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Low Speed Collision Avoidance Using Ultrasonic Sensor Input

Master's thesis in Systems, Control and Mechatronics

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Abstract

To avoid collision, a driver should be aware of the surroundings, judge distances to obstacles and manoeuvre accordingly. But there are many situations where the driver misjudges or misses obstacles in the blind spot and ends up in a collision. This thesis presents development of a human in loop collision avoidance function for a vehicle which predicts collisions and assists the driver accordingly. The concept of potential field is used to model obstacles and dynamics of the vehicle is coupled with the potential fields to calculate torque to be applied on the steering wheel to assist the driver to avoid collision. In addition to this, the function monitors the distances to the obstacles from the vehicle contour to calculate the brake pressure and apply whenever necessary. The function is developed in Matlab/Simulink, with features that suite both to suite level-1 and level-2 vehicle automation. The function, when used as a level-1 function, is evaluated in a test vehicle and the results depict the feasibility of this approach.

Keywords: Potential field, projected points, steering resistance, brake control, collision avoidance function.

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First we need to thank Andrew Backhouse our supervisor at Volvo Car Corporation who gave us this interesting topic for the thesis work. Being there right from the beginning, helping us with the right inputs and helping us with the car testing whenever we wanted to test the system. We are also thankful Clase Boberg supervisor at Volvo Cars Corporation , helping us with the insights of the projects with regards to sensors, explaining things about the future of sensors.

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We would also like to thank everyone who supported us in any respect for the completion of the project. This is the result of the team effort and would like to dedicate a small bit of contribution to the big future of the Volvo Car Corporation.

In the end we would like to be grateful to our family and friends, without them this would not haven been possible.

Vishnu Muraleedharan Kuttiyel & Raghunandan Sidhanti, Gothenburg, July 2016

Contents

List of Figures

List of Tables

1
Introduction

1.1 Introduction

Most of us would have been involved or seen a collision in a parking lot, as parking often involves narrow manoeuvring between objects. Allianz insurance company has done a research [**12**] on randomly selected insurance claims made within Third Party Liabilities (TPL) and Motor Own Damages (MOD). In this research, 1000 claims in TPL for material damage and 983 claims in MOD were selected. From these, 44% claims in TPL were relevant to Parking and Maneuverings Accidents (PMA) and 39% claims in MOD (Collisions) were relevant to PMA. Most of these claims have happened during reversing the vehicle into parking or reversing out of a parking spot. These kind of collisions which occur while manoeuvring at low speed are referred to as low speed collisions. The most affected part of the car due to these low speed collisions, is the area around the driver's blind spot (bumper and side panel rear). These results motivate the need for a function which assists the driver in collision avoidance. There are many ongoing researches in the field of active safety. Among the automotive manufacturers, Volvo Cars Corporation (VCC) is actively involved in developing advanced driver assistant systems (ADAS).

ADAS functions developed for collision avoidance functionality will have direct control of the safety critical functions like steering, throttle or braking of the vehicle. Vehicles equipped with such functions are called automated vehicles based on the policy released by National Highway Traffic Safety Administration, NHTSA (U.S. Department of Transportation)[**18**]. NHTSA has categorised the vehicle automation into 5 levels ranging from zero automation to fully automated vehicles.

In level-0, the driver is in complete control of the vehicle with no automation of any of the safety critical functions. In level-1, driver has overall control of the vehicle and is completely responsible for operating safely. At this level, vehicle automation may provide functionalities which assist the driver in performing certain tasks like lane change assist by directly influencing any one of the safety critical functions. In level-2, vehicle automation functions may take over two or more safety critical functions at the same time under certain traffic situations. Driver is expected to be available for urgent take over of controls under such situations. In level-3, vehicle automation takes complete control of the vehicle when certain driving conditions are met and system continuously monitors the environment to identify situations where the driver has to take control. At this level, driver is not expected to be available for urgent take over requests as compared to level-2. In level-4, vehicle automation is in complete control of the vehicle at all operating conditions and driver has no role in driving operation. These levels are summarised in the figure below.

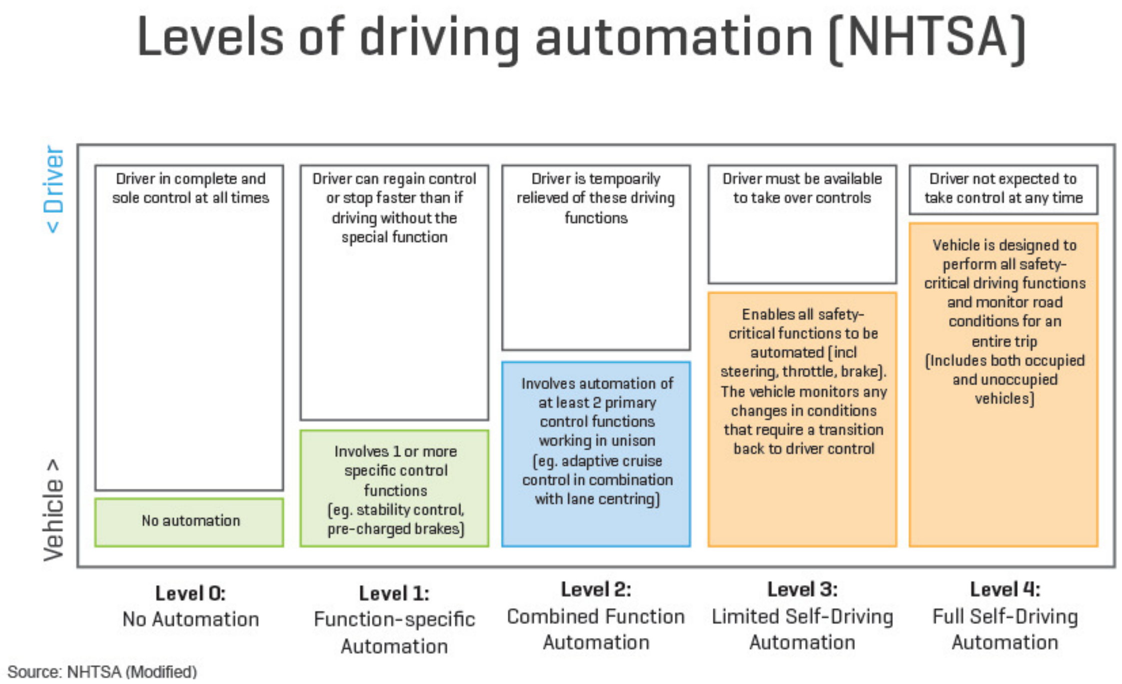

Figure 1.1: Levels of Vehicle Automatation as per National Highway Traffic Safety Administration.

1.2 Purpose

Figure 1.2: An image of HMI display from a Volvo car's dash board. The right part of the image describes obstacles in the range using ultrasonic sensors mounted around the vehicle. The picture depicts the range of the sensors and displays positions of the obstacles. The golden brown and red coloured space around the car picture signifies a obstacle in that range.

According to [**12**], a function for low speed collision avoidance has very high potential to reduce number of low speed collisions. The function developed in this thesis makes use of measurement data form the ultrasonic sensors present around the vehicle (Volvo V40). This vehicle uses the ultrasonic sensors to display the range of obstacle on the dash board along with a beep sound as the vehicle gets closer to an obstacle. The screen shot of such a dash board notification is shown in Figure 1.2.

In the right end of Figure 1.2, an image of vehicle with position of obstacles in the range of sensors is displayed. The golden brown patches in front and back indicates the positions of the obstacle in that range. The colour of these ranges changes according to the distance of the obstacle from the vehicle. For example, the red patch at the rear end of vehicle indicates that the objects are closer to the vehicle. Another indicator to the driver is the beep sound which increases its frequency as the vehicle gets closer to an obstacle. Such notifications are generally helpful during the manual parking scenario which warns the driver for the obstacles present around the vehicle in the range of the sensors. But, there are always cases where the driver misjudges the distance to an object or not seeing the object itself where vehicle might lead into collision. In addition to this conventional visual and audio warning system, a function which can provide resistive torque (tactile feedback) on the steering wheel to alert the driver about the obstacles will be advantageous. Tactile feedback in addition to the conventional warning system will assist the driver to pay more attention and analyse the situation faster. Tactile feedback is considered to be an effective form of human to machine interface which reduces the number of human errors [**17**].

The low speed collision avoidance function (lsCAF) developed should be a function which can be easily overridden by the driver. However, the function shouldn't be an intrusive system and shouldn't interfere with driver's intentions.

1.3 Literature Review

The concept of potential field was introduced by Oussama Khatib [**1**] in 1986 to develop real time obstacle avoidance for manipulators and mobile robots. Khatib studied the movement of a manipulator in a field of forces and used potential field to calculate the repulsive force, which is applied on the manipulator to avoid the collision. The concept of potential field was further extended to develop collision avoidance for vehicles [[**3**]-[**6**]]. In [**5**], a potential field function was used to model obstacles for highway driving and also discusses about implementing potential field function for change in velocity or calculation of lateral force required for lane change. Other researchers have also studied in similar direction of using potential field for autonomous driving. In [**6**], authors used the force acting on the vehicle from the potential field to develop a torque based steering actuation for autonomous driving. All these papers discussed involves different approach to connect potential field concept with the vehicle functions and developing different functions.

