CHALMERS

Trailer Parking Assist (TPA)

Master of Science Thesis in the Master Degree Programme, System, Control and Mechatronics

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The TPA prototype vehicle

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Abstract

The modern society has seen many mechatronic implementations to improve and assist in everyday life. The automotive industry is a leading figure in this development with several autonomous functions. This report depicts the work and result of a thesis work focused on building an assist function for reversing an articulated vehicle, i.e. trailer coupled to a vehicle. The interesting aspect of this type of vehicle is that the motion control while moving forward is stable, while reversing the motion is unstable. The work presented in this report is meant to be a proof of concept from which a commercial product can be developed. A model based approach is used for constructing the system following the traditional control design steps i.e. create a model of the system using differential equations and then design a controller for the model. Both a linear and a nonlinear controller is designed and compared in both simulation and validation experiments. It is shown that both are viable options for control with their own advantages and disadvantages. The linear controller is sufficient for controlling the articulated vehicle, with the disadvantage of slow rise time. On the other hand, the nonlinear controller can be tuned to have a faster response to changes, the tradeoff however is an overshoot which can be critical when the system is near its boundaries.

1 Introduction

Electronic aids have become increasingly popular in the modern society, innovations range from aids with small mundane tasks as buying a bus ticket to more advanced systems such as collision avoidance in the automotive industry. The need for these smart electronics are greatest in the two extremes, were the task is hard for a human to do or when it is too trivial.

The trailer-car system is an area where electronic aids can be very beneficial for many people, as reversing an articulated vehicle can be hard for many drivers due to: lack of experience, variation of trailer length, weight distribution, road variation and tire pressure. Trailers have a big economical and environmental advantage, they can greatly increase the load capacity of a car at a low price due to their low production and operating costs.

However, a car coupled with a trailer or an "articulated vehicle" has drawbacks when it comes to motion control. The motion can be separated into two cases, one when the car is leading and pulls the trailer, which according to Jae Il Roh and Woojin Chung (2011) is open loop stable, the other motion is when the trailer is leading and the car is pushing, which in contrast to pulling is open loop unstable, Jae Il Roh and Woojin Chung (2011). Reversing an articulated vehicle is very similar to balancing an inverted pendulum, the trailer desires to move to the equilibrium point, however this point is occupied by the car and is therefore unfeasible.

One important factor with the successes of electronic assistant products is how they interact with the people that are supposed to use them, products which add complexity and are hard to use are naturally not received as well as product that are intuitive and easy to use. Human machine interfaces or HMIs are commonly used to handle the interaction between the user and the machine. The specifications for how an HMI should look can vary widely since each individual has different preferences and how advanced application that the HMI should handle. The level of autonomy is also important to take into account, for some applications the user would only need to define what destination he or she desires to go to, and the HMI needs to generate a trajectory for the machine to follow which avoids collision with obstacles on the path. Other application are much simpler where the machine only turns right or left according to an input and is not concerned with its surroundings or what the goal is, in this case the HMI could be as simple as a joystick.

Actors in the automotive industry have presented results in the field of articulated vehicles. For example Land-Rover have a trailer assist function that focuses on visual support. The rear view camera display has been integrated with a trajectory calculating algorithm, which shows the driver indicator lines for the trailer movement in accordance to the current steering wheel input (Land Rover LR4: How to hitch a trailer, 2010). Audis have an assist function that features a more autonomous approach where the actual steering of the car is left to the computer and the driver relays input through a separate console (AUDI trailer assistant, 2011).

1.1 Problem statement

The research presented in this report, and the main goal of the thesis is to expand the theory of modeling and controlling articulated vehicles to a commercial product that can help people in their day to day activities. Two main features are explored, one is to simplify the reversing by making an assist function where the driver uses an HMI to give input to the system instead of using the steering wheel. The other is reversing the vehicle in accordance to a predefined path. The main areas of the thesis is shown in Figure (1).

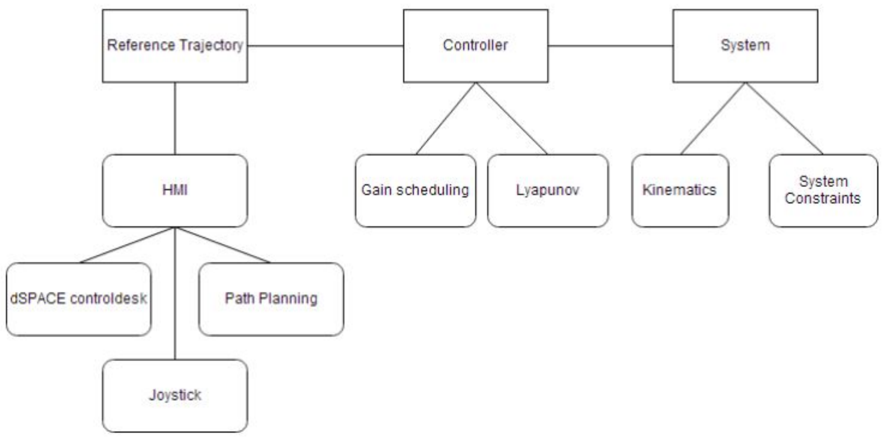

Figure 1: Thesis overview

In this project the traditional control design steps are followed i.e. a mathematical model of the system will be derived, a controller will be designed, and the result will be verified and validated. Two different controllers are designed for the model, a linear controller using gain scheduling and a nonlinear controller using Lyapunov theory. In the ideal case, this would be unnecessary, however when using a model to design a controller, model errors may leads to problems with robustness and constructing two different controllers is done in order to choose the best and most suitable controller for the system at hand.

The controllers are evaluated on their performance with correctly maneuvering the vehicle with respect to a reference trajectory while considering the physical limitations of the system. The physical limitations are present due to practical reasons such as limits in the maximum steering angle of the front wheels, physical limits on how fast the wheels can be moved from one angular position to another i.e rate of change, and the jack-knife phenomenon. These limitations act as saturations and constraints on the system and restricts the response speed and robustness of the system. Model errors may cause instability which can cause the system to enter an uncontrollable state that results in jack-knifing. Tests are done in both simulation and real environments. In order to compare results of the tests a path planning algorithm is also constructed so that the simulation environment can imitate the real world test.

2 Modeling the articulated vehicle

An articulated vehicle is defined as a vehicle with a permanent or semi-permanent pivoting point. Example of articulated vehicles are: trains, towing vehicle, articulated hauler etc. In this chapter a mathematical model is derived for an articulated vehicle or more specifically a car and trailer combination, using the kinematic relations. Comparing an articulated vehicle with an inverted pendulum one may draw some analogies e.g. for an inverted pendulum there exist two equilibrium points: one is stable at the position where the inverted pendulum is pointing downward, and the other is unstable where the inverted pendulum is pointing upwards. In the car-trailer system there only exist one unstable equilibrium point because the second equilibrium point is physically impossible to get in practice since the car and trailer can't occupy the same space at the same time. The feasible equilibrium point of the system is defined as $(\phi_0, \delta_0) = (0, 0)$. The articulated vehicle is modeled similarly to the work done by Paolo Bolzern et. al. (1998). This model is simple while still adequate to describe the important parameters of the articulated vehicle: wheelbase L1, overhang L2, the distance from the hitch to the trailer axis L3, the steering angle δ, and the angle between car and trailer ϕ.

