Handwheel Force Feedback for Lanekeeping Assistance: Combined Dynamics and Stability

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Lanekeeping assistance holds the promise to save thousands of lives per year by maintaining lane position in the absence of driver steering commands. Here we combine force feedback with a lanekeeping controller based on lateral and heading error, and analyze the effect of various sources of force feedback on the stability of the vehicle. In addition to force feedback based on the aligning moment or artificial damping and inertia, the force can be based on the level of assistance being given. This coupling of the force feedback and assistance systems can destabilize the vehicle if not designed properly. Linear modeling verified by experiments shows the effect of varying the gains on both the force feedback and the lanekeeping assistance itself. This analysis shows that within a range of values that feel reasonable to the driver, changes to the lanekeeping controller or force feedback can have marked affects on the response of the vehicle.

Topics / Lane Departure Prevention, Driver Assist Systems, Steering Assistance and Control

1. INTRODUCTION

According to the U.S. National Highway Administration, 55 % of vehicle fatalities are the result of unintended lane departure. By maintaining lane position in the absence of adequate driver steering commands a large number of lives can be saved. The lanekeeping system analyzed here [4] applies a corrective force to the vehicle based on its lateral and heading deviation from lane center. Intuitively, the system attaches a spring between the car and the road center line, and this force attracts the vehicle to lane center. The driver can still steer the vehicle with the handwheel, and the driver command is simply added to the lanekeeping command. This lanekeeping controller has been shown both analytically and experimentally to keep the vehicle in the lane in the absence of driver steering commands.

A lanekeeping controller of this type requires steer-by-wire to allow computer control of the road wheel steering angle. When the mechanical connection between the hand wheel and road wheels is broken in steer-by-wire, there is no longer a natural source of force feedback. Here we explore a variety of force feedback sources in conjunction with the lanekeeping system described above:

- Added inertia
- Added damping
- Aligning moment
- Force based on assistance being given

Most work on handwheel force feedback has focused on transmitting the mechanical aligning moment resulting from the steering geometry in a comfortable way to the driver. This is largely a result of the fact that the only source of torque available to be transmitted on a conventional vehicle is the aligning moment. To date, researchers have mainly explored ways to recreate the feel of a conventional vehicle in steer-by-wire. Many researchers have investigated nonlinear modeling of steering feel [10],[7],[11],[5] as well as ways to ensure the road wheels track the handwheel adequately [8]. Other work has developed force feedback for alternative input sources such as a joystick [12], or schemes to cancel out vehicle induced accelerations on the input device [1].

From a different perspective, attempts have been made to gauge the acceptability of various assistance systems to drivers. Some of these systems are passive, using noise or torque to warn the driver of an imminent lane departure. Sato et al.[6] found that a torque warning to the driver of imminent lane departure is more effective than sounds while Suzuki[9] found that a torque warning can cause the driver to steer in the wrong direction if not designed properly. Some researchers have developed driver models to allow analysis of human response to assistance systems [3], while others have designed systems that take control authority away from the driver when necessary [2].

The goal of the lanekeeping system analyzed here is to keep the vehicle in the lane in the absence of driver inputs. Thus when combined with force feedback we seek to meet two basic objectives:

1. Present easily controllable feel to driver: The system should generate forces on the handwheel to enable the driver to control the vehicle.
2. Remain stable with hands off handwheel: The overall system consisting of the handwheel and the vehicle itself must remain stable and in the lane.

In a mechanically steered vehicle, stability of the overall system is assured by designing the steering system such that the aligning moment acts to return the handwheel to its center position. With the force feedback now based on vehicle position states, the forces on the handwheel may not always be in a stabilizing direction.

To analyze the combined system of force feedback and lanekeeping assistance, linear models of the vehicle and force feedback subsystems are presented. Next these models are combined to form a linear model of the entire system. The specific types of force feedback of interest are added to this model as functions of the states. A linear root-locus analysis is then performed on this linear system to examine the effects of modifying the force feedback. This analysis shows that within a range of values that feel reasonable to the driver, changes to the lanekeeping controller or force feedback can have marked affects on the response of the vehicle. Experiments on a steer-by-wire vehicle allow validation of the linear modeling and qualitative evaluation of the force feedback.

2. LANEKEEPING CONTROLLER

This work builds on the lateral and heading error based lanekeeping controller of [4]. This controller seeks to keep the vehicle in the lane through the application of forces derived from an artificial potential energy. The potential is shown conceptually in Figure 1, where it provides zero force on lane center, and increasing force as the vehicle deviates from the specified path. This force is derived from the lateral and heading errors of the vehicle, and can be thought of as a spring connecting the vehicle to the lane center. The controller has two parameters: the potential field gain k, which represents the effective spring constant, and a lookahead distance x_{la}. This lookahead distance is a gain on the heading error of the vehicle, and is necessary for stability at high speeds. Because a range of lookahead values will result in a stable vehicle, it can be chosen to give a comfortable driver feel.