Developing vehicle model for low speed involves various assumptions which are discussed in text book [**9**] and also in the lecture compendium [**10**] for the course vehicle dynamics in Chalmers University. Similar assumptions were made in [**11**] which deals with low speed vehicle model.

1.4 Scenarios

In this thesis, parking scenario is considered to test the developed function as most of the low speed collisions occur in a parking lot.

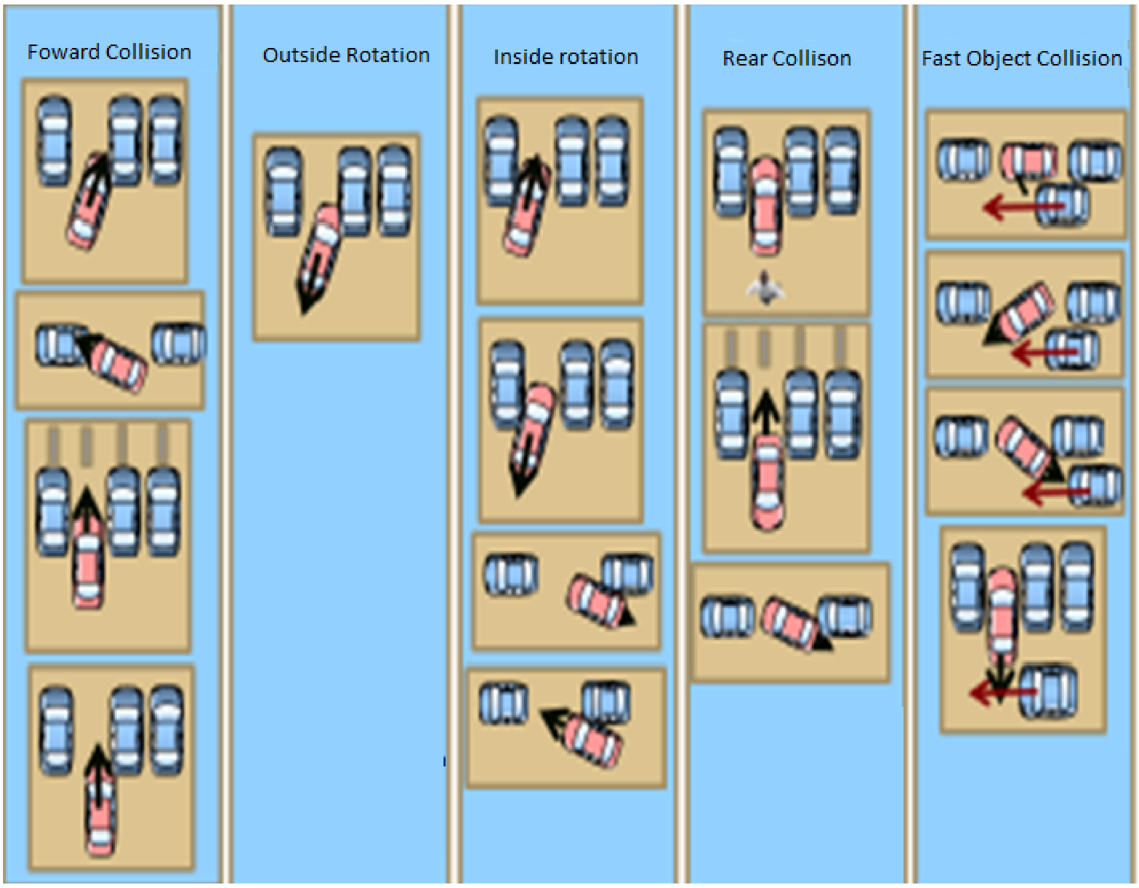

Figure 1.3: Common parking accidents scenes from a parking lot. The image is provided by the VOLVO cars. There are different types of collision displayed through which few of them are selected for the testing of the function in simulation and real testing.

Figure 1.3 shows the most common parking accident situations. Some of these scenarios, i.e the inside rotation, rear collision and forward collision were included into thesis simulations for testing the function. These include 1) a vehicle going straight to hit a obstacle, 2) a vehicle reversing into an obstacle and 3) a vehicle moving into a tight parking scenario.

The National Highway Traffic Safety Administration under U.S Department of Transportation has given out a laboratory test procedure for *Rear Automatic Braking Feature* on any passenger vehicle [**16**]. According to this procedure the definition of the Rear Automatic Braking Feature is mentioned as the vehicle equipment that has the ability to sense the presence of objects behind a reversing vehicle, alert the driver of the presence of the object(s) via auditory and visual alerts, and automatically engage the service brake system to stop the vehicle.

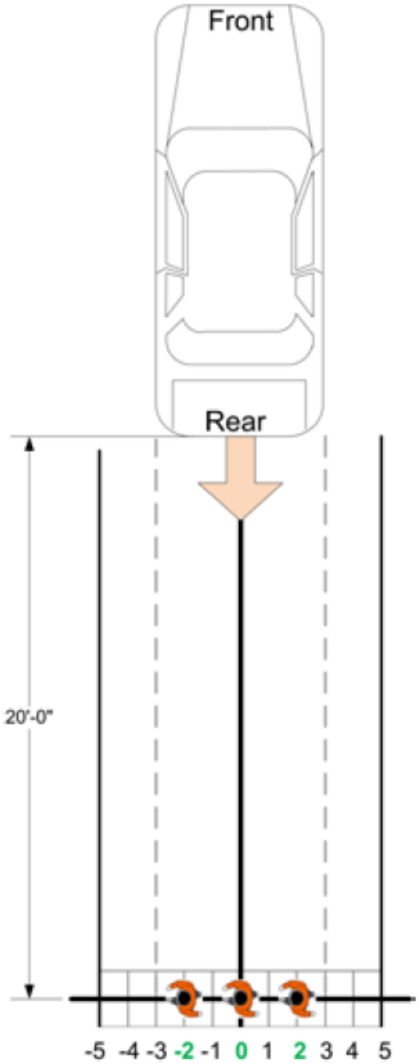

Figure 1.4: Test procedure for rear automatic braking from the US road safety department. The three red spots shows the positions for the obstacles. The position might be centre aligned to the car or 2m away from each side as displayed in the scale with green numbers.

According to the procedure, the vehicle has to be at least 20 feet away from the obstacle. Three obstacles are positioned perpendicular to vehicle's centre line. One obstacle is placed centred along the line perpendicular to vehicle's centre line and two more obstacles are positioned at 2 feet from the centre line toward the vehicle passenger's side. Figure 1.4 displays the procedure setup with three obstacles (red spots) placed 20 feet from the rearmost point on the vehicle's rear bumper. This requirement from the US safety department is the reason why the scenario of rear collision is considered in the simulation.

1.5 Problem Description

The lsCAF function developed should prevent collisions with obstacles during low speed manoeuvring without resorting to harsh interventions. In lsCAF-l1 function, the driver should be allowed to be in control, but gently guide them away from obstacles. The guidance from the function should be felt by the driver on the steering wheel, but should be suggestive and not forceful. To create and model such a collision avoidance system, various physical analogies were imagined to describe the desired functionality. Such as, the vehicle and obstacles could behave like repelling magnets or the obstacle can be imagined sitting on a small hill. To capture this behaviour, the function was developed using the concept of potential field. A potential field can be imagined as a area of repelling force. Potential fields are generated around all the obstacles which are in the range of vehicle sensor and can be felt both as torque in steering wheel and as a reduction in vehicle speed to avoid collision. The function developed should have a two-tiered solution with torque on steering first and combined steering and braking second. As braking interventions is considered to be more intrusive than torque on steering, Braking is more severe form of override. To describe how such a function can be achieved, the problem is divided into the following parts :

- **Modelling of Obstacle (Potential Field):** The relative position of the obstacles from the ultrasonic sensor outputs are used to generate a potential field around the obstacles. The normal distribution function [**15**] is used to generate a potential field. The potential field is divided into two zones. The inner zone is used for calculating brake pressure (brake zone) and the outer zone (steer zone) is used to calculate the resistive steering torque.
- **Future position of Vehicle:** The vehicle contour (coordinates of the outer dimensions) are projected forward in time, by assuming that the vehicle will maintain its velocity and wheel angle at that instant. Projected points are used as an estimate to understand the probability of collision with the obstacles.
- **Torque applied on the Steering wheel:** The torque applied on steering wheel is calculated based on the number of projected vehicle contour points entered into the potential field and the depth of the projected points inside the potential field.
- **Brake Control:** Once the projected vehicle contour points are inside the brake circle of the potential field, the minimum stopping distance to the brake circle is used to calculate the brake pressure. If the brake applied by the driver to stop the car is not enough, then the brake control will calculate the extra amount of brake pressure required. If the driver does not apply brakes, then the brake controller will apply the required amount of brake pressure.

The lsCAF developed can be used as a level 1 (Figure 1.1) automation function which is abbreviated as lsCAF-l1 and similarly level 2 function which is abbreviated as lsCAF-l2. The lsCAF-l1 is developed to provide a tactile feedback to the driver in the form of resistive torque on the steering wheel and thus alert the driver to take decision to avoid collision. The resistive torque applied on the steering rod is the tactile feedback on the steering wheel to the driver if the vehicle is moving towards an obstacle. This resistive torque should increase as the vehicle gets closer towards an obstacle and should drop to zero when the vehicle moves away from the obstacle. In the case when the vehicle continues in the direction of collision, the lsCAF-l1 will try to avoid the collision by braking. This function is developed to alert the driver about the obstacles ahead and brake if needed.

