Automatic Steering Control System for ASM Vehicle using DC Motor

Term Project
Estimation and Control of Ground Vehicle Systems
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Abstract - In this project, an optimal tracking (Linear Quadratic Tracker) controller is developed for automatic steering of a vehicle using a DC motor. The objective is to track a reference signal for the steering wheel angle (and therefore, the vehicle trajectory) in simulation real-time. The vehicle model used is Automotive Simulation Models (ASM) and the developed controller is shown to improve upon the performance of the in-built driver model.

1 Introduction and Motivation

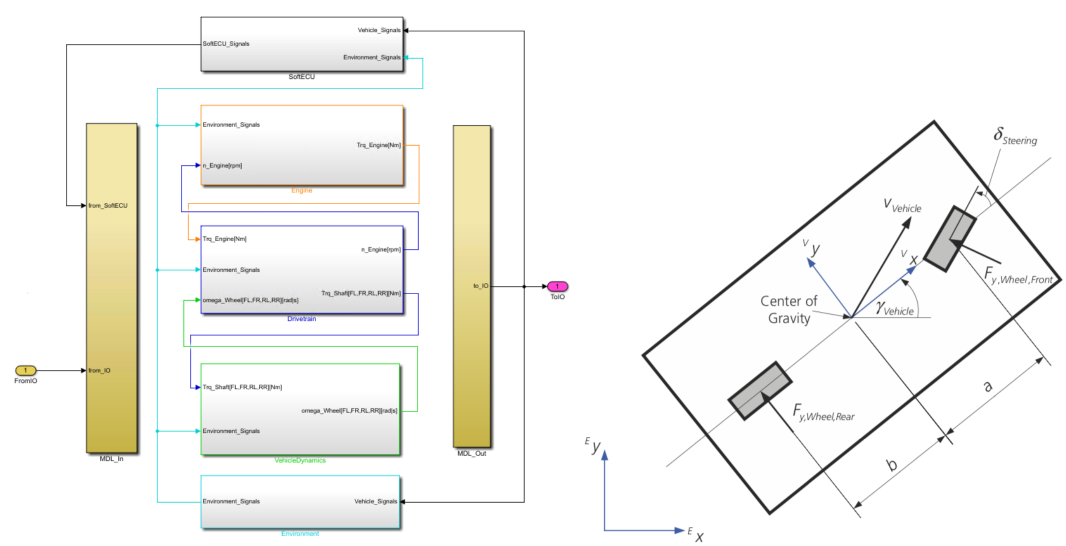
The advent of autonomous vehicle technology has called for the proliferation of development of vehicle trajectory tracking algorithms and control systems. One of the major hurdles in developing the technology required to further the state-of-the-art in the field is the high cost and risk of testing vehicle systems. A solution to that is using computer simulation to design systems before implementing them on an actual vehicle. However, the quality of simulation data depends on the quality of the vehicle model used. Automotive Simulation Models (ASM) by dSPACE is a high-fidelity vehicle model which can be used to develop vehicle control systems with high accuracy and relatively low cost.

Once the system is validated in a simulation environment, the next level is to bring hardware-in-the-loop, while simulating the remaining parts of the system. Finally, a validated system can be pushed to the next phase of development on an actual vehicle with a higher chance of success.

2 System Modeling

2.1 Vehicle model in ASM

Automotive Simulation Models (ASM) by dSPACE is a comprehensive and detailed vehicle model created in Simulink. The software contains mathematical models of all major vehicle subsystems in order to fully simulate the behaviour of a vehicle for any simulated state. For the purposes of this project, the subsystems of concern are the Vehicle Dynamics subsystem and the Environment subsystem.



(a) Block diagram structure of ASM [1]

(b) Single-track vehicle dynamics model used in ASM to calculate $\delta_{Steering}$

Figure 1: Schematics of the models used to calculate the optimal steering angle at the wheels [1]

Steering control in ASM is done using the Driver model in the Environment subsystem. More specifically, the lateral control subsystem contains the implementation of the steering controller. This lateral controller uses preview information about the road from the Environment subsystem to generate the reference trajectory for the vehicle. A simplified, linear, single-track model of a vehicle is then used to calculate the optimal steering angle $\delta_{steering}$ required at the wheels to generate the necessary tire forces needed to track the reference trajectory previously calculated. $\delta_{Steering}$ is then converted to $\delta_{SteeringWheel}$ using a steering ratio $i_{Steering}$ [1].