In order to simplify the model some assumptions are made:

- the ground plane is flat
- the track is slip free
- the speed of the vehicle is controlled by the driver

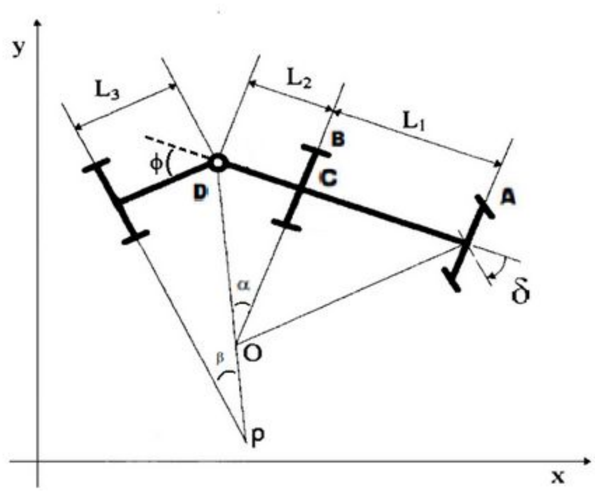

Figure 2: Model of the articulated vehicle

Figure (2) shows the model of the articulated vehicle, and the parameters of the model are presented in Table (1)

System parameters	
θ_1	The angle the towcar is traveling at with respect to a global coordinate system
θ_2	The angle the trailer is traveling at with respect to a global coordinate system
ϕ	The angle between the car and the trailer
δ	The steering angle of the vehicle
V	Speed of the car
$V_{trailer}$	Speed of the trailer
K	Kerb to kerb turning diameter
f	Tyre width
T	Track width
O	The cars' center of rotation
P	The trailers' center of rotation
R_n n=A,B,C,D	Distance from the center of rotation to point A to D
$L1$	Wheelbase of the car
$L2$	Overhang from the rear axle of the car to the hitch point
$L3$	Distance from the trailer axle to the hitch

Table 1: Parameters of the model

2.1 Kinematics of an articulated vehicle

Important for the controller design is ϕ, which is the relative angle between the car and the trailer that is to be controlled and also δ, which is the system input, therefore the system dynamics with respect to the angular positions and velocities is derived. The relative angle between the car and trailer, ϕ, is defined as

$$\phi = \theta_2 - \theta_1 \tag{1}$$

Taking the derivative of the angle, ϕ, yields:

$$\dot{\phi} = \dot{\theta}_2 - \dot{\theta}_1 \tag{2}$$

Figure (2) shows the car with the current steering angle δ. The point where the line projected orthogonally from δ, intersects the line projected along the rear wheel axis O, is also known as the center of rotation. Using the distance to this point from the cars rear axis, an expression for the angular velocity of the car is obtained:

$$\dot{\theta}_1 = \frac{V}{R_C} \tag{3}$$

Trigonometric relation yields:

$$\tan(\delta) = \frac{L1}{R_C} \tag{4}$$

Combining equations (3) and (4) gives

$$\dot{\theta}_1 = V \cdot \frac{\tan(\delta)}{L1} \tag{5}$$

The angular velocity $\dot{\theta}_1$, is expressed with respect to the steering input δ, and the cars longitudinal speed. The angular velocity of the trailer is derived in a similar fashion, in accordance to the work done by Morales et al. (2009), the only inputs to the articulated system are the longitudinal velocity, V, and angular velocity, $\dot{\theta}_1$, of the car. The longitudinal speed and the angular velocity of the trailer are propagated through the kinematic chain:

$$V_{trailer} = -L2 \cdot \dot{\theta}_1 \cdot \sin(\phi) + V \cdot \cos(\phi) \tag{6}$$

$$\dot{\theta}_2 = -\frac{(L2 \cdot \dot{\theta}_1 \cdot \cos(\phi) + V \cdot \sin(\phi))}{L3} \tag{7}$$

Replacing (5) and (7) in equation (2) yields

$$\dot{\phi} = \frac{-V}{L3} \cdot \sin(\phi) + \frac{-V}{L1} \cdot \left(1 + \frac{L2 \cdot \cos(\phi)}{L3}\right) \cdot \tan(\delta) \tag{8}$$

Equation (8) describes the angular velocity of the relative angle ϕ, and its dependence directly on the steering input δ.

2.2 System constraints

Another important part of the articulated vehicle dynamics is the phenomenon referred to as jack-knifing. This phenomenon can be defined as: at a sufficiently large angle between the car and the trailer, the driver will not be able to steer or straighten the trailer in the desired direction while reversing, instead the angle between the car and the trailer will continue to grow until the trailer is in contact with the vehicle. Thus once jack-knife occurs the system will be in an uncontrollable state.

According to Mills (2003), jack-knifing occurs because the trailers angular velocity exceeds that of the towcar i.e. the trailer is moving around its axis faster than the car can even when giving maximum steering input. The geometric interpretation of this is that the centre of rotation point of the trailer exceeds the point of the car, thus the critical point is where the two coincide.

To prevent the occurrence of jack-knifing a constraint on the operating angle is introduced. The stable region is where the angle between car and trailer is less than the critical angle, where the critical angle is defined as:

$$critical\,angle = \alpha + \beta \tag{9}$$

Where α and β, are the resulting angles when the two centre of rotation points coincide, see Figure (3).

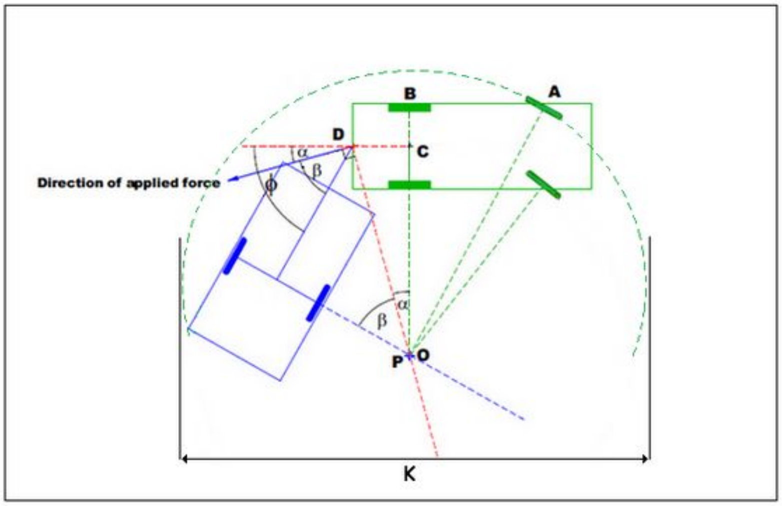

Figure 3: Jack-knife phenomenon

Using the geometric properties of the the articulated vehicle, an expression for the critical angle can be derived in terms of known length constants (f, T and kerb to kerb diameter):

$$\alpha = \arctan(\frac{L2}{R_C}) \tag{10}$$

$$\beta = \arcsin(\frac{L3}{R_D}) \tag{11}$$

The distance to point D can be described with Pythagoras theorem and the distances L2 and R_C:

$$R_D = \sqrt{(R_C^2 + L2^2)} \tag{12}$$

R_C equals R_B minus half the track width, T:

$$R_C = R_B - \frac{T}{2} \tag{13}$$

Pythagoras theorem in conjunction with L1 and R_A expresses the distance to the point B

$$R_B = \sqrt{(R_A^2 - L1^2)} \tag{14}$$

The kerb to kerb distance is defined as the diameter the car turns with, measured from the outer point of the wheel. By subtractracting half the tyre width f, from half the kerb to kerb diameter K, the distance to the point A is obtained.