On the other hand lsCAF-l2 will be able to autonomously move away from an obstacle by taking over both steering and brake controls. The major difference between lsCAF-l1 and lsCAF-l2 is in the magnitude of torque applied on the steering wheel. In lsCAF-l1, the maximum magnitude of the torque applied is limited such that the driver is always in control and is never intended to override the driver applied steering torque.

In both lsCAF-l1 and lsCAF-l2, the intervention in the braking should be to hard brake if the driver is not braking or to add extra brake pressure if the driver applied brake pressure is not enough to avoid the collision. Both lsCAF-l1 and lsCAF-l2 should first try to mitigate the collision by applying the torque on the steering wheel. This is taken care by the steer zone developed in the obstacle model and if the vehicle moves closer to the obstacle i.e it enters the brake zone, then brake controls takes over to avoid the collision.
The lsCAF should be able:

- To model an obstacle using the proximity (co ordinates) data obtained from the ultrasonic sensors around the vehicle.
- To find the future positions of the vehicle by assuming the vehicle will have constant velocity & wheel angle and predict for collision.
- To calculate the amount of torque to be applied on steering rod according to how much the vehicle is into the obstacle model in future time steps and brake pressure to be applied according to the distance to the obstacle.
- To alert the driver about the collision by using tactile feedback on steering wheel and braking when necessary.

1.6 Scope and Limitations

The scope and the limitations of thesis are:

- Obstacles are simulated
- lsCAF-l1 is implemented on a real system
- lsCAF-l2 automation is tested only in the simulation
- In the low speed vehicle model we assume that there is no tire slip [**10**].
- The relation between steering wheel angle and wheel angle is directly related using a given gear ratio.

2

Modelling

Mathematical modelling of obstacle and vehicle are described in this chapter.

2.1 Obstacle Modelling

A collision avoidance system relies heavily on the perception of surrounding environment of the vehicle and how it is modelled. Majority of the collision avoidance algorithms are based on a collision free path finding problem. Once the location of the obstacles are known, a collision free path is found by solving a set of constraints or minimising a cost function problem. Such optimal collision free path based approaches are best suitable when navigating through a static environment and the controller has the full control over the velocity and direction of the vehicle. Since the driver is always in the loop and the controller has to work together with the driver for a collision free navigation, the optimisation algorithm should work in real time and generate new paths based on the current status of the environment and the vehicle. The continuously changing environment and the human in loop puts a demand on the optimiser to be powerful and faster, making it costlier for the real time application.

If an optimal path strategy is chosen, the ADAS will always intervene to correct the driver to an optimal path even if the path chosen by the driver is collision free. As mentioned earlier, this thesis aims at developing a system which gives a haptic feedback to the driver to ensure a collision free path without regarding the optimality of the path taken while driving. This mimics typical decisions by human drivers who are more concerned with a feasible (collision free), rather than optimal path.

This thesis proposes an artificial potential field (APF) based collision avoidance algorithm which has an advantage over the optimal path based approach. The proposed approach is inspired by the work of Khatib [**1**], but here, instead of using APF for robotic application, we apply APF for vehicle application, by creating a torque on the steering wheel like a gentle invisible hand which guides the driver to perform manoeuvres and avoid collisions. The correction torque should not act when the driver is performing a manoeuvre which is not a collision path. APF helps in embedding the information about the location of the obstacles and the drivable path at the same time. The accuracy of the relative position information of the obstacles depends on the type of proximity sensors used. This uncertainty in the position information can also be easily handled by controlling the spread of the potential field.

In this thesis, it is assumed that the location of the obstacles O are known in the vehicle coordinate system. Each of these obstacles act as centres of the APFs U_i and the cumulative sum of all the APFs give the resultant APF as

$$U_{resultant} = \sum_{1}^{n} U_i. \tag{2.1}$$

Thus, changes in the number and position of the obstacles can be easily handled as an addition or subtraction of potential fields, making them suitable to model a dynamic environment around the car.

Based on the resultant potential field, velocity of the vehicle and the predicted path of the vehicle a steering and brake control system is designed. Construction of APF, design of steering and brake control systems are discussed in detail in the following sections.

2.1.1 Artificial potential field Design

Following section discusses the construction of an APF. Some of the features of the APF implemented are listed below,

- APF is continuous.
- APF strength decreases radially from the centre of the obstacle to outside.
- APF function has parameters to control the gradient or strength of the potential field.
- A method to represent zones with in APF, to describe a steer and brake zone. Steering control is active in the steer zone of the potential field and in brake zone of the potential field, steering and brake control are active.

There are different functions available to represent potential field mathematically and which also have the features for an APF discussed above. In this thesis, a potential with strength decreasing exponentially from the centre of the obstacle is employed. Steer and brake zones are represented as two different potential fields, mathematically described as

$$\phi_{BrakeZone}(x, y; x_o, y_o, \alpha_b, \beta_b, \gamma_b) = \begin{cases} \alpha_b e^{-(\frac{x-x_o}{\beta_b}^2)-(\frac{y-y_o}{\gamma_b}^2)}, & r_{pos} < r_b; \\ 0 & r_{pos} \geq r_b \end{cases} \tag{2.2}$$

$$\phi_{SteerZone}(x, y; x_o, y_o, \alpha_s, \beta_s, \gamma_s) = \begin{cases} \alpha_s e^{-(\frac{x-x_o}{\beta_s}^2)-(\frac{y-y_o}{\gamma_s}^2)}, & r_{pos} < r_s; \\ 0 & r_{pos} \geq r_s \end{cases} \tag{2.3}$$

$$r_{pos} = \sqrt{((x - x_o)^2 + (y - y_o)^2)},$$

where (x, y) is the point at which the value of the potential field is calculated, (x_o, y_o) is the estimated location of the obstacle which acts as the centre of the potential field, α is a constant whose sign determines the nature (attractive or repulsive) of the potential field, (β, γ) are two tunable parameters which can be used to adjust the steepness or strength of the potential field in x and y directions respectively.

The parameter r_s defines the radius of the potential field that surrounds the zone where the steering resistance function gets activated. Similarly the parameter r_b defines the radius of the brake zone within the steer zone, where the vehicle will start decelerating. Radius r_s and r_b can be visualised in Figure 2.1.

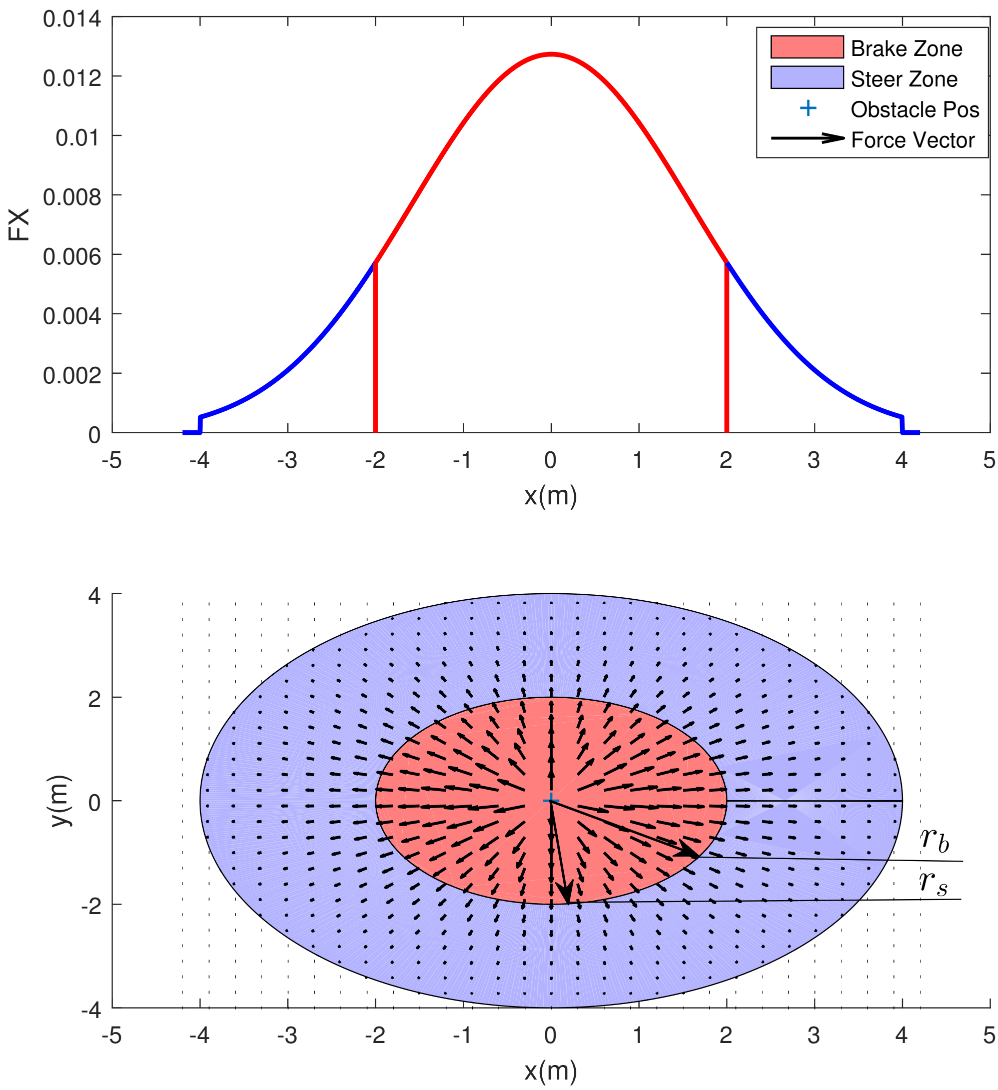

Figure 2.1: Potential field around the mean position of an obstacle. The field is divided into brake and steer zone to control the way potential field interact with the vehicle.

