}{\text{Wheel Radius}}$$
 (6)

Where, Displacement calculated from the equation (5) in meters
 Wheel Radius is the radius of the wheel in meters
 Wheel Rotations are commanding angles for each instant in Radians

The distance between ICR and the inner wheel's joint is calculated using Pythagorean theorem as mentioned below

$$ICRO = \sqrt{\text{wheelbase}^2 + (\text{turning radius} + \frac{\text{Track-width}}{2})^2}$$
 (7)

To calculate the displacement of front inner wheel joint along the arc drawn about ICR as the center is calculated using the below equation,

$$\text{Displacement} = ICRO \times \text{Angular Velocity}$$
 (8)

Where, ICRO is obtained from (7) in Meters
 Angular Velocity is obtained from navigation stack in Radians per Second

The rotations required to cover the distance is calculated using the equation below,

$$\text{Wheel Rotations} = \frac{\text{Displacement}}{\text{Wheel Radius}}$$
 (9)

Where, Displacement calculated from the equation <insert equation number> with unit meters
 Wheel Radius is the radius of the wheel in meters
 Wheel Rotations are commanding angles for each instant in Radians

Deriving equations to compute steering angle for four-wheel steering.

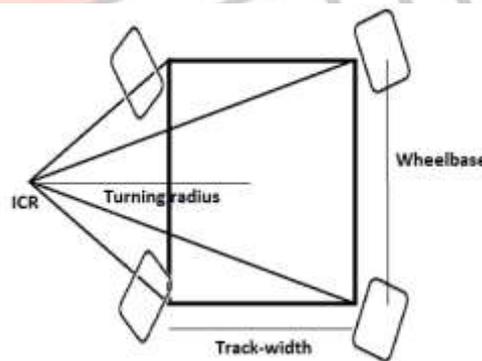


Fig 9: Parameters and variables used in derivation for four-wheel Steering.

Turning Radius is first calculated using the equation (1)

Let θ be the steering angle which is to be computed.

Assuming symmetry horizontally along the center of the vehicle, the steering angle for both front and rear steering angles remain same.

Therefore,

$$\tan \theta = \frac{\frac{\text{wheelbase}}{2}}{\text{turning radius}}$$
 (10)

$$\tan \theta = \frac{\text{wheelbase}}{2 \times \text{turning radius}} \quad (11)$$

Steering Angle θ is obtained by,

$$\theta = \tan^{-1} \frac{\text{wheelbase}}{2 \times \text{turning radius}} \quad (12)$$

Hence steering angle for front and rear wheels is given by,

$$\text{front wheel steering angle} = \text{rear wheel steering angle} = \tan^{-1} \frac{\text{wheelbase}}{2 \times \text{turning radius}} \quad (13)$$

Deriving equations for electronic differential for four-wheel steering.

First the displacement of wheel joints along the arc drawn about ICR as the center is calculated using the below equation,

$$\text{Displacement} = (\text{Turning Radius} \pm \text{Trackwidth}/2) \times \text{Angular Velocity} \quad (14)$$

Where, Turning Radius is obtained from equation (1) in Meters
Angular Velocity is obtained from navigation stack in Radians per Second

The sign in equation (14) changes based on the position of the wheel.

From Figure 9,

$(\text{Turning Radius} + \text{trackwidth}/2)$ is used for outer wheel.

$(\text{Turning Radius} - \text{trackwidth}/2)$ is used for inner wheel

The rotations required to cover the distance is calculated using the equation below,

$$\text{Wheel Rotations} = \frac{\text{Displacement}}{\text{Wheel Radius}} \quad (15)$$

Where, Displacement calculated from the equation (14) in meters
Wheel Radius is the radius of the wheel in meters
Wheel Rotations are commanding angles for each instant in Radians

IV. IMPLEMENTATION

Mechanically, the motors are housed on the chassis with gear reduction mechanism connected mechanically to the wheels. The steering mechanism is implemented using Pitman arm which is actuated using a linear actuator and assembled with a rotary encoder for feedback from steering.