$$R_A = \frac{(K-f)}{2} \tag{15}$$

Solving α and β by the parameters R_A, R_B, R_C and R_D yields:

$$\alpha = \arctan\left(\frac{L2}{\sqrt{\left(\frac{K-f}{2}\right)^2 - L1^2} - \frac{T}{2}}\right) \tag{16}$$

$$\beta = \arcsin\left(\frac{L3}{\sqrt{\left(\sqrt{\left(\frac{K-f}{2}\right)^2 - L1^2} - \frac{T}{2}\right)^2 + L2^2}}\right) \tag{17}$$

Thus:

$$critical\,angle = \arctan\left(\frac{L2}{\sqrt{\left(\frac{K-f}{2}\right)^2 - L1^2} - \frac{T}{2}}\right) + \arcsin\left(\frac{L3}{\sqrt{\left(\sqrt{\left(\frac{K-f}{2}\right)^2 - L1^2} - \frac{T}{2}\right)^2 + L2^2}}\right) \tag{18}$$

The critical angle derived here is the theoretical maximum that ϕ, can attain without being jack-knifed.

3 Controller design

In this chapter two types of controllers are introduced, the first controller is a gain scheduling controller which is a family of linear controllers and it's used to control nonlinear systems, the second controller is a nonlinear controller where the control input is chosen to cancel the nonlinearities in the feedback loop which makes the system input-output linear.

The reason for introducing two different types of controllers in this chapter is to be able to compare and choose the best one in terms of stability, path tracking, performance and how easy they are to implement in the real world plant.

3.1 Gain scheduling controller

Gain scheduling control is used as an approach for controlling nonlinear systems, one example is aircraft control, Glad and Ljung (2000). The controller contains a set of gains and it selects an appropriate control gain depending on which operating point the closed-loop system is operating in. Linear interpolation is applied on adjacent control gains if the system is operating at intermediate conditions, Rugh (1991). The advantages of gain scheduling approach "is that linear design methods are applied to the linearized system at each operating point, wealth of linear control methods i.e. much studies have been done in the field of linear control, performance measures and design intuition", Rugh (1991). Figure (4) shows a block schematic of the gain scheduling controller.

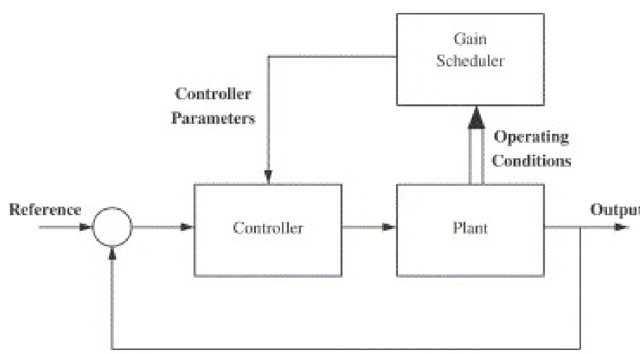

Figure 4: A schematic of the closed-loop system using a gain scheduling controller

Since the design of the gain scheduling controller is based on linear design methodology, the system of the car-trailer combination has to be linearized around one or several operating points to represent the system in the standard linear form $\dot{x} = Ax + Bu$. The operating points are chosen in ranges where the system varies slowly or behaves linear. The controller is designed to be operational in 17 regions within the interval of $\{-40° : 40°\}$ with $5^{°}$ interval.

The input-output dynamics of the system are described by equation (8) and as it can be seen from this equation, the system is nonlinear. More specifically, the nonlinearity comes from the dynamic that the control angle ϕ, will monotonically increase with higher velocity as the system approaches the angle $\frac{\pi}{2}$. Linearization of equation (8) by applying first order Taylor series yields:

$$\Delta\phi = \phi - \phi_0 \tag{19}$$

$$\Delta\dot{\phi} = \frac{V}{L3} \cdot \Delta\phi + \frac{V}{L1} \cdot \left(1 + \frac{L2}{L3}\right) \Delta\delta \tag{20}$$

The system is on the standard linear form, and the state of the system i.e. the relative angle between the car and the trailer, is measurable and also controllable.

The controller is designed by applying the pole placement method, and in this project the pole of the system for each operating point is placed in a specific place on the left side of the S-plane to fulfill the criteria $\| (\phi_{ref} - \phi) \| \leq fault_{tolerance}$.

A $fault_{tolerance}$ of ± 1 degrees is chosen to be allowed and it ensures that the specific characteristics of the system are met. Figure (5) shows the characteristics of the system around one of its operating points with different pole placements. Poles with a higher real value results in a slow system, slower rise time thus the output signal exceeds the reference signal and vise versa for poles with a lower real value resulting in a fast system which has a shorter rise time and falls below the reference signal. Since there is no integral action there will always exist a remaining error.

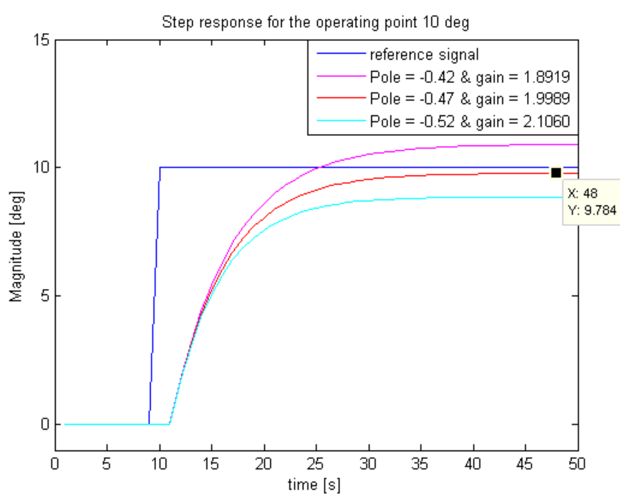

Figure 5: Shows the step response of the system with different pole placements

3.2 Lyapunov based controller

Lyapunov function can be seen as an energy function that decreases in magnitude as time evolves. In particular $V(x(t)) \leq V(x(t_0))$ for all, t, that are greater than the initial time t_0, and $V(x(t))$ converges to some value that is ≥ 0, Glad and Ljung (2000). Lyapunov theory serves as one of the main techniques for establishing stability of nonlinear systems and can help engineers to understand the characteristics of the system, and also explore in what regions the controller can stabilize the system. The main challenge when using this tool is finding a suitable Lyapunov function, Ahmadi (2006).