There are different approaches to compute forces generated by a potential field. Traditional approach to compute force at any point is based on the gradient of the potential field at that point. In this thesis, resultant of the forces generated by individual obstacle potential fields at any point is calculated as

$$\vec{F}_{resultant}(x,y) = \sum_i \phi_i(x,y) * C_{Tuning} \frac{[(x - x_{o_i}), (y - y_{o_i})]}{\sqrt{(x - x_{o_i})^2 + (y - y_{o_i})^2}}, \qquad (2.4)$$

where C_{Tuning} is multiplied to facilitate tuning of forces from the potential field. In (2.4), force generated by an individual potential field U_i at a point is expressed as a vector with magnitude proportional to the potential field value ϕ_i and direction radially outwards from the obstacle centre to that point. The resultant force vector at any point is then calculated as the vector sum of all the forces generated by individual potential fields at that point. In (2.4), the resultant force is expressed as a vector with magnitude proportional to the resultant potential field and direction radially away from the obstacle. For navigation using potential field, the forces computed in the (2.4) have to be coupled with the vehicle dynamics. This is described in more details in chapter 3.2.
In this this thesis , brake zone is used as a boundary to compute braking distance, which is then used by brake controller to generate required brake request. This can be further extended, by coupling brake with brake potential field forces similar to steering controller as described in chapter 3.2.

One disadvantage with APF based navigation is the existence of local minima in the resultant potential field. APF will make the vehicle to behave like a positively charged particle moving through a positively charged repulsive potential field around the obstacles. Repulsive potential field always intends to push the vehicle to a low potential region (minima) or away from the obstacle. So the vehicle might get trapped in a local minimum region. In lsCAF-l1, driver will always be able to override such situations and in lsCAF-l2 such situations can be avoided by defining an attractive potential field towards a goal which is not within the scope of this thesis.

2.2 Vehicle Model

Tracking the vehicle position is an important part of the driver assistance system functions. Mathematical model of the vehicle is essential to track the relative position of the vehicle in the surroundings. The mathematical model is used to predict the future course of the vehicles and take decision based on the threat assessment. Depending on the application, different vehicle models can be used to represent the vehicle motion, with a various degree of accuracy.

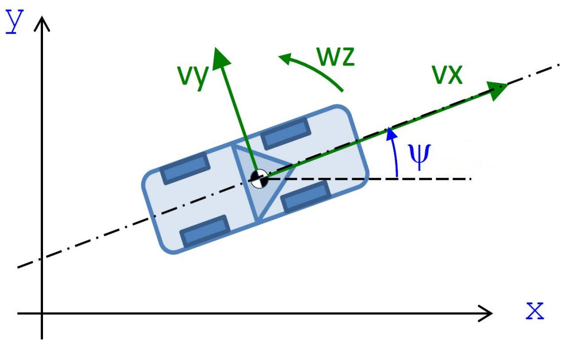

Figure 2.2: Global Coordinate System XY and yaw ψ, longitudinal velocity vx, lateral velocity vy and yaw rate wz expressed in vehicle coordinate system.

Proximity sensors and vehicle speed sensors give measurements in vehicle coordinate system. From Figure 2.2 velocity in the vehicle coordinate system can be expressed in global coordinate system as

$$\begin{bmatrix} \dot{X}(t) \\ \dot{Y}(t) \\ \dot{\psi}_Z(t) \end{bmatrix} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x(t) \\ v_y(t) \\ \omega_z(t) \end{bmatrix}. \tag{2.5}$$

where,

ψ	- Yaw angle
$v_x(t), v_y(t), \omega_z(t)$	- longitudinal velocity, lateral velocity, yaw rate in vehicle co-ordinates
$\dot{X}(t), \dot{Y}(t), \dot{\psi}_Z(t)$	- longitudinal velocity, lateral velocity, yaw rate in global co-ordinates

Position of the vehicle in global coordinate system can then be obtained by time integration of (2.5).

2.2.1 Point Mass model-Motion model

In a point mass model, the entire vehicle is represented as a point mass located at the centre of gravity (CG) of the vehicle. Even though the vehicle consists of many moving parts, while braking the entire vehicle behaves as a point mass slowing down. So a point mass model is sufficient for brake control analysis. The equations of motion of the vehicle can be represented in the state space form as

$$\begin{bmatrix} \ddot{x}_i(t) \\ \dot{x}_i(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}(t) \\ x(t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} a_d(t). \tag{2.6}$$

Equation (2.6) represents longitudinal position and velocity as the states and current desired acceleration $a_d(t)$ as the input. Actuation lag between the desired and actual acceleration as mentioned in [**9**] can be captured by modifying the state equation as

$$\begin{bmatrix} \dddot{x}(t) \\ \ddot{x}(t) \\ \dot{x}(t) \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau} & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \ddot{x}(t) \\ \dot{x}(t) \\ x(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{\tau} \\ 0 \\ 0 \end{bmatrix} a_d(t), \tag{2.7}$$

where τ is the time constant.

2.2.2 Bicycle model

Point mass model presented in the previous section captures only the longitudinal behaviour of the vehicle and does not describe the complete planar motion of the vehicle. A complete planar motion model which can describe motion of the vehicle including vehicle contour is essential to take appropriate actions to avoid collisions, when working with short range proximity sensors.

At low speeds, the lateral forces generated at the wheels are negligible and the tyres can be assumed to roll without any slip. With this assumptions, it is possible to develop a kinematic model of the vehicle which describes the planar motion. A bicycle model with Ackermann geometry as shown in the Figure 2.3, is a good vehicle model for low speed with ideal tracking axles. Here ideal tacking axles means that the instantaneous centre of rotation of the vehicle and the intersection of wheel rotation axes coincide.

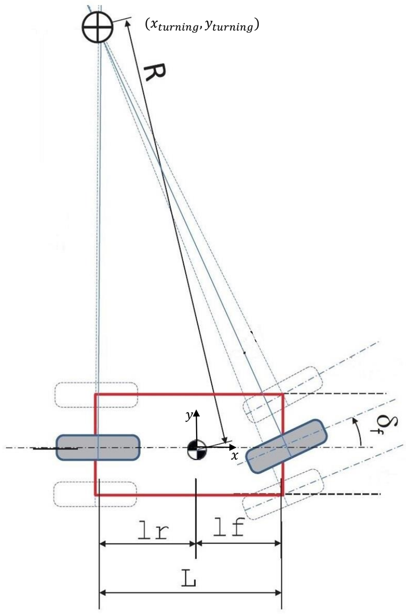

Figure 2.3: One track model of the vehicle, showing the wheel angle δ_f, turning radius R, distance from CG to rear wheel base l_r, distance from CG to front wheel base l_f and wheel base L.

From Figure 2.3, turning radius R and turning centre can be computed as

$$R = \sqrt{(L/tan(\delta_f))^2 + lr^2}, \tag{2.8}$$

$$\begin{aligned} x_{turning} &= -lr, \\ y_{turning} &= (L)/tan(\delta_f). \end{aligned} \tag{2.9}$$

where,

L - Wheel Base

δ_f - wheel angle

lr - distance from CG to rear wheel base

lf - distance from CG to front wheel base

Equations (2.8) and (2.9) describe the planar motion of a vehicle at low speed and are used to predict the future positions of the vehicle which is discussed in section 3.1.

3

Methods and Control Design

The following sections discuss the methods used to foresee the future positions of the vehicle and the control strategies used to alert the driver about the detected obstacles. The control functions are developed using Matlab/SIMULINK software environment.

3.1 Future Position of the Vehicle

Previous chapter discussed about the construction of a potential field around the obstacle points. The future position of the vehicle is required to foresee the collision and to calculate force required to the avoid the collision if present. The information about the repulsive forces from the potential field acting on the vehicle needs to be converted into torque to be on the steering wheel. The default option to predict the position of the vehicle is to use the swept area (area between the outermost and innermost corner trajectories) of the vehicle considering constant velocity and wheel angle. The swept area can be used to detect any overlap with the potential field to predict any collisions and to calculate the repulsive forces acting on the vehicle. This swept area can be convex (when wheel angle is 0°) or non-convex. Mathematical operations involving non-convex shapes are computationally costly and the solution takes time. To avoid this, in this thesis a method is developed which involves projecting the contour points of a vehicle instead of swept area and these points are referred to as projected points. Therefore the concept of projected points is used to develop the function to be easy to implemented in the vehicle embedded system. The method used is not the perfect solution to predict the vehicle positions but, it is being done to implement and it does decent job to calculate the torque required to avoid collision.