The Navigation module after planning the path sends out Linear & Angular velocity at which the robot has to cruise. Steering & Differential module implemented in C++11, takes in these inputs, passes them through Mathematical equations from (1) to (16) which adhere to mobile robot kinematics and impulses the steering angle and wheel rotations per second to the next module called motor driver which drives the motors and actuates steering actuators as per given input. The implementation of Navigation module and motor driver module is beyond the scope of this paper. An input to select the preferred steering mechanism is employed to furnish upgradeability in the near future to which, the input is pipelined from another module. In case of selecting Ackermann steering, the value for rear wheel steering actuator will be pipelined as zero to the motor driver module. While, the value for rear wheel steering actuator will be pipelined as computed in (13) to the motor driver module. The high-level design for integration is as shown in Figure 10.

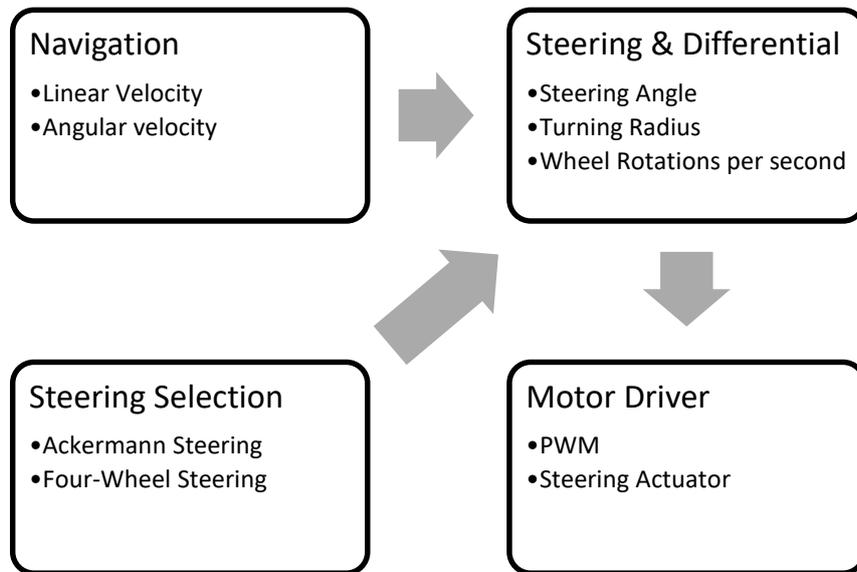


Fig 10: High level design

The module first takes in Linear and Angular velocities from Navigation module and computes Turning Radius using the equation (1). Steering Angle required is computed having known the value of Turning Radius and Wheelbase which is a constant using the equation (16) for Ackermann Steering mode and equation (12) for four-wheel steering mode. Following the computation, Steering Angle is given out as one of the outputs. On the other hand, Linear velocities for each wheel is computed. Having the Linear velocities for each wheel known, number of rotations required per second is calculated and given out as outputs. The detailed design for both the steering modes are depicted in Figure 11.