Similar studies have been done by Matsushita and Murakami (2006), they proposed a pushing motion controller for a two trailer system based on Lyapunov functions. In the research presented by Mitsuji Sampei et al, they use exact linearisation to achieve path tracking control for straight and circular paths, Mitsuji Sampei et al (1995).

In order to derive a control law for stabilizing the articulated vehicle, a Lyapunov function candidate based on the error is chosen:

$$V = \frac{1}{2} \cdot e^2 \tag{21}$$

Where the error, e, is defined as:

$$e = \phi - \phi_{ref} \tag{22}$$

Since ϕ_{ref} is constant, the derivative of, e, with respect to time is:

$$\dot{e} = \dot{\phi} \tag{23}$$

In order to show asymptotic stability, V(x) must satisfy the following constraints:

$$V(0) = 0 \tag{24}$$

$$V(x(t)) > 0,\ x \neq x_0 \tag{25}$$

$$\dot{V}(x(t)) \leq 0 \Longleftrightarrow e \cdot \dot{e} \leq 0 \quad \forall t > 0 \tag{26}$$

The function V is quadratic which implies that the constraints in equations (24) and (25) are fulfilled when, $t \geq 0$. Expanding $\dot{V}$:

$$\dot{V} = e \cdot \dot{e} = e \cdot \dot{\phi} = e \cdot \left(\frac{V}{L3} \cdot \sin(\phi) + \frac{V}{L1} \cdot \left(1 + \frac{L2 \cdot \cos(\phi)}{L3} \right) \cdot tan(\delta) \right) \tag{27}$$

In order to satisfy the constraint (26), it is necessary to choose a control law that makes equation (27) negative semi definite. Substituting $\tan(\delta)\, with,\ u,\ and,\ \dot{\phi}, with\, (-k\cdot z)$ in equation (27) and solving, the following control law is obtained:

$$u = \tan(\delta) = \frac{-k \cdot e - \frac{V}{L3} \cdot \sin(\phi)}{\frac{V}{L1} \cdot (1 + \frac{L2}{L3} \cdot \cos(\phi))} \tag{28}$$

Thus equation (27) becomes:

$$\dot{V} = -k \cdot e^2 \leq 0 \tag{29}$$

In this case $\dot{V}$ is negative definite, which means it is possible to conclude asymptotic stability of the equilibrium point. This control law, which is a nonlinear state feedback, is only valid if the system is in the operating region $\{-40° : 40°\}$, thus the system is locally asymptotically stable.

Replacing the control law u, in terms of the steering wheel angle delta δ, is done by taking $arctan(u)$:

$$\delta = \arctan\left(\frac{-k \cdot e - \frac{V}{L3} \cdot \sin(\phi)}{\frac{V}{L1} \cdot (1 + \frac{L2}{L3} \cdot \cos(\phi))}\right) \tag{30}$$

Where equation (30) can be directly used as a control law to steer the articulated vehicle. Figure (6) shows how the controller is implemented, much similar to a regular PID controller the control is applied to the error magnitude in contrast to the control used with gain scheduling.

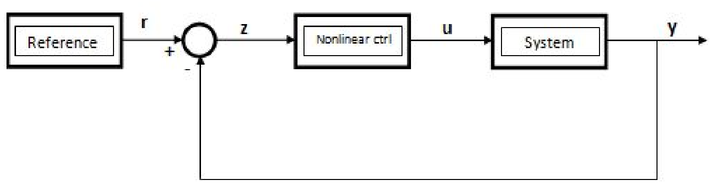

Figure 6: A schematic of the closed-loop system using Lyapunov controller

4 Generating references

For simulation and verification purposes a reference signal needs to be generated. HMIs are designed for the two scenarios that are explored; for the case where the HMI is used to directly steer the vehicle according to driver input or when it is intended to drive more automatically with only a predefined path as an input.

In this chapter ideas are gained from some researches that have been done in motion planning where the input to the system is considered. Dieter Zöbel illustrates a method to use trajectory segmentation for autonomous backward motion control, Dieter Zöbel (2003). Another example is Murray and Sastry's research where they derive a method for steering a car-trailer system using sinusoids, Murray and Sastry (1993).

4.1 Manual steering

A software based HMI is constructed for validation using dSPACE ControlDesk. This HMI is meant to be used in the validation of the controllers, therefore the HMI has to be able to read the various system parameters and record test data. As the input interface a scrollbar is available with set values in the range of ± 20 which represents the desired angle between the car and the trailer in degrees. The relevant parameters for the tests are; current angle between the car and the trailer (the system response), current steering wheel angle (actuator response), requested angle on the steering wheel (the controller output). These will give the user an insight of what the controller is trying to do and the resulting actuator and system response.

A hardware based HMI is constructed for demonstration, a joystick is used as an input console that allows the driver to specify if the trailer should move to the right or to the left. The main focus on this HMI is simplicity, it is intended to be used by a wide variety of people and ideally should be intuitive to use so that the amount of instructions needed for every new user is kept to a minimum. The joystick used is a potentiometer that outputs a voltage of a magnitude $[0:10]$Volt over the range $[0:360]^\circ$. The voltage is scaled and converted to a corresponding value in degrees within the range in the operating region ± 20. The joystick value is fed to the system as a reference signal.

4.2 Automatic driving - Potential field

For the case when the HMI is used to steer the articulated vehicle automatically, it needs to generate a reference signal according to a user defined goal given the starting location. It is desired to find a path between the starting point and the goal for the articulated vehicle without colliding with any predefined obstacles. To achieve this a potential field method is introduced, the method is used to generate gradients such that an optimization algorithm (Steepest Descent, Newton Raphson method, A-star etc.) can be applied to find a feasible path between the starting point and the goal. The potential field method is based on the physical forces attraction and repulsion, the idea is that the attraction forces will be large when the vehicle is far from the the goal , and decrease monotonically when it is close to the goal. The repulsion forces will be zero when the vehicle is outside the minimum desired distance to obstacles and large when the vehicle is close to the obstacles.

Figure (7) shows that the potential field can be represented by an array of vectors with a certain magnitude and direction which is typically drawn with arrows or level curves.

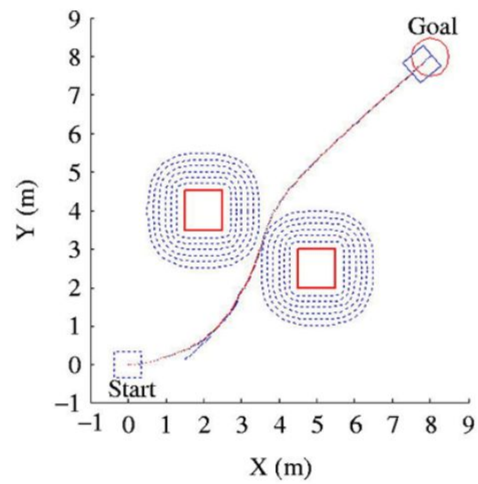

Figure 7: Attraction and repulsion forces, Falcone (2012) [3]