3.1.1 Projected Points

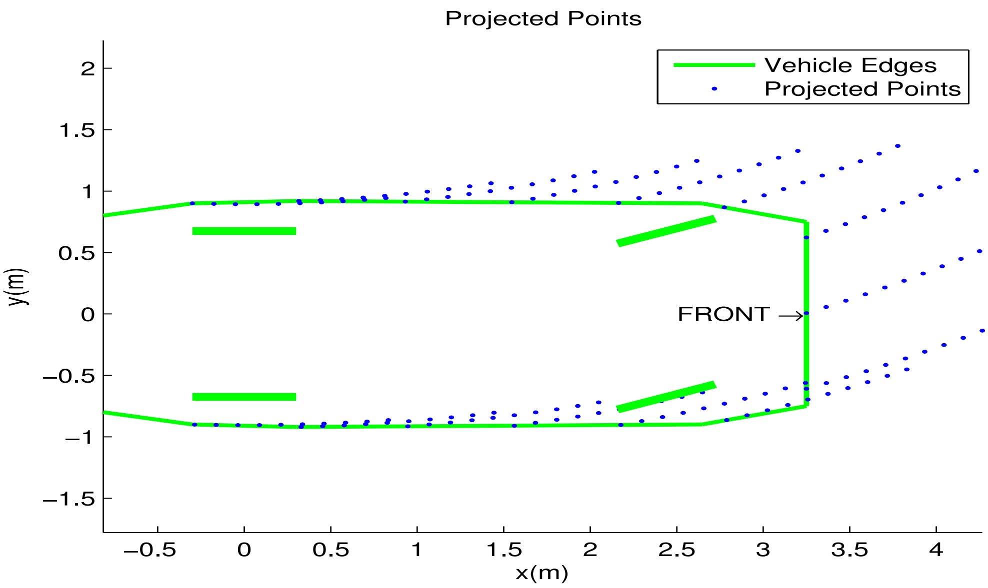

Figure 3.1: Vehicle and the projection of the points. The depicted scenario illustrates a vehicle is moving towards left. The green edges are the vehicle contour and blue coloured points are projected points.

The construction of projected points can be described in the following steps.

1. In Figure 3.1, the car is depicted as a set of edges. Based on the wheel angle and the direction of motion of the vehicle, respective edges are selected which are used to project. For example, in the figure above the vehicle is moving ahead and the edges to the sides & the front are selected.
2. These selected edges (i.e vehicle contour) are then converted into equidistant points which become the initial points of the projection. The turning centre is calculated according to Equation (2.9).
3. These equidistant points selected on the edges are then projected with respect to the turning centre and the velocity of the vehicle.

The length of the projection is dependent on the velocity (m/s) and the time steps (s) to which future positions of the vehicle is to be predicted. The maximum length of the projection is limited to the range of the sensors used. Within this range, the length of projection varies according to the velocity. For example, consider a vehicle with sensors of range 6 m and moving with velocity of 5 m/s. Future positions are to be predicted for 1 s ahead. The length of projection in this situation is 5 m (5 m/s $\times$ 1 s = 5 m). Now, consider another situation with the same vehicle but moving with velocity of 8 m/s. The length of projection in this situation will be restricted to range of sensor i.e 6 m.

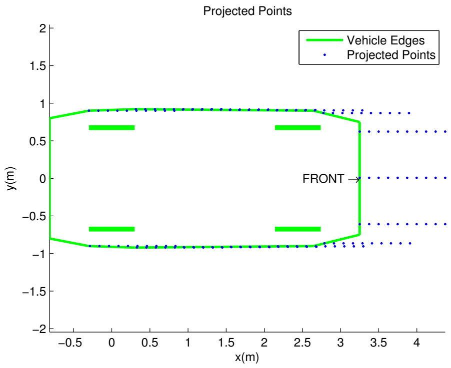

Figure 3.2: Forward projection of points while moving straight with zero steering angle.

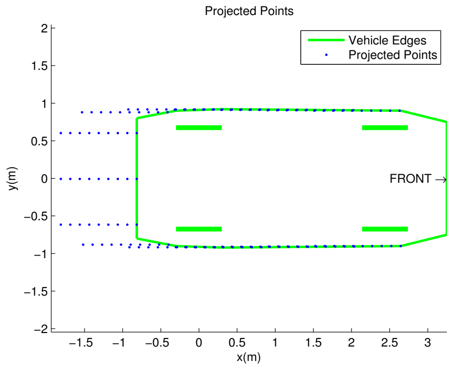

Figure 3.3: Reverse projection of points while reversing the vehicle with zero steering angle.

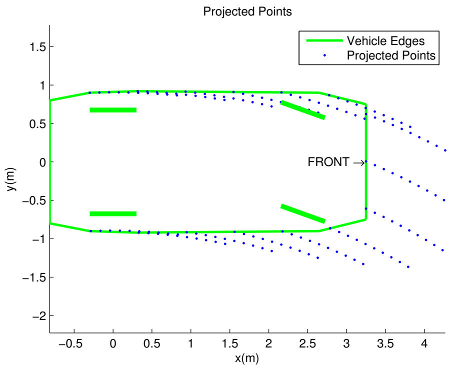

Figure 3.4: Forward projection of points when the vehicle is turning to it's right.

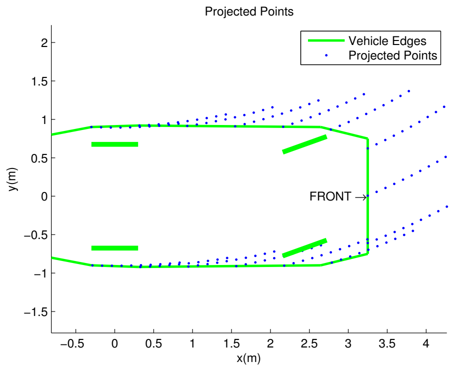

Figure 3.5: Forward projection of points when the vehicle is turning to it's left.

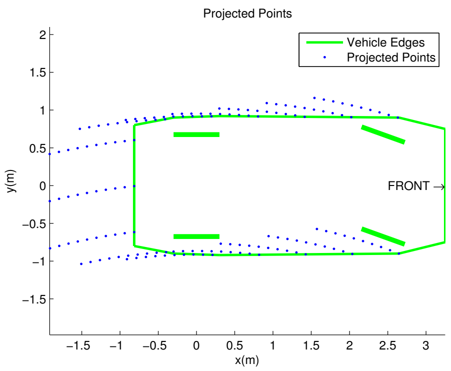

Figure 3.6: Reverse projection of points when the vehicle is turning towards right and reversing.

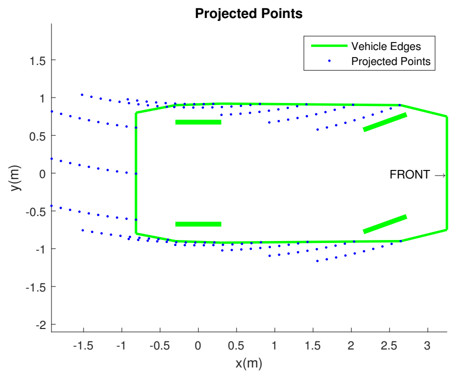

Figure 3.7: Reverse projection of points when the vehicle is turning towards left and reversing.

The projected points of a vehicle in different scenarios of motion can be seen from Figure 3.2 to Figure 3.7. Figure 3.2 displays the vehicle motion in forward direction and the corresponding projection of points. Similarly, Figure 3.3 displays car reversing and the respective projected points in that direction. When vehicle is moving in reverse, the rear edges and the edges in the each sides of the vehicle are selected. Figure 3.4 displays the projection of the points when the vehicle is moving forward and turning to it's right. Similarly, Figure 3.5 displays forward motion and vehicle turning to it's left. Figure 3.6 and Figure 3.7 displays projection of points in reverse motion while the vehicle is turning to it's right and left respectively.

The projected points are mainly used to find two things. 1) To find how deeply the vehicle will be entering the potential field, which checks the severity of the torque to be applied on the steering wheel to avoid an obstacle ahead in the path. 2) to find the minimum distance from the vehicle edges to the obstacle for calculating the brake pressure to brake whenever necessary.

3.2 Steering Control

The following section discusses the method used to calculate the resistive torque from the intersection between potential field developed around the obstacle and the projected points. The torque from the potential needs to be converted into resistive torque value which will be applied to the steering rod as a tactical feedback to the driver. This conversion is done using a Mass-Damper control system.

A. Mass-Damper Control System

This section discusses how the potential field and the projected points together can be used to assess the situation in which the vehicle is in at a given point of time and what actions are needed to avoid collision. The highest probability of finding an obstacle inside a potential field function is the mean position and the probability decreases on either side of the mean. The points inside the intersection area between the projected points and the potential field contains the information about the severity of a collision and how the collision can be mitigated.