The linearized model equations are shown here without derivation:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & V_{x,Vehicle} \\ 0 & \frac{-2(C_F+C_R)}{m_{Vehicle}V_{x,Vehicle}} & \frac{2(bC_R-aC_F)}{m_{Vehicle}v_{x,Vehicle}} - v_{x,Vehicle} & 0 \\ 0 & \frac{2(bC_R-aC_F)}{J_{Vehicle}v_{x,Vehicle}} & \frac{-2(a^2C_F+b^2C_R)}{J_{Vehicle}v_{x,Vehicle}} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{2C_F}{m_{Vehicle}} \\ \frac{2aC_F}{J_{Vehicle}} \\ 0 \end{bmatrix} \delta_{Steering} \tag{1}$$

In order to simulate human reaction times, the steering wheel signal generated by the lateral controller is delayed by a first order delay, the time constant of which can be parameterized through dSPACE ModelDesk®. The purpose of this project is to compare the performance of a motor controlled steering wheel to that of the delayed simulated 'human' driver.

2.2 Motor model

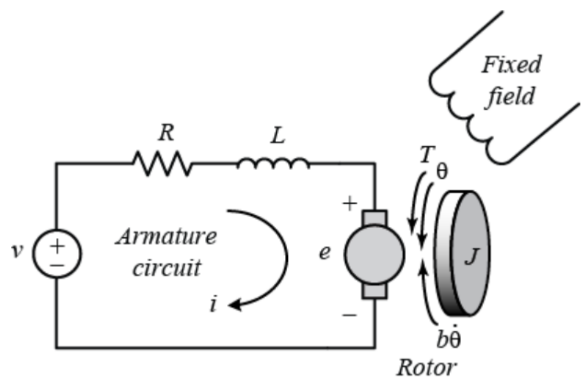


Figure 2: Motor model schematic [2]

Symbol, Quantity	Value, Units
R, Motor resistance	0.5 Ω
L, Motor inductance	2.75 $\times 10^{-4}$ H
J, Motor and load inertia	0.04 kgm^2
b, viscous damping constant	10 Nms
K, Torque and back emf constant	0.05 Nm/A

Table 1: Constants in the motor model explained

The following model of a DC motor was chosen as the actuator for the motor steering system. The model shown is a linear one and takes into account both the mechanical and the electrical dynamics of a DC motor. An additional position error state w was added to the system in order to implement integral action in the motor model as well (not shown here).

$$\begin{gathered} \begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -b/J & K/J \\ 0 & -K/L & -R/L \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix} V \\ y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ i \end{bmatrix} \end{gathered} \tag{2}$$

3 System Analysis and Design

3.1 Defining the control problem

The driver environment subsystem in ASM provides the reference signal for the steering wheel angle generated using preview information about the road. The control problem then is to design a controller that makes the motor track the reference angle. The performance of this motor steering is expected to be better than the driver since the motor will operate instantaneously as opposed to the driver being delayed by human reaction times.

To perform the comparison between the motor steering vs. the ASM driver, the oval track shown in figure 3 is used. The 'ideal' vehicle trajectory is generated by using the ASM driver with zero delay. The vehicle speed on the straights is set to 80 km/h, however ASM adapts the speed during the turns in order to safely perform the turn.