As an initial step of the design, the current state of the vehicle, q_i, should be defined. Where q_i, is a vector of the current position of the vehicle with the coordinates $\{x_i, y_i\}$ and by applying the minimization method of the steepest descent algorithm, the next state, q_{i+1} is computed:

$$q_{i+1} = q_i - \gamma \nabla U(q_i) \tag{31}$$

Where $\nabla U(q_i)$ is the gradient of the potential field and γ, is the step size. $U(q_i)$ is defined as the sum of the attractive and repulsive forces:

$$U(q_i) = U_{att}(q_i) + U_{rep}(q_i) \tag{32}$$

Defining some important equation in order to solve equation (31):

$$U_{att} = \begin{cases} \frac{1}{2} \cdot \xi \cdot \rho_f^2(q) & if\, \rho_f \leq d \\ \xi \cdot d \cdot \rho_f(q) - \frac{1}{2} \cdot \xi \cdot d^2 & if\, \rho_f > d \end{cases} \tag{33}$$

$$\nabla U_{att} = \begin{cases} \xi \cdot (q - q_{final}) & if\, \rho_f \leq d \\ \frac{d^2 \cdot \xi \cdot (q - q_{final})}{\rho_f(q)} & if\, \rho_f > d \end{cases} \tag{34}$$

$\rho_f = \|(q - q_{final})\|^2$: is defined as the distance from the current postion to the goal.

d: is the desired distance from the goal.

ξ: is a tuning parameter.

$$U_{rep} = \begin{cases} \frac{\eta}{2} \cdot \left(\frac{1}{\rho(q)} - \frac{1}{\rho_o}\right)^2 & if\, \rho(q) \leq \rho_o \\ 0 & if\, \rho(q) > \rho_o \end{cases} \tag{35}$$

$$\nabla U_{rep} = \begin{cases} \frac{\eta}{2} \cdot \left(\frac{1}{\rho(q)} - \frac{1}{\rho_o}\right) \cdot \frac{1}{\rho^2(q)} \cdot \nabla\rho(q) & if\, \rho(q) \leq \rho_o \\ 0 & if\, \rho(q) > \rho_o \end{cases} \tag{36}$$

$\nabla\rho(q) = \frac{q-b}{norm(q-b)}$: is defined as the distance from the current postion to the obstacle.

Equation (31) is re-iterated until the vehicle is sufficiently close to the goal. Some problems may occur when using this method:

- Local minima
  - Attractive and repulsive forces can balance and that can make the articulated vehicle stand still.
  - Dead end i.e. trap situations; it can happen at a local minima.
- Unstable oscillations
  - The attractive and repulsive forces cause the vehicle to move endlessly between two points (can occur when the vehicle is between two obstacles)

These problems can be avoided with the help of simulations or intelligent algorithms (e.g. generating a random step when stuck at a local minima).

The x and y coordinates that make up the path are converted to a reference angle that is used with the controllers. This is done by letting the reference position proceed the current position of the articulated vehicle, the reference is then updated and moved before the articulated vehicle catches up. The measured difference between the current position and reference position results in a triangle (with an element from x and y respectively) thus taking atan of this difference yields a reference angle.

5 Simulations and results

With the unstable nature of articulated vehicle and the scale of a real world experiment, it is essential to have good simulation results before conducting experiments due to safety concerns. The focus on the simulation is to make the controllers have desirable properties such as low overshoot, small remaining error and small control input.

5.1 Simulink model

For simulation and verification purposes a simulink model is built, shown in Figure (8). The controller subsystem contains either the gain scheduling or Lyapunov controller depending on which simulation is desired. In order to follow a trajectory an outer loop is used that compares the calculated (x, y) coordinates of the trailer with the reference values. ϕ is continuously measured and compared with the critical angle i.e. when jack-knife occurs. The simulation is stopped if ϕ, reaches the limit for jack-knifing. The implementation of this constraint uses a relaxed version (i.e a slightly lower value), since it has to be guaranteed that the critical angle won't be reached even if there are disturbances.

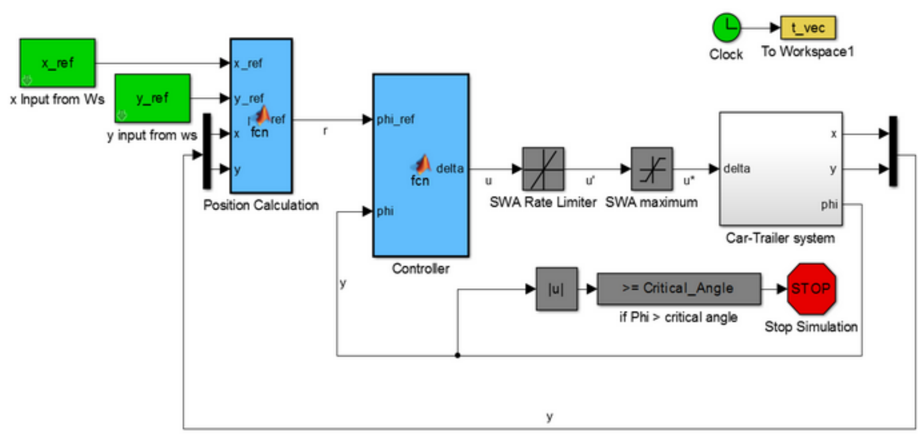

Figure 8: A model of the closed-loop system

Two simulations are run that are considered possible to conduct in a real world experiment as well, one is a step response and the other is following a trajectory.

5.2 Step response of the system

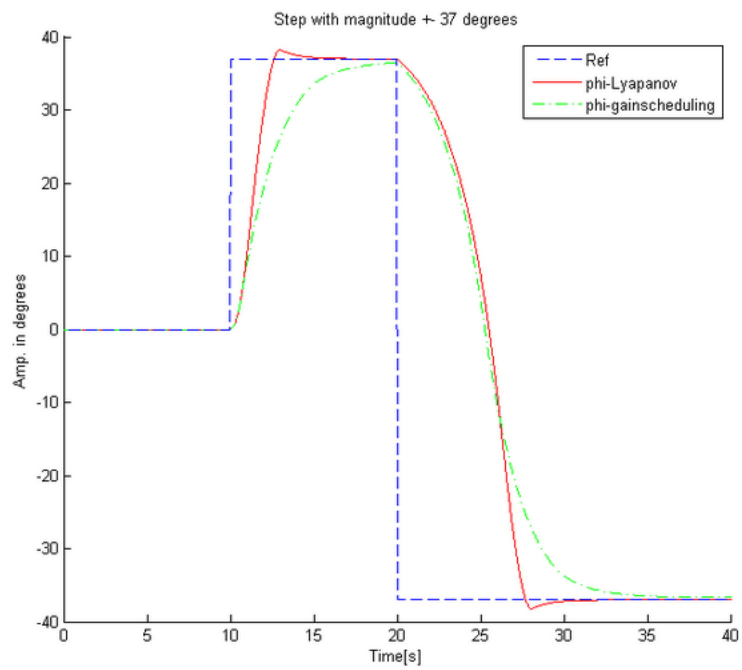

Figure 9: Comparision between Lyapunov control and gain scheduling control

Figure (9) shows the step response for the controllers. The Lyapunov controller is easily tuned by changing one gain parameter and result is that of a typical P-controller where it gives a faster response at the cost of overshoot. In contrast, the gain scheduling controller is able to achieve a final error of about ± 1 degree however the tuning of the controller couldn't affect the overshoot. The gain scheduling controller needs a lot more tuning to reach an acceptable fault level for the final value of the output.