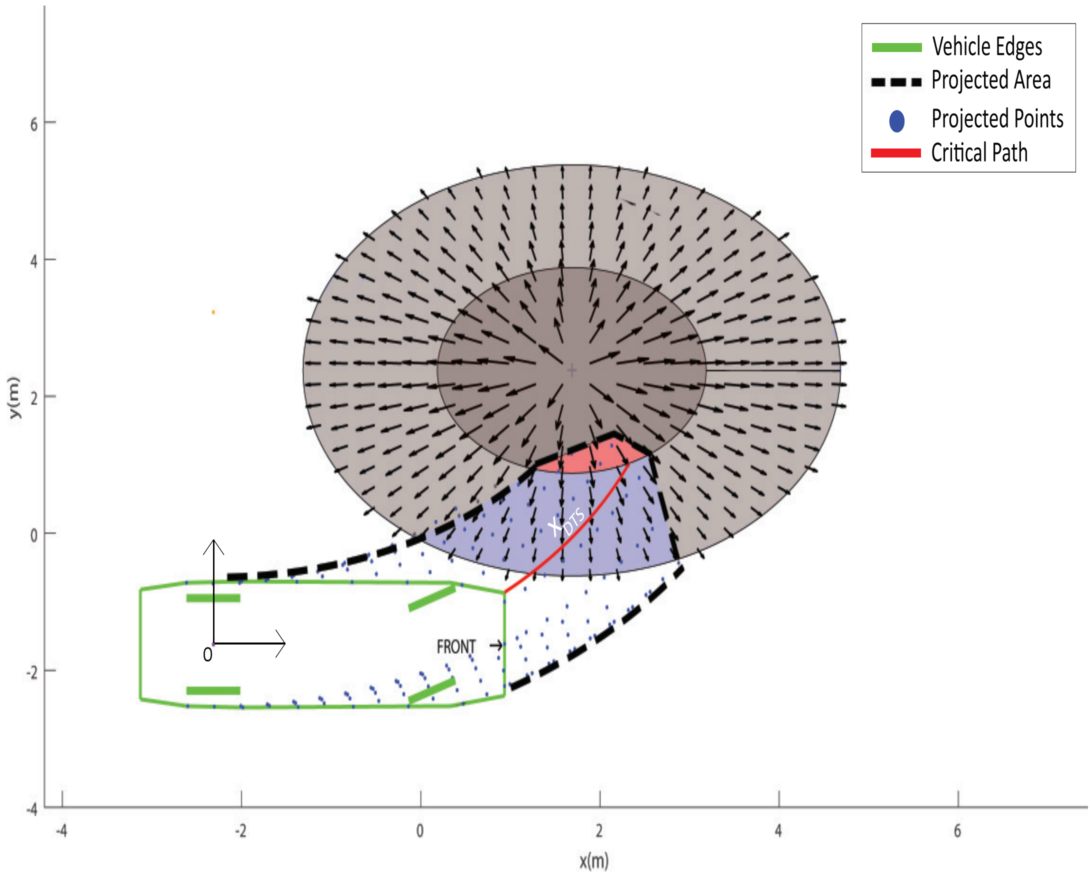

Figure 3.8: Illustration of a vehicle moving towards an obstacle surrounded by the artificial potential fields. Dotted black lines enclose the projected points. The intersection between the enclosure and potential field, shown in colour, is used for the calculation of steering torque.

This embedded information is converted into a numerical value by computing a virtual torque generated from the potential field on the vehicle. The virtual torque computed is unit-less and has to be tuned subjectively before using it in the function. The torque at the point O in Figure 3.8, is the torque applied from a point (x, y) in the potential field on the vehicle about the centre of gravity O and is calculated as

$$T_{(x,y)} = \vec{r_{(x,y)}} \times \vec{F_{(x,y)}}, \tag{3.1}$$

where $\vec{F_{(x,y)}}$ is the force vector calculated using (2.2) and $\vec{r_{(x,y)}}$ is the position vector. Total torque acting on the vehicle can be calculated by integrating $T_{(x,y)}$ over the intersection area. Because of the practical difficulty in implementing a real time algorithm to find the intersection between non convex polygons and then integrating over the intersection area with the available computational resources in the vehicle, a discretised approach is considered.
In this approach, the projected points are used for the calculation of virtual torque. Number of projected points and distribution of projected points along the vehicle contour are tunable parameters. First potential force vector is calculated at all the project points and by definition the points which lie outside the potential field

are assigned zero magnitude. So the projected points with a positive value will automatically represent the intersection area and are used to calculate the virtual torque acting on the vehicle using 3.1. The total torque acting is then calculated as

$$T_{pf} = \sum_{1}^{n} T_i, \tag{3.2}$$

where n is the number of projected points.
The calculated torque needs to be converted to the torque which can be applied on the steering rod for the function lsCAF-l1. The objective of this conversion is to warn the driver with right amount of resistance on steering wheel according to the severity of the threat assessed for lsCAF-l1 and to apply required torque to steer away in lsCAF-l2. The intention of tactile force feedback to the driver in lsCAF-l1, is not to override the driver at any moment and to ensure this, the saturation value of resistive torque needs to be calculated. Using one of the Volvo Car's test vehicle, different values of resistive torque on the steering wheel are tested to find the saturation limit. The saturation limit is 3 Nm according to the tests conducted and torque above this value overrides the driver.

The control system is designed based on the mass-stiffness-damper [**13**] system (Impedance Control). The system is based on the concept of the mechanical impedance (*Mechanical impedance is a measure of the way a structure resists motion when subjected to a given force*).
The control algorithm to calculate the torque to be applied to the steering rod is derived from the concept of impedance. The mass constant M is multiplied with the torque from the potential field to convert it into a control torque. The dampness constant D is multiplied with the negation steering angle rate $\dot{\alpha}$ of the driver steering the vehicle. This negation is to damp the steering angle rate whenever necessary. This is to ensure that the resistive torque does not drastically change with the unusual behaviour from the driver. The derived equation can be represented as

$$T = -\dot{\alpha} \times D + T_{pf} \times M, \tag{3.3}$$

where
T - Resistive torque to be applied on steering
D - Dampness Constant
M - Mass Constant
T_{pf} - Torque output from the potential field
$\dot{\alpha}$ - Steering Angle rate is taken from the vehicle.

The control torque does not include the force required that may bring back the steering wheel to original position. The Constants M and C are tuning parameters whose value depends on the vehicle model and the steering comfort or the resistive feeling on the steering wheel for different drivers in lsCAF-l1.

The parameters are tuned with hardware in loop simulation where the function developed is loaded into the testing car using the dSpace hardware. Control desk from dSpace is a desktop software which helps to visualise and access/monitor the states of the vehicle on-line. Using this software the M and D are tuned online by creating some of the scenarios mentioned in the previous sections. The reason to tune the system on-line is to understand the feeling of the resistance torque applied on the steering wheel when using as lsCAF-l1 and this feeling might be different for different drivers according to their arm strengths. The feeling of the resistance is very important because the driver might get frightened and behave unusual.

The calculated torque applied on the steering wheel in lsCAF-l1 increases gradually to saturation as the projected points go deeper into the potential field. However, in lsCAF-l2 there is no saturation limit and the required torque is applied on the steering wheel.

3.3 Longitudinal brake Control

As discussed in the previous chapter, Brake zone describes the region where the brake control function gets activated. Before entering the brake zone, the torque applied on the steering wheel tries to avoid the obstacle by steering the vehicle. Brake zone gives a way to describe a safety region around the obstacles from where its possible to stop the vehicle within the limitations of the actuator.
The whole planar contour of the vehicle is used to calculate the projected points. It means that if the predicted points have entered the brake zone, the vehicle will enter the brake region by the end of the time for which vehicle positions are predicted. Based on this observation brake control function is activated to slow down the vehicle and prevent collision.
The aim of the brake controller is to stop the vehicle at the boundary of the brake zone. Critical point is the point based on which deceleration is calculated. Critical point is chosen such that

- Critical point is in the projected points set.
- Critical point lies at the boundary of the brake zone.
- Critical point has the shortest distance to the boundary of the vehicle among the points in the brake zone.

Once the location of the critical point is determined, the distance to stop x_{DTS} as shown in Figure 3.8, can be calculated using current vehicle coordinates, orientation, vehicle contour and the coordinates of critical point. Based on the stopping distance and current velocity V_c, deceleration a_d is computed using the equation

$$a_d = -\frac{{V_c}^2}{2x_{DTS}}, \tag{3.4}$$

which is derived from the point mass model assuming that the final velocity of the vehicle is zero. This deceleration is converted into brake torque which can be fed into the vehicle interface for the longitudinal control of the vehicle. Brake torque is calculated as

$$T_B = T_P - M_v \times g \times C_r + M_v \times R_w(|a_d| + a_c), \tag{3.5}$$

where T_P is the propulsion torque, C_r is the rolling resistance and a_c is an acceleration correction term added to the a_d which is determined experimentally to compensate for the delays in the system.

4

Results and Discussions

This chapter discusses the results from the functions developed using the methods presented in the previous chapters. This chapter is divided into two sections with the results from simulation using lsCAF-l1 and data collected from the lsCAF-l2 in the test vehicle. The simulation environment is developed in MATLAB/SIMULINK and CONTROL DESK software from dSPACE which builds the functions developed in SIMULINK into the test vehicle system was used.