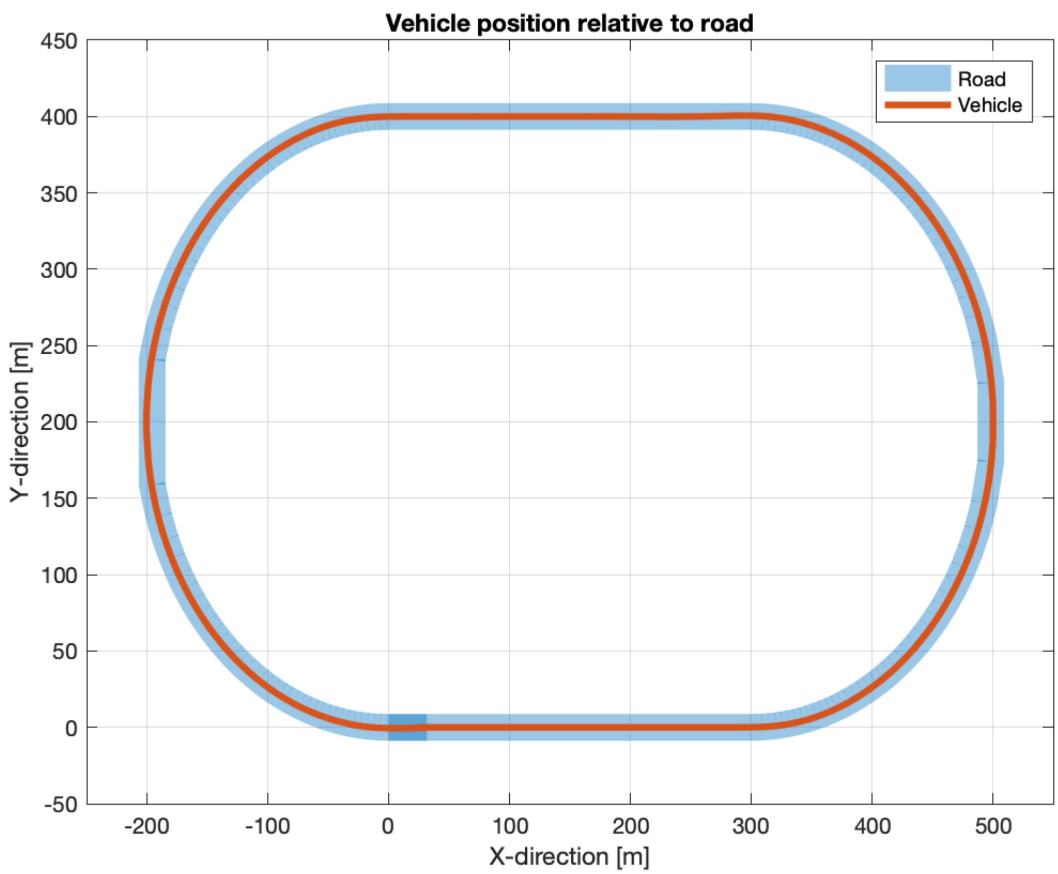


Figure 3: The road used to test the system. Shown above is the reference trajectory of the vehicle that the motor steering control system needs to follow.

3.2 Generating vehicle reference trajectory

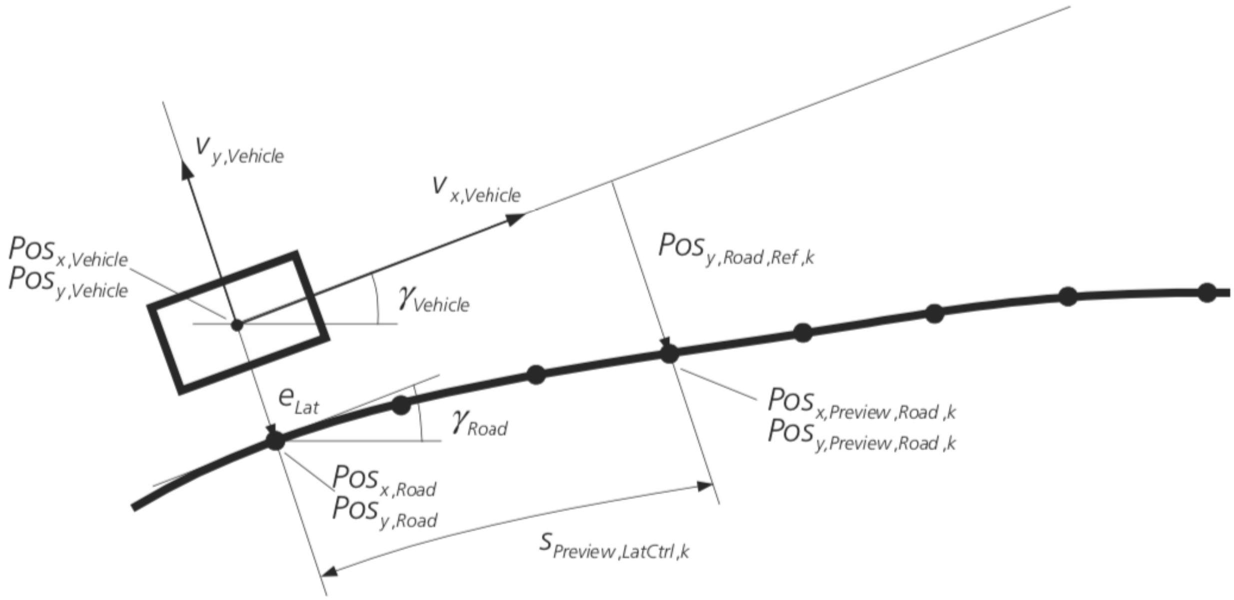


Figure 4: Block diagram structure of ASM [1]

The reference trajectory for the vehicle is calculated by making use of preview information about the road. This is done by calculating the preview distance as the distance the vehicle moves during the preview time $t_{Preview}$. This is set to 1 s in the model's parameterization. The vehicle's state is calculated at ten equidistant points along the preview distance and this is used as the reference value in the cost function for the optimization (discussed in section 3.3).