5.3 Simulation of system constraints

Simulation is also done to check what the step response of the system is if the reference input for ϕ, exceeds the critical angle for jack-knife, see Figure (10):

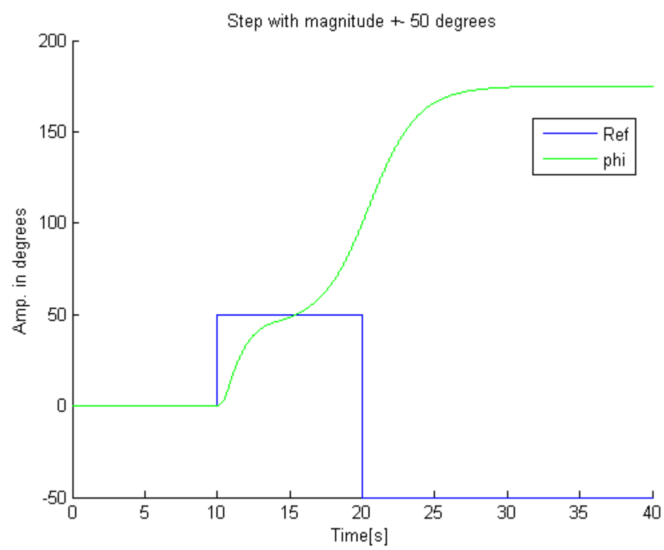

Figure 10: Jack-knife angle simulation

By allowing higher angles for ϕ than the critical angle, jack-knife phenomenon can be simulated. The result of the simulation is as expected, the controller is not able to stabilize ϕ, once it reaches a certain value. Instead it continues to grow until it reaches the next equilibrium point at $180°$ which is physically impossible to get in practice, since the car and trailer can't occupy the same space at the same time.

5.4 Trajectory simulation using the potential field algorithm

After tuning the controllers with respect to their step responses, the reference input is replaced by a trajectory given by the potential field algorithm, see Figure (11).

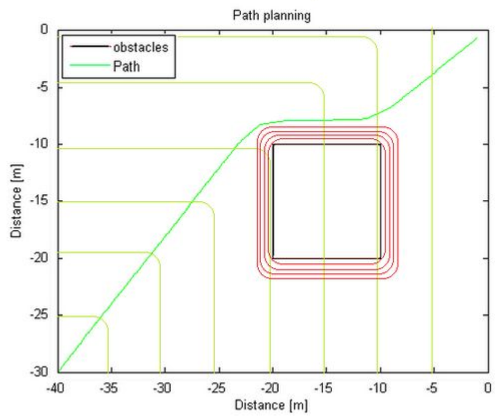

Figure 11: Trajectory given as input to the system. Green level curves indicate attractive forces and red indicates repulsive forces.

The trajectory is then smoothed by taking the mean value of several samples to give the reference signal a smoother appearance, which is more likely that the articulated vehicle is able to follow. As can be seen in the figure the path starts slightly outside of origo and ends in the coordinates (-40,-30), the start has an offset to simulate that the reference is a future value for the controller.

The gain scheduling controller makes the articulated vehicle follow the trajectory well, turning is also very soft as can be seen when the blue line changes direction, the distance between each sample remains similar with indicates slow and smooth turning.

The Lyapunov controller makes also the articulated vehicle follow the trajectory well. As expected it turns a bit faster than the other controller, the first turn done shows signs of more rapid turning.

Simulation shows that both controllers are viable solutions to the control problem at hand. The Lyapunov controller gives more room for tuning but also requires the most calculation at each time step but it gives a quick response and its easy to implement. Gain scheduling on the other hand has a drawback because the controller needs to be tuned every time when the length of the trailer is changed and that can cost time. The advantages though: wealth of linear control methods, performance measures, design intuition and also easy to implement. Figure (12) shows the simulation results of trajectory response for both of the controllers.

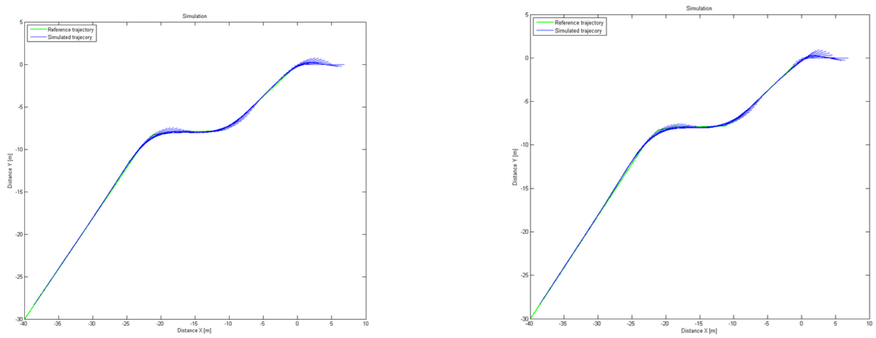

Figure 12: Gain scheduling controller vs Lyapunov controller

Figure (13) shows the control signals for both of the controller:

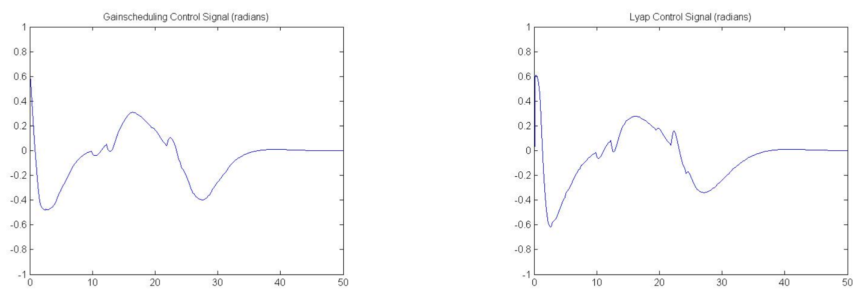

Figure 13: Control signals for Gain scheduling vs Lyapunov controller

6 Validation

This chapter presents the embedded part of the research where the hardware is configured to test the simulated control algorithms (See also appendix for the implementation figures in dSPACE).

6.1 Hardware setup

A test rig is constructed where the controller receives information from the car's CAN-bus and two auxiliary potentiometers. The received information from the car is the speed over ground and the steering wheel angle. The car used in this experiment has a separate CAN-bus that handles the Electric Power Assisted Steering-EPAS communication. Some modifications are done to the car in order to facilitate the tests.

- Relay switches are added in order to start the different components in the car in a specific order; Car, Autobox and EPAS.
- Two potentiometers are installed, one to measure the angle between the car and the trailer and one to be used as steering input from the driver. The information for the potentiometers is converted to CAN-messages and sent via the Ipetronik to the CAN-bus (See Ipetronik (2013-09-19)).