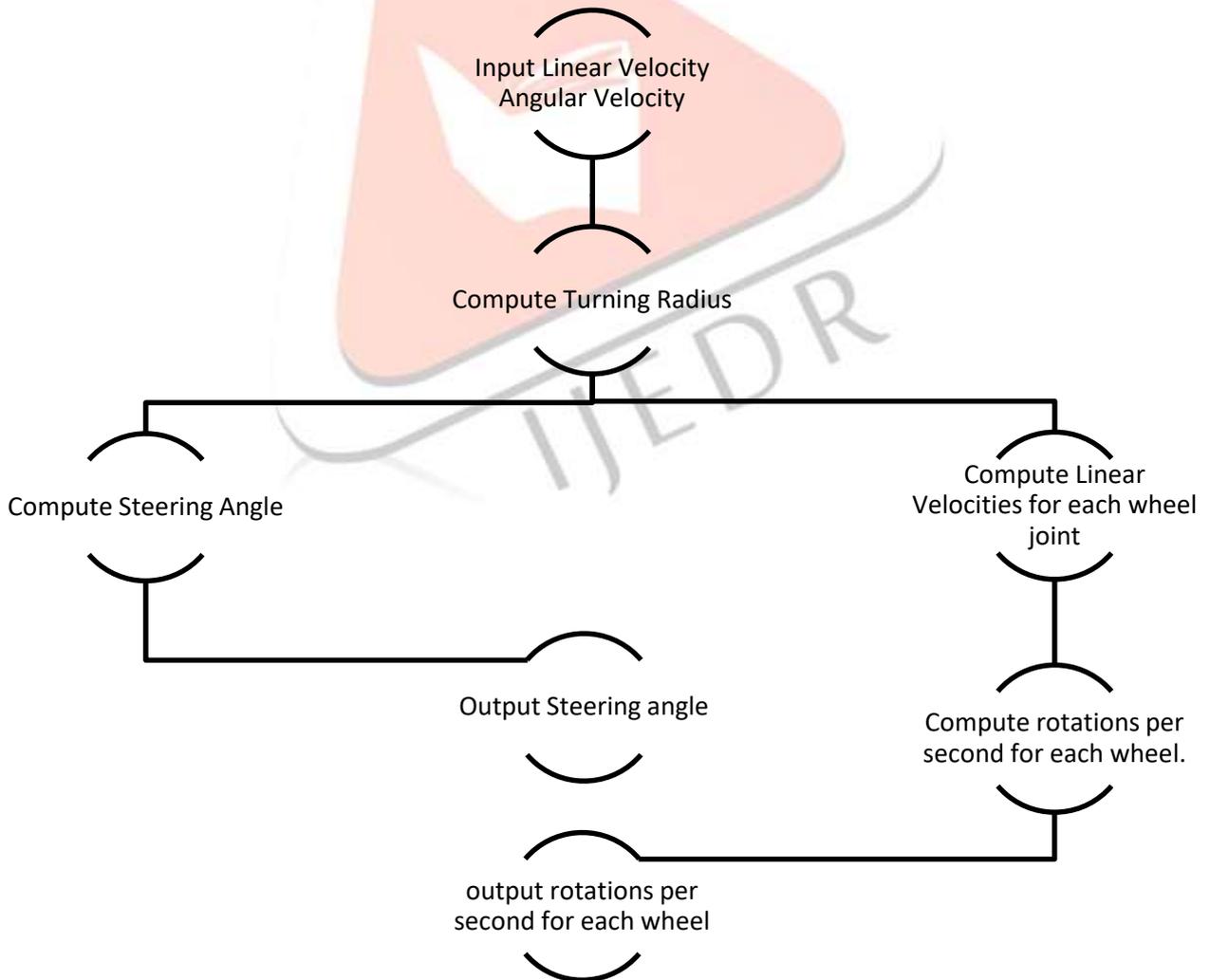


Fig 11: Detailed design of steering & differential module

The objective of computing steering angle for a car-like mobile robot adhering to mobile robot kinematics with two-wheel steering is as mentioned below which is already derived and put to use in many of the car-like mobile robots,

$$\text{steering angle} = \tan^{-1} \frac{\text{wheelbase}}{\text{turning radius}} \quad (16)$$

Equations (1) to (16) are implemented in Robot Operating System with C++ 11.

The observed data values for Ackermann steering are tabulated as follows in Table 1 and Table 2. The data from the Table 1 portrays that during Left Turn, the front right wheel covers maximum distance which is why it has higher rotations per second while rear left wheel has lowest rotations per second as it covers minimum distance. While Table 2 portrays that during Right Turn, the front left wheel covers maximum distance which is why it has higher rotations per second while rear right wheel has lowest rotations per second as it covers minimum distance.

Table 1: Data readings for Left Turn taken during the test run for Ackermann Steering.

Command Velocity		Steering		Wheel Rotations				Turn
[Linear Velocity]	[Angular Velocity]	Front wheels' Steering Angle	Rear wheels' Steering Angle	Front Left Wheel Speed	Front Right Wheel Speed	Rear Left Wheel Speed	Rear Right Wheel Speed	
mps	radps	Degrees	Degrees	rps	rps	rps	rps	
0.5000	0.00	0.00	0.00	2.50	2.50	2.50	2.50	
1.0000	0.00	0.00	0.00	5.00	5.00	5.00	5.00	
1.5000	0.00	0.00	0.00	7.50	7.50	7.50	7.50	
2.0000	0.00	0.00	0.00	10.00	10.00	10.00	10.00	
0.5000	0.03	5.00	0.00	2.42	2.59	2.42	2.58	Left Turn
1.0000	0.06	5.00	0.00	4.85	5.19	4.83	5.17	
1.5000	0.09	5.00	0.00	7.28	7.78	7.25	7.75	
2.0000	0.12	5.00	0.00	9.70	10.38	9.66	10.34	
0.5000	0.06	10.01	0.00	2.37	2.71	2.33	2.67	
1.0000	0.12	10.01	0.00	5.31	7.73	3.42	6.58	
1.5000	0.17	10.01	0.00	7.11	8.12	6.99	8.01	
2.0000	0.23	10.01	0.00	9.48	10.83	9.32	10.68	
0.5000	0.09	15.01	0.00	2.34	2.84	2.24	2.76	
1.0000	0.18	15.01	0.00	4.68	5.68	4.48	5.52	
1.5000	0.26	15.01	0.00	7.01	8.52	6.72	8.28	
2.0000	0.35	15.01	0.00	9.35	11.36	8.96	11.04	
0.5000	0.12	20.01	0.00	2.33	2.99	2.15	2.85	