3.3 Generating reference steering angle

ASM uses optimal control theory to calculate the steering angle required to follow the road. This is done by solving the system described in 1 and calculating the optimal control input $\delta_{Steering}$ that minimizes the following discrete cost function J

$$y(kT) = C\Phi(kT)x(0) + C\Gamma(kT)Bu(0)$$

where $\Phi(kT) = e^{AkT}$ and $\Gamma(kT) = \int_0^{kT} \Phi(r)dr$ and

$$J = \sum_{k=1}^{m} \left(y_{ref}(kT) - y(kT)\right)^2 w_k$$

where w_k are the weights assigned to each preview point and are set to unity for this project, meaning all preview points are equally weighted. The optimal control input to track the reference trajectory is given as

$$\delta_{Steering} = \frac{\sum_{k=1}^{10} \left(Pos_{y,Road,Ref,k} - C\Phi(kT)x(0)\right)\left(C\Gamma(kT)Bw_k\right)}{\sum_{k=1}^{10} \left((C\Gamma(kT)B)^2 w_k\right)}$$

3.4 Linear Quadratic Tracking position control for the Motor

A Linear Quadratic Tracker (LQT) controller was developed for the motor model shown in section 2.2 to track the reference steering wheel angle generated by the ASM driver subsystem. A LQT provides the control input that minimizes the following cost function:

$$J = \frac{1}{2}\left([C\underline{x}(T_f) - \underline{r}(T_f)]^T P[C\underline{x}(T_f) - \underline{r}(T_f)]\right) + \frac{1}{2}\int_0^{T_f} \left([C\underline{x}(t) - \underline{r}(t)]^T Q[C\underline{x}(t) - \underline{r}(t)] + u^T Ru\right) dt \quad (3)$$

The weighting matrices used in the cost function for the LQT were as follows:

$$P = I,\, Q = \begin{bmatrix} 1\times10^{-3} & 0 & 0 & 0 \\ 0 & 1\times10^{-7} & 0 & 0 \\ 0 & 0 & 1\times10^{3} & 0 \\ 0 & 0 & 0 & 1\times10^{2} \end{bmatrix} \text{ and } R = \begin{bmatrix} 1\times10^{4} \end{bmatrix}$$

The weighting matrices were selected based on the relative importance of the states that we want to track best, therefore the weights for the i and w states are given more importance to reduce the current/voltage used by the motor and to reduce the position error of the motor.

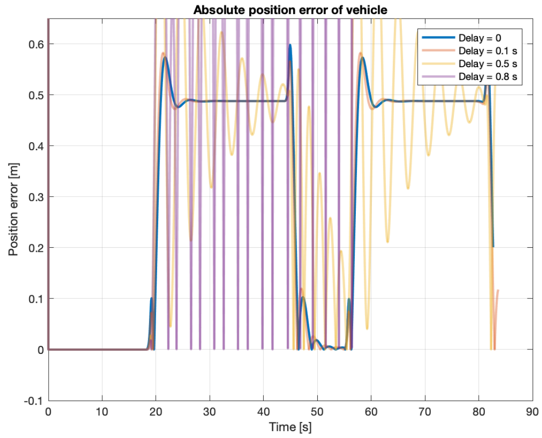
The motor driver system was implemented by modifying the blocks within the ASM model in Simulink. The un-delayed steering wheel angle $\delta_{SteeringWheel}$ was used as the reference input to the combined motor model and LQT system and the simulation was run for one full lap around the oval. The results are presented in the following section.

4 Simulation Results and Discussion

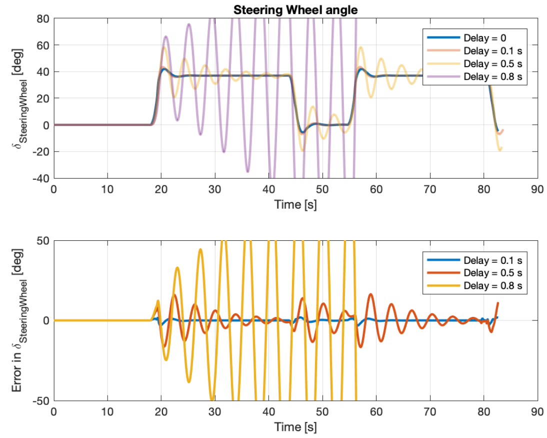
Effect of delay on ASM Driver

According to [3], typical human time to steering while driving are approximately 1.67 s. While human drivers enjoy a much larger preview distance than the one used in this simulation, their reaction time (delay time in simulation terms) is generally higher than the values used. The performance of the ASM driver model with equivalent human reaction time delays was tested against the performance of the motor system.