A dSPACE Autobox is used as the interface between the car, the control algorithm and the HMI for the driver. The Hardware setup can be seen in Figure (14):

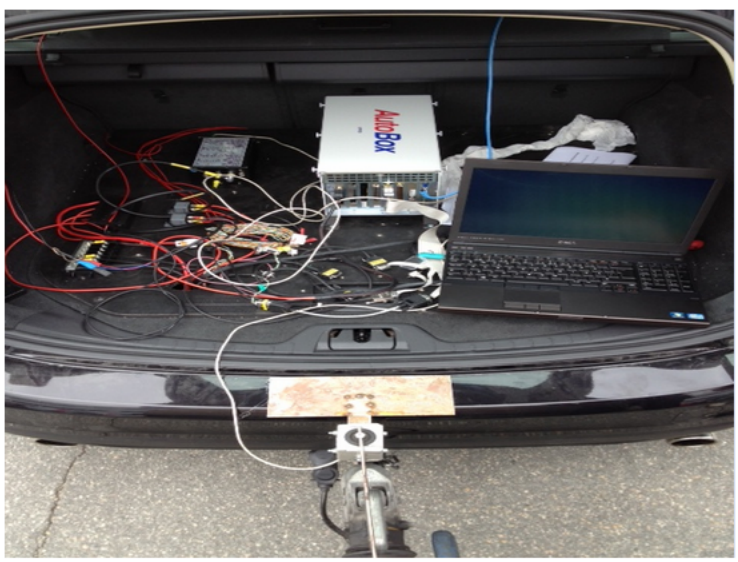

Figure 14: The hardware setup

6.2 Experiment setup and results

The goal of the experiment is to validate the results found in the simulations, therefore the software based HMI (constructed with dSPACE ControlDesk) is used to generate a step response and record the system data. The control algorithms are used to steer the car while the driver has the responsibility to both control the propulsion system of the car and make sure not to collide with any obstacles. The HMI allows the driver to give input to the controller in terms of degrees for the desired angle between the car and the trailer, then the controller calculates a new steering wheel angle and feeds it to the EPAS actuator. The real time system uses a potentiometer attached to the hitch to determine the current state of the system which is fed back and compared to the generated reference. Figure (15) shows the flow of how the tests were conducted.

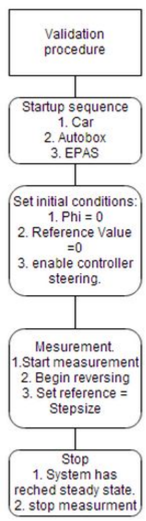

Figure 15: Start sequence of the experiment

Due to limits in space, the tests are stopped before any obstacles are hit, however steady state is possible to achieve within this space. The validation test are done by setting initial conditions (angle between car and trailer to zero, reference angle to zero). Measurements are recorded and the car starts reversing, the measurement is halted as the system appears to be in steady state and the procedure is repeated until sufficient measurements are collected. The speed over ground information provided from the vehicle sensors is not very accurate at low speeds, to account for this and have consistent experiments, no brake or throttle input were given, which results in a speed close to 1 m/s. The system at hand has some specific constraints on the steering, the electronic steering unit in the car is limited to set the steering wheel angle to approximately $\pm 230°$, this translates into a maximum steering angle between the car and the trailer of roughly $\pm 20°$. Which means that steering near to this angle is difficult as the actuator reaches its saturation level. Figures (16) and (17) show the results for the Lyapunov and Gain Scheduling controller respectively.

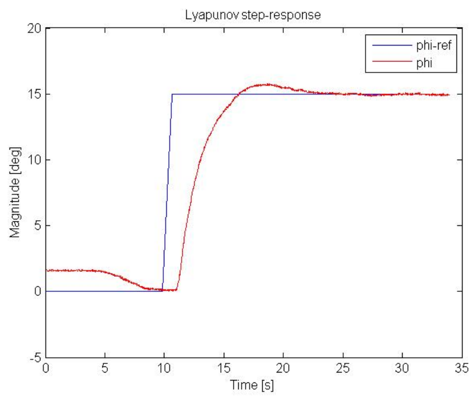

Figure 16: Validation using Lyapunov control

The Lyapunov controller shows the same characteristics as the simulation with a slight overshoot. Small disturbances come from the sensor used to measure the angle between car and trailer. Additionally there is an apparent delay in the real system that was not accounted for in the simulation model. The delay in the systems is the result that comes from the dynamics of the system i.e. inertia, time that takes the actuators to react to the new input, and backlash.

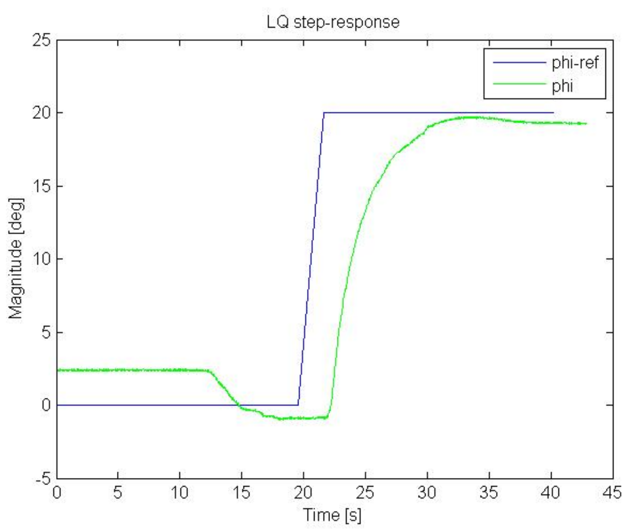

Figure 17: Validation using LQ control

The results from test with the gain scheduling matches the simulation ones well. The control looks slow and does not have any significant overshoot. In order to correctly follow the set point it is also necessary to tune the controller for the specific car-trailer combination at hand. The system delay is also apparent with this controller.

7 Discussion

The Lyapunov control equations has some issues due to using the speed vector of the vehicle in the denominator, resulting in that any speed sufficiently close to zero will result in a desired steering angle of 90 or -90 degrees. This coupled with how uncertainty of the low speed measurement data results in the speed vector causing more trouble than what is gained using it. Setting the speed vector to a constant value appeared sufficient to still control the vehicle correctly without the drawbacks of the measured vector.

Another convenience issue is that the algorithm needs to be configured according to the specification of the trailer/car combination currently in use. This means that a customer using the Trailer Parking Assist-TPA function needs to reconfigure the algorithm through some HMI every time the trailer size is changed.

The TPA system is intended to be sold as an electronic accessory, in practice though it is probable that a hardware sensor is needed. One of the more important part of this is that this sensor should ideally be mounted exclusively on the car since it would be impractical for the customer to need to mount the sensor on the trailer him/herself. Additionally the sensor must avoid interfering with other patents currently on the market (Audi's tow sensor, Land Rovers optical sensor). As this research has shown that the model does not need to be complicated if the sensor data is good enough. It shifts the focus to what kind of sensor do we need to use. The ideal is to use no sensor at all to measure the angle between car and trailer and instead calculate this angle used the vehicle speed information from the sensor already present in the car, however it is unlikely that this will work given the quality of the sensor data at low speeds and the unstable nature of reversing with an articulated vehicle (i.e the action will fail due to very small errors). A combination of measurement and estimation could probably be successful to compensate for the errors that occur, however the algorithm to estimate this behavior is hard to construct given the wide variety of disturbance sources in the application environment that algorithm is meant to function in (urban environment) varies greatly.