1.0000	0.24	20.01	0.00	4.66	5.99	4.29	5.71
1.5000	0.36	20.01	0.00	7.00	8.98	6.44	8.56
2.0000	0.48	20.01	0.00	9.33	11.98	8.59	11.41

Table 2: Data readings for Right Turn taken during the test run for Ackermann Steering.

Command Velocity		Steering		Wheel Rotations				Turn
[Linear Velocity]	[Angular Velocity]	Front wheels' Steering Angle	Rear wheels' Steering Angle	Front Left Wheel Speed	Front Right Wheel Speed	Rear Left Wheel Speed	Rear Right Wheel Speed	
mps	radps	Degrees	Degrees	rps	rps	rps	rps	
0.5000	0.00	0.00	0.00	2.50	2.50	2.50	2.50	
1.0000	0.00	0.00	0.00	5.00	5.00	5.00	5.00	
1.5000	0.00	0.00	0.00	7.50	7.50	7.50	7.50	
2.0000	0.00	0.00	0.00	10.00	10.00	10.00	10.00	
0.5000	-0.03	-5.00	0.00	2.42	2.59	2.42	2.58	Right Turn
1.0000	-0.06	-5.00	0.00	5.19	4.85	5.17	4.83	
1.5000	-0.09	-5.00	0.00	7.78	7.28	7.75	7.25	
2.0000	-0.12	-5.00	0.00	10.38	9.70	10.34	9.66	
0.5000	-0.06	-10.01	0.00	2.71	2.37	2.67	2.33	
1.0000	-0.12	-10.01	0.00	5.41	4.74	5.34	4.66	
1.5000	-0.17	-10.01	0.00	8.12	7.11	8.01	6.99	
2.0000	-0.23	-10.01	0.00	10.83	9.48	10.68	9.32	
0.5000	-0.09	-15.01	0.00	2.84	2.34	2.76	2.24	
1.0000	-0.18	-15.01	0.00	5.68	4.68	5.52	4.48	
1.5000	-0.26	-15.01	0.00	8.52	7.01	8.28	6.72	
2.0000	-0.35	-15.01	0.00	11.36	9.35	11.04	8.96	
0.5000	-0.12	-20.01	0.00	2.99	2.33	2.85	2.15	
1.0000	-0.24	-20.01	0.00	5.99	4.66	5.71	4.29	

1.5000	-0.36	-20.01	0.00	8.98	7.00	8.56	6.44	
2.0000	-0.48	-20.01	0.00	11.98	9.33	11.41	8.59	

The observed data values for four-wheel steering are tabulated as follows in Table 3 and Table 4. The data from the Table 3 portrays that during Right Turn, the front left wheel and rear left wheel covers more distance which is why it has higher rotations per second while rear left wheel and front left wheel has lower rotations per second as it covers lesser distance comparatively. On the other hand, Table 4 portrays that during Left Turn, the front right wheel and rear right wheel covers more distance which is why it has higher rotations per second while rear left wheel and front left wheel has lower rotations per second as it covers lesser distance comparatively.

Table 3: Data readings for Right Turn taken during the test run for four-wheel Steering.