4.1 Results from simulation environment

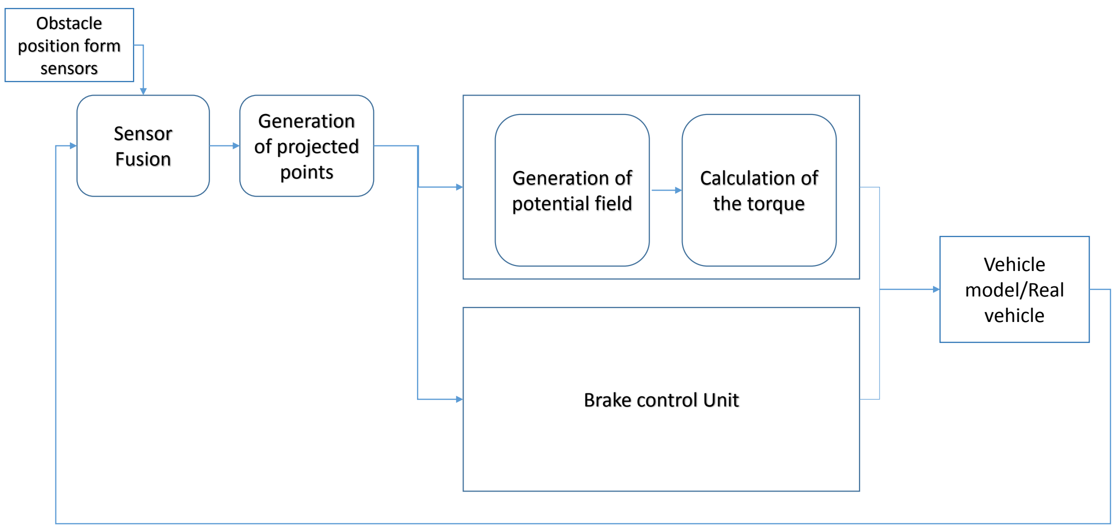

Figure 4.1: The flow of the data in the simulation from the vehicle model to different functions calculating the steering resistance and brake pressure.

The function developed in SIMULINK has the work flow as in Figure 4.1. This flow chart is same for the lsCAF-l2 function in the simulation environment and for lsCAF-l1 function tested in test vehicle. The sensor fusion block calculates relative position of vehicle from the obstacle positions (proximity) detected through the sensors. According to the orientation of the vehicle and turning centre the projected points are generated. Once these points are in potential field, the steering torque

and the brake pressure are calculated. This information is fed into the vehicle model, which in turn takes the decision for the next step.
The results from the scenario, where the vehicle is reversing into obstacle as described in Section 1.4 from the simulation using lsCAF-l2 and results from the test vehicle using lsCAF-l1 for the same scenario are presented below.

A. Scenario: The vehicle is reversing into an obstacle in simulation using lsCAF-l2

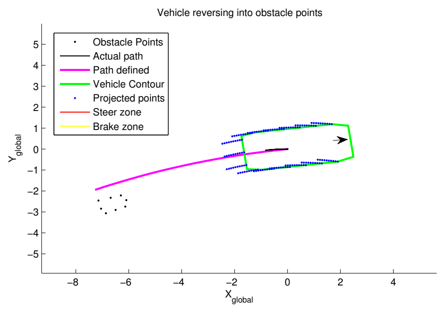

Figure 4.2: Initial condition of the scenario.

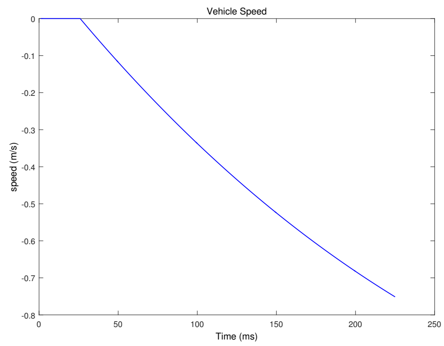

Figure 4.3: Velocity of the vehicle.

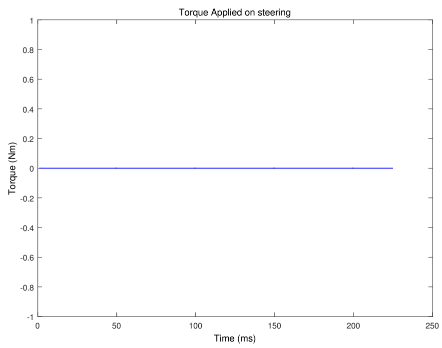

Figure 4.4: Torque applied on the steering rod from the beginning of the simulation.

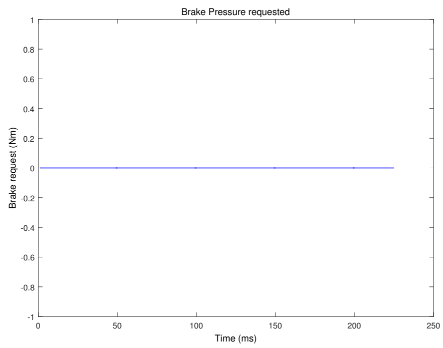

Figure 4.5: Brake pressure applied from the beginning of the simulation.

Figure 4.6: Illustration of four time steps vehicle positions and to explain the working of lsCAF-l2.

Figure 4.6 shows the vehicle reversing into the obstacle points at one of the initial time steps. The sub figures 4.3, 4.4 and 4.5 show the velocity profile, torque applied on the steering rod and the brake pressure applied from initial time step respectively. In sub Figure 4.2, the vehicle is moving along the magenta coloured predefined path, blue points are the projected points, black coloured curve is the actual path taken and black points are the obstacle positions. As explained earlier, the potential field are constructed around these obstacle points shown. Torque or brake pressure is not calculated as the projected points of the vehicle have not entered any potential field.

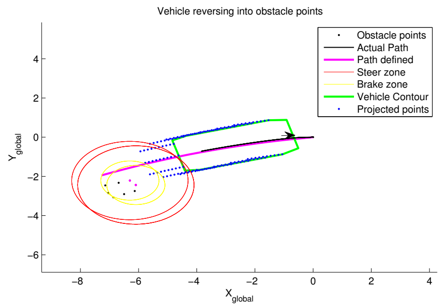

Figure 4.7: Once the projected points enter the potential field, torque is calculated.

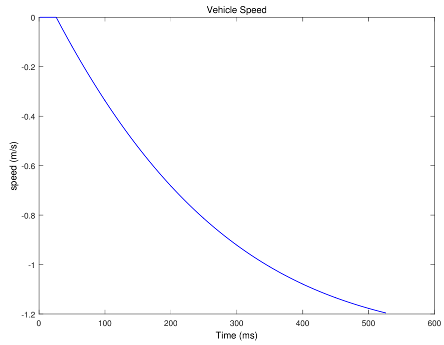

Figure 4.8: Velocity of the vehicle.

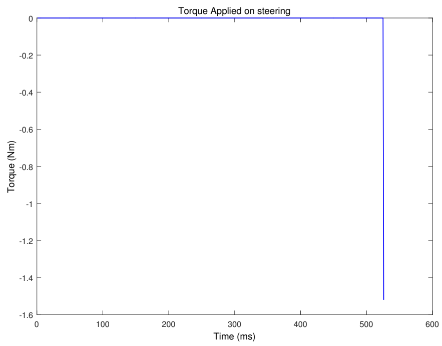

Figure 4.9: Torque applied on the steering rod from the beginning of the simulation.

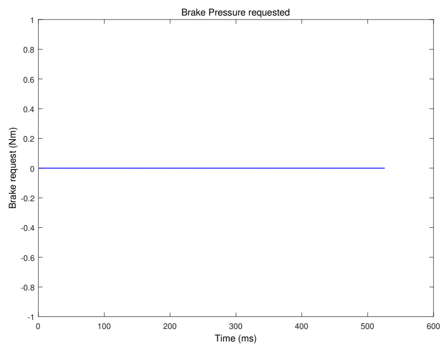

Figure 4.10: Brake pressure applied from the beginning of the simulation.

Figure 4.11: Illustration of four different time steps in simulation explaining the torque and brake pressure calculated respective to the vehicle positions.

As the vehicle moves closer to nearest obstacle points, the projected points enter the steer zone and brake zone as in Figure 4.7. The projected points enter the steer zone (red circles) and few of the points have entered brake zone (yellow circles) of the nearest obstacle point's (magenta coloured points) potential field. Once the points enter the steer zone the required torque to steer away from the obstacle points is calculated and is applied on the steering rod as shown in Figure 4.9. As few points have entered the brake zone at this time step, brake pressure is being calculated. Figure 4.8 shows the velocity profile of the vehicle.

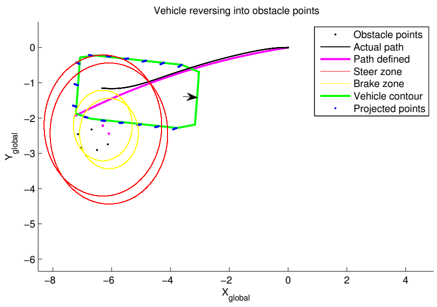

Figure 4.12: Vehicle steers away and brakes to avoid collision.

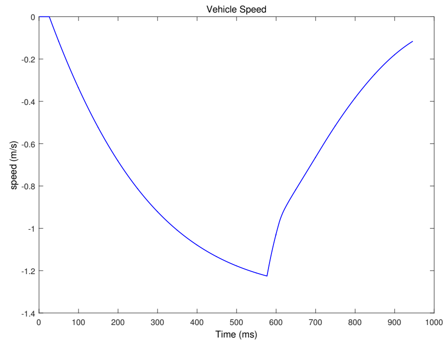

Figure 4.13: Velocity of the vehicle.

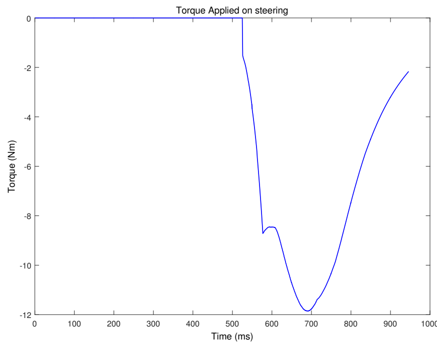

Figure 4.14: Torque applied on the steering rod from the beginning of the simulation.