Another interesting area is the HMI, while testing and displaying the function for people we got a lot of good feedback about the system. Additionally it became apparent that different HMI solutions appealed to different people. Some handled the car better with a joystick solution, some prefered using the laptop and some prefered to use the TPA system as a stabilizer just leaving the reference at zero and then steering in a traditional way with the steering wheel. It's important to choose a user friendly interface when the TPA system is developed. Ideally the HMI should be intuitive so that the customer doesn't need to read a manual in order to get any assistance from the function the HMI should preferably not add clutter to the dashboard. It also became apparent that in addition to steering one of the key difficulties when reversing an articulated vehicle is the lack of vision, many that tested the function failed to maneuver the car to a desired position using a simple left/right input interface due to not being able to see and comprehend the movement of the vehicle. One suggestion to solve this issue is to add a camera at the back of the trailer and display indicator lines to the driver in accordance to the direction he/she is currently steering in.

8 Conclusion

The research presented in this paper has shown that a controller designed from a simple kinematic model is sufficient to maneuver an articulated vehicle while it is reversing. This conclusion is built on both simulations and real time experiments. Both of the controllers constructed showed good results in both simulation and validation.

The Gain Scheduling controller is able to follow the reference signal with a fault tolerance of ± 1 degrees and has no overshoot, but there is a drawback since the controller needs to be tuned by heavy simulations when the length of the trailer is changed and that affects directly the cost of the hardware that needs to be implemented i.e. powerful microprocessors.

The Lyapunov controller showed good results as well; it has a faster response compared to the previous controller but at the cost of an overshoot, it is easily tuned since there is only one parameter for tuning the controller, and easy computations which contributes to hold down the cost thus there is no need for investing in powerful microprocessors. The drawback of this controller is when an overshoot occurs at the bounderies of jack-knife, which can be critical since the driver will not be able to steer the trailer in a desired direction unless he/she drives forward to come outside the jack-knife region.

An HMI must be developed that makes the function easy to use, a sensor measuring the angle between car and trailer must be constructed and security features implemented so that it is not possible to jack-knife the car trailer combination.

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Part I

Appendix

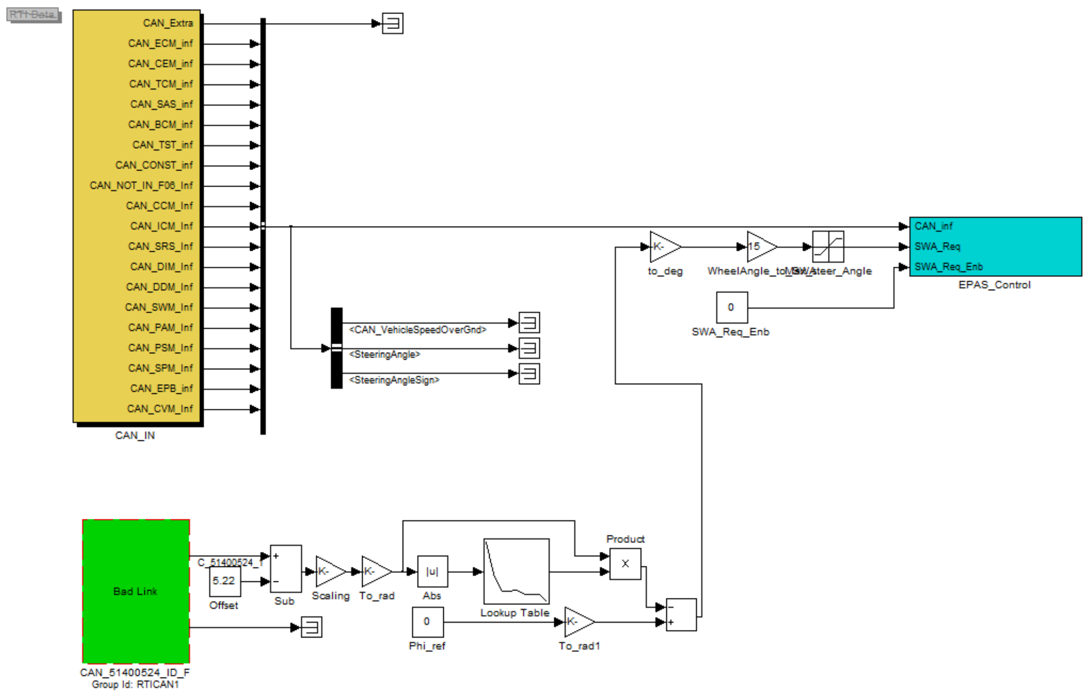

Figure 18: LQ dSpace model

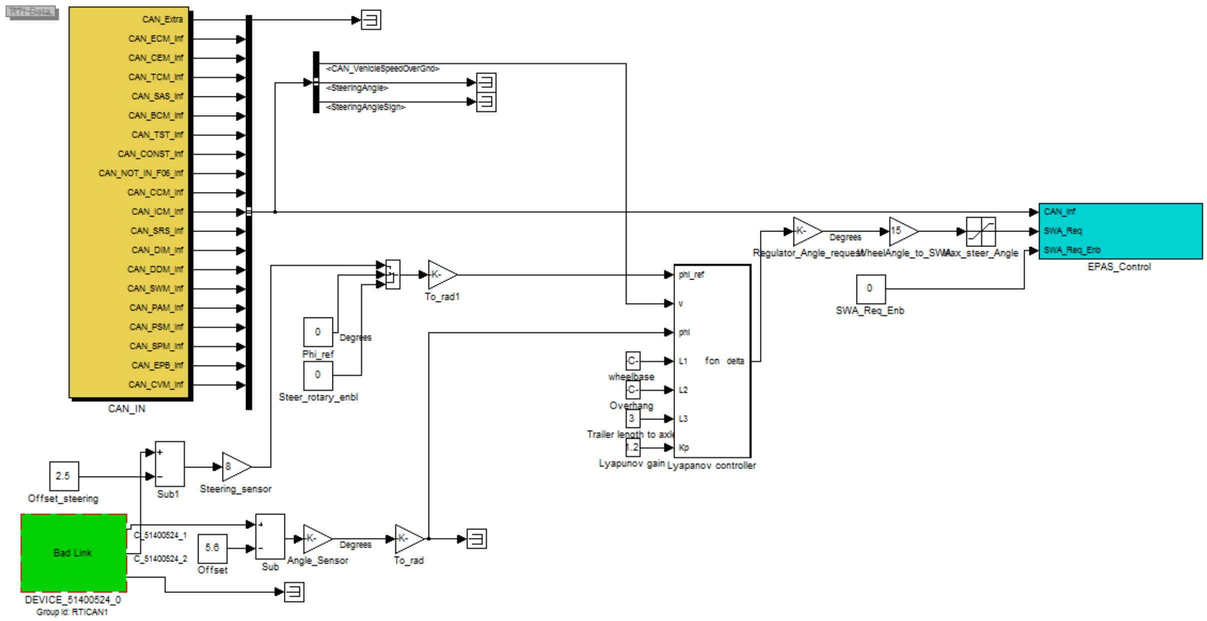

Figure 19: Lyapunov dSpace model