Shown below are plots of vehicle position error and steering wheel angle (and error) during a lap of the oval track for increasing values of time delay (0.1 s, 0.5 s, 0.8 s). As can be noted from the figure, higher delays result in system instability which translates to the vehicle significantly veering off the reference trajectory.



(a) Absolute error in vehicle position for various delays

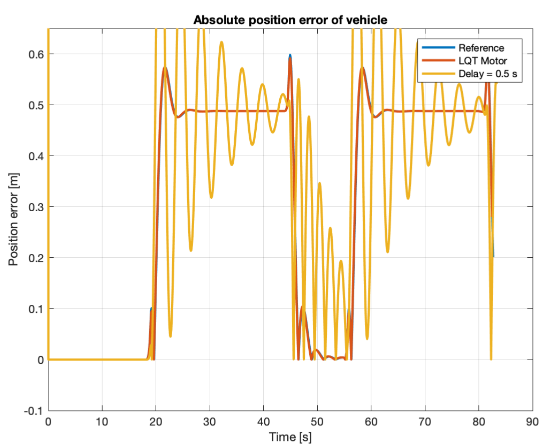


(b) Error in steering wheel angle with respect to reference for various delays

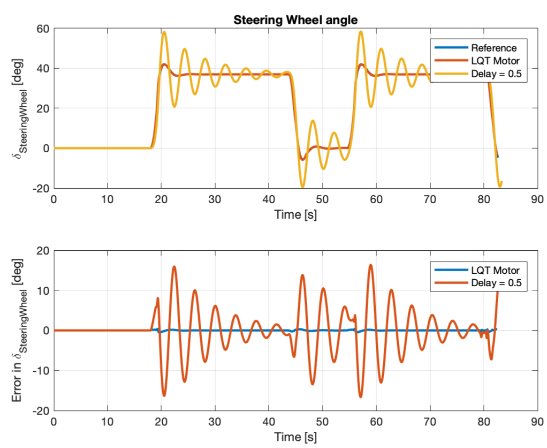
Figure 5: Response of the vehicle for various levels of delay in the driver model

Performance of Control system vs. Delayed case

The plots shown in figure 6 compare the motor steering system to that of a 0.5 s delayed ASM driver. As can be noted, the motor steering system tracks the reference very closely, while the delayed ASM driver has significant oscillations around the reference trajectory.



(a) Absolute error in vehicle position for the Motor driver



(b) Error in steering wheel angle with respect to reference for the motor driver

Figure 6: Response of the vehicle for various levels of delay in the driver model

Discussion

From the previous section, we know that the delayed ASM driver has lower performance than the motor driven steering wheel. However, actual drivers enjoy much larger preview distances and are therefore more resilient to delays (able to withstand higher delays before becoming unstable). For the purposes of this project, the data collected was with a fixed preview distance based on a fixed preview time of 1 s.

5 Conclusions and Future Work

In conclusion, the developed motor steering was able to perform better than the delayed ASM driver. One must note that actual human drivers have a much larger preview distance than the ASM driver and therefore are more robust to delays, however, a large enough delay will cause even them to make the vehicle system unstable.

For future work, a more realistic motor model may be used for the steering wheel motor. This model may consider coulombic friction within the motor and also the inherent nonlinearities associated with it. Additionally, a more realistic system could be considered by using environment information made available by sensors rather than assuming perfect knowledge of the environment (road preview information). This would include sensor noise and dynamics in the system, making it more realistic while increasing the overall complexity. Finally, this control system can be developed with hardware-in-the-loop with steering control being performed by an actual DC motor while the rest of the vehicle may be simulated by a real-time processor.

References

[1] dSPACE. *ASM Environment Reference*, release 2019-a edition, May 2019.

[2] Dc motor position: System modeling.

[3] Daniel V. McGehee, Elizabeth N. Mazzee, and G.H. Scott Baldwin. Driver reaction time in crash avoidance research: Validation of a driving simulator study on a test track. 2000.