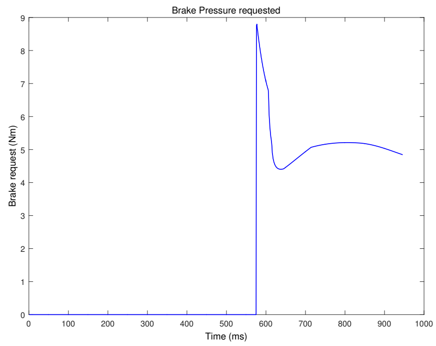

Figure 4.15: Brake pressure applied from the beginning of the simulation.

Figure 4.16: Vehicle trying to avoid the collision by steering and braking.

The torque calculated is fed into the steering system of the vehicle to steer away from the predefined path (which leads to collision) as shown in the Figure 4.12. This can be seen in Figure 4.14 where the torque is applied to steer away the vehicle. The brake pressure is also applied on the vehicle as the vehicle is close to the obstacle points. The brake pressure is as shown in Figure 4.15, where there is a hard braking at first and decreases gradually. As the brakes are applied the velocity reduces as shown in the Figure 4.13.

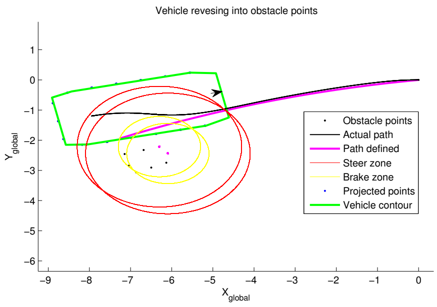

Figure 4.17: Simulation stops after avoiding the obstacles.

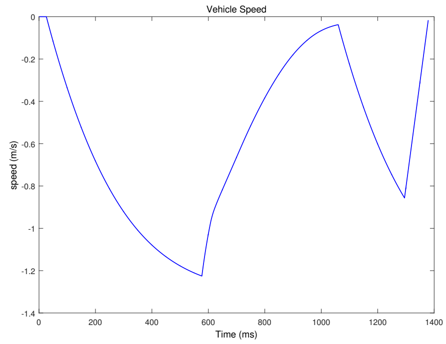

Figure 4.18: Velocity of the vehicle.

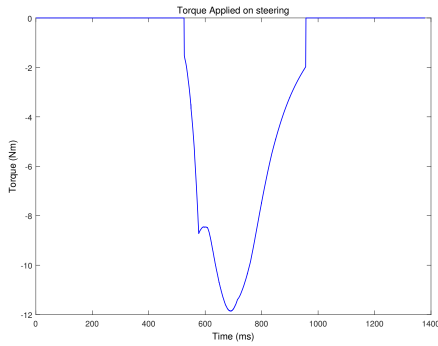

Figure 4.19: Torque applied on the steering rod from the beginning of the simulation.

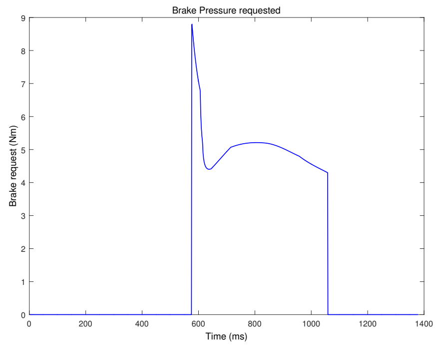

Figure 4.20: Brake pressure applied from the beginning of the simulation.

Figure 4.21: Vehicle halts once collision is avoided.

Once the vehicle has avoided the collision, the projected points are out of the potential field and the torque and brake pressure reduces to zero. This is shown in Figure 4.17 where the actual path taken by the vehicle to avoid the collision is observed as the black coloured curve. From Figure 4.19, the torque applied on the steering rod is reduces as the projected points leave the potential field and drops to zero once projected points are completely out of potential field. Similarly from Figure 4.20, the brake pressure reduces gradually from sudden surge as the vehicle slows down. Figure 4.18 shows the velocity decreasing as the brakes are applied and we can see a increase of velocity after avoiding the collision i.e. the vehicle starts moving with the initial condition.

In the simulation environment (when using lsCAF-l2), the concept of steering resistance is not included. This is because of the non existence of the driver to make the resistant feeling evident.

B. Scenario: The vehicle is reversing into an obstacle in test vehicle using lsCAF-l1

The same scenario considered in simulation is tested in the test vehicle with lsCAF-l1 function. Here the vehicle is made reverse into virtual objects with idle speed (7km/hr) with driver. The results from the test are shown below.

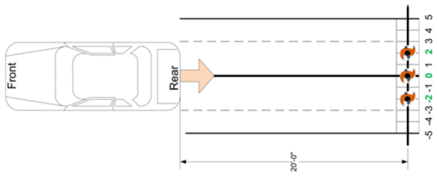

Figure 4.22: Scenario

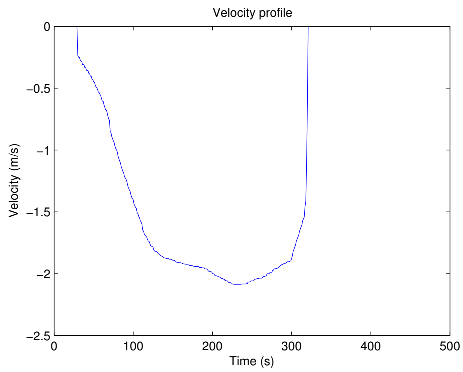

Figure 4.23: Velocity of the vehicle.

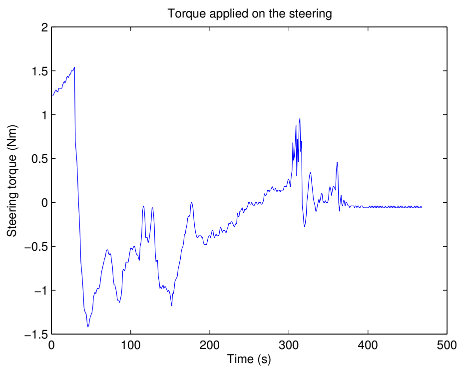

Figure 4.24: Torque applied on the steering rod from the beginning of the simulation.

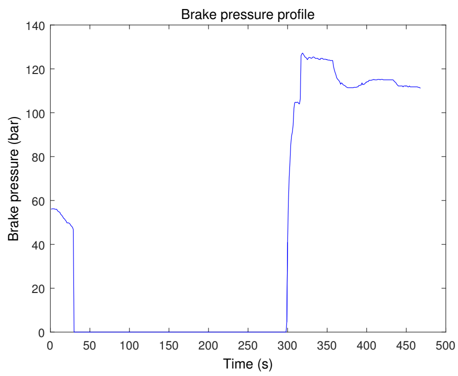

Figure 4.25: Brake pressure applied from the beginning of the simulation.

Figure 4.26: Driver experiences the torque as resistance on the steering wheel and the vehicle halts once it gets closer to the obstacle.

Figure 4.22 depicts the scenario of the testing. During testing, the vehicle is set such that it reverses into the potential field with a wheel angle instead of going straight as in Figure 4.22. This is done to test the resistive torque applied on the steering wheel by the potential field. Once the projected points of the test vehicle enter the potential field, resistive torque is applied to the steering wheel as shown in Figure 4.24. Once these points enter brake zone, the brake pressure is applied to stop the vehicle as shown in the figure 4.25. Sudden surge in the brake profile indicates of hard braking initially and reduces gradually. The vehicle stops before the obstacle as seen from the velocity profile in Figure 4.23. The brake pressure is active until the driver makes next move.

5
Conclusion and Future Work

The following chapter discusses the conclusions on the thesis work and few points on the future work.

5.1 Conclusion

Based on the results from the simulation using the function developed for the automation level-2 (lsCAF-l2), it can be concluded that the concept of potential field used to develop an obstacle model is a feasible approach and can be used to calculate the required torque to be applied on the steering rod to avoid collision. The method of projecting the points from the vehicle contour can be used to predict the future position of the vehicle instead of the swept area of the vehicle. By tweaking the torque calculated to apply on steering rod in lsCAF-l2, the function can be changed to a level-1 automation function (lsCAF-l1) to assist the driver with tactile feedback on the steering wheel and brake whenever necessary.
The driver assisting function lsCAF-l1 is tested in the test vehicle and as intended a resistive torque on the steering wheel is applied when projecting points are inside the potential field. Brake control is also activated once the projected points entered the brake zone in the potential field.

5.2 Future Work

The function developed in this thesis work can be extended to other low speed scenarios such as slowing down in the signal, slow moving traffic jam etc. The tuning parameters in the steering control function in lsCAF-l1 should be tuned more by conducting tests involving different drivers. The proposed lsCAF-l2 system can be experimentally validated by testing it in the test vehicle. If the future vehicles have more computational powerful then the number of projecting points can be increased to have more precise response from the potential field.
With the use of other sensors which have longer range, the function developed in this thesis can be modified to use it for higher velocities. The method of calculating the brake pressure directly from the potential field (similar to torque calculated from potential field) can be investigated. The scenarios can be extended for moving obstacles and the function developed can be tested for such scenarios as well.

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