Command Velocity		Steering		Wheel Rotations				Turn
[Linear Velocity]	[Angular Velocity]	Front wheels' Steering Angle	Rear wheels' Steering Angle	Front Left Wheel Speed	Front Right Wheel Speed	Rear Left Wheel Speed	Rear Right Wheel Speed	
mps	radps	Degrees	Degrees	rps	rps	rps	rps	
0.5000	0.00	0.00	0.00	2.50	2.50	2.50	2.50	Straight line motion
1.0000	0.00	0.00	0.00	5.00	5.00	5.00	5.00	
1.5000	0.00	0.00	0.00	7.50	7.50	7.50	7.50	
2.0000	0.00	0.00	0.00	10.00	10.00	10.00	10.00	
0.5000	-0.03	-5.00	0.00	2.42	2.58	2.42	2.58	Right Turn
1.0000	-0.06	-5.00	0.00	5.17	4.83	5.17	4.83	
1.5000	-0.09	-5.00	0.00	7.75	7.25	7.75	7.25	
2.0000	-0.12	-5.00	0.00	10.34	9.66	10.34	9.66	
0.5000	-0.06	-10.01	0.00	2.67	2.33	2.67	2.33	
1.0000	-0.12	-10.01	0.00	5.34	4.66	5.34	4.66	
1.5000	-0.17	-10.01	0.00	8.01	6.99	8.01	6.99	
2.0000	-0.23	-10.01	0.00	10.68	9.32	10.68	9.32	
0.5000	-0.09	-15.01	0.00	2.76	2.24	2.76	2.24	
1.0000	-0.18	-15.01	0.00	5.52	4.48	5.52	4.48	
1.5000	-0.26	-15.01	0.00	8.28	6.72	8.28	6.72	
2.0000	-0.35	-15.01	0.00	11.04	8.96	11.04	8.96	

0.5000	-0.12	-20.01	0.00	2.85	2.15	2.85	2.15
1.0000	-0.24	-20.01	0.00	5.71	4.29	5.71	4.29
1.5000	-0.36	-20.01	0.00	8.56	6.44	8.56	6.44
2.0000	-0.48	-20.01	0.00	11.41	8.59	11.41	8.59

Table 4: Data readings for Left Turn taken during the test run for four-wheel Steering.

Command Velocity		Combined steering angle	Front Wheel Steering Angle	Rear Wheel Steering Angle	Wheel Speeds				Turn
[Linear Velocity]	[Angular Velocity]				Front Left Wheel	Front Right Wheel	Rear Left Wheel	Rear Right Wheel	
mps	radps	Degrees	Degrees	Degrees	radps	radps	radps	radps	
0.50	0.00	0.00	0.00	0.00	2.50	2.50	2.50	2.50	Straight Line Motion
1.00	0.00	0.00	0.00	0.00	5.00	5.00	5.00	5.00	
1.50	0.00	0.00	0.00	0.00	7.50	7.50	7.50	7.50	
2.00	0.00	0.00	0.00	0.00	10.00	10.00	10.00	10.00	
0.50	0.03	5.00	2.50	2.50	2.42	2.59	2.42	2.59	Left Turn
1.00	0.06	5.00	2.50	2.50	4.84	5.17	4.84	5.17	
1.50	0.09	5.00	2.50	2.50	7.25	7.76	7.25	7.76	
2.00	0.12	5.00	2.50	2.50	9.67	10.35	9.67	10.35	
0.50	0.06	10.01	5.00	5.00	2.34	2.68	2.34	2.68	
1.00	0.12	10.01	5.00	5.00	3.90	6.86	3.90	6.86	
1.50	0.17	10.01	5.00	5.00	7.02	8.04	7.02	8.04	
2.00	0.23	10.01	5.00	5.00	9.36	10.72	9.36	10.72	
0.50	0.09	15.01	7.50	7.50	2.26	2.78	2.26	2.78	
1.00	0.18	15.01	7.50	7.50	4.53	5.56	4.53	5.56	
1.50	0.26	15.01	7.50	7.50	6.79	8.34	6.79	8.34	
2.00	0.35	15.01	7.50	7.50	9.06	11.12	9.06	11.12	
0.50	0.12	20.01	10.01	10.01	2.19	2.89	2.19	2.89	
1.00	0.24	20.01	10.01	10.01	4.39	5.78	4.39	5.78	

1.50	0.36	20.01	10.01	10.01	6.58	8.67	6.58	8.67	
2.00	0.48	20.01	10.01	10.01	8.77	11.55	8.77	11.55	

V. CONCLUSION

This paper aspires to provide a baseline for developing a self-driving car with independent motors for each wheel eliminating the mechanical implementational overhead of differential gear mechanism. The derived mathematical models were implemented and tested in simulation and thus validated. Post validation, the same was implemented on a real vehicle and verified. Upon setting the goal, the vehicle steered towards the goal and reached without overshooting and undershooting. Also, it was observed from the feedback logs that the electronic differential is completely functional with values matching the calculated values. Hence the mathematical models are proved.

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