The linear yaw-plane, or "bicycle", model has been shown to accurately model the dynamics of a vehicle in the linear region of handling, and will be used for this analysis. Added to the bicycle model is the steering from the lanekeeping controller:

$$\delta_{pf} = \frac{ke + kx_{la}\psi}{C_f} \tag{1}$$

where C_f is the front cornering stiffness. This steering angle results in a force applied to the vehicle at the front axle:

$$f_{pf} = k(e + x_{la}\psi) \tag{2}$$

With the potential field force added in, the bicycle model in state space form is

$$\begin{bmatrix} \dot{e} \\ \ddot{e} \\ \dot{\psi} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{2k}{m} & \frac{-(C_f+C_r)}{mU_x} & \frac{(C_f+C_r)-2kx_{la}}{m} & \frac{(-aC_f+bC_r)}{mU_x} \\ 0 & 0 & 0 & 1 \\ \frac{-2ka}{I_z} & \frac{(-aC_f+bC_r)}{I_zU_x} & \frac{(aC_f-bC_r)-2kx_{la}a}{I_z} & \frac{-(a^2C_f+b^2C_r)}{I_zU_x} \end{bmatrix} \begin{bmatrix} e \\ \dot{e} \\ \psi \\ \dot{\psi} \end{bmatrix} \tag{3}$$

Here e is the lateral error, the perpendicular distance of the center of gravity of the vehicle to lane center; ψ is the heading error, or the difference between the heading of the vehicle and the direction of the lane center line; C_f and C_r are the front and rear cornering stiffnesses; m and I_z are the mass and inertia respectively; and a and b are the distances from the center of mass of the vehicle to the front and rear axles. U_x is the longitudinal speed, and is assumed to be constant.

3. FORCE FEEDBACK SYSTEM

3.1 System Description

The force feedback system consists of a brushless DC motor connected to the handwheel shaft via a synchronous belt drive, with a drive ratio of 5:1. The system is pictured in Figure 2 in the test vehicle, a 1997 Corvette modified to steer-by-wire. A high resolution encoder measures the position of the motor shaft. The system is designed to be able to recreate the large torques on the handwheel present

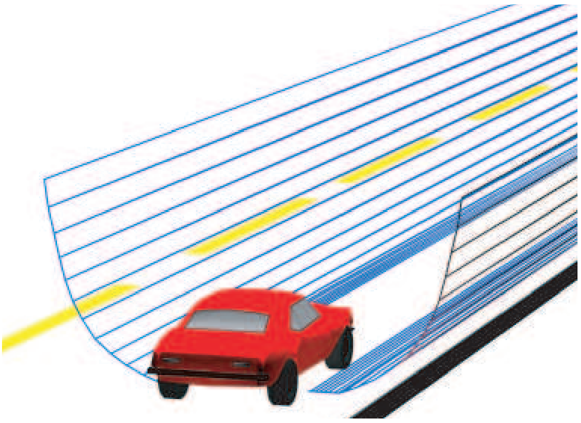

Fig. 1: Potential Field Lanekeeping Controller

Fig. 2: Force Feedback Mechanical System

in emergency driving. It can reproduce 20Nm while spinning at 700deg/s. To minimize torque ripple, sinusoidal commutation is used, and no gearbox is present.

3.2 Modeling the System

The system can be modeled as a mass damper system, with a torque input from the motor. This inertia is the combined inertia of the handwheel and the effective inertia of the motor through the belt drive. Thus it can be described by a simple second order equation as

$$I\ddot{\theta} + b\theta = \tau_{motor} + \tau_{driver} \tag{4}$$

where τ_{driver} is zero if the driver's hands are off the handwheel. τ_{motor} is a combination of the torques from the various force feedback sources:

$$\tau_{motor} = \tau_{damp} + \tau_{inertia} + \tau_{align} + \tau_{pf} \tag{5}$$

I and b are found experimentally to be $.019 kgm^2$ and $.01 Nm/rad/s$ respectively. This model assumes the handwheel system is linear. In reality the friction in the system is not viscous friction and thus is not perfectly described by linear damping. We choose to model the friction linearly here to allow the use of linear analysis tools such as root locus, which provide insight into the dynamics of the system.

3.3 Added Inertia and Damping

To recreate the feel of a conventional steering system, inertia and damping can be added to match that of a mechanical steering system. The artificial damping is purely a function of the handwheel velocity:

$$\tau_{damp} = -k_{damp}\dot{\theta} \tag{6}$$

The added inertia is calculated by twice differentiating the encoder position signal and feeding it back with a constant gain.

$$\tau_{inertia} = -I_{add}\ddot{\theta} \tag{7}$$

3.4 Aligning Moment

To feed back the aligning moment to the user, it is useful to express it in terms of the lateral and heading error coordinates e and ψ. The aligning moment in the linear region is

$$\tau_{align} = -k_a(\beta + \frac{ar}{U_x} - \delta) \tag{8}$$

where k_a is a constant taking into account the steering geometry and tire characteristics. Here δ is the total steering, a combination of the user commanded steering and the potential field contribution.

$$\delta = \frac{\theta}{s_r} + \delta_{pf} \tag{9}$$

$$\delta_{pf} = \frac{ke + kx_{la}\psi}{C_f} \tag{10}$$

Where s_r is the steering ratio, such that $\theta = s_r\delta$. Expressed in error coordinates and making small angle approximations, the sideslip angle β is

$$\beta = \frac{U_y}{U_x} = \frac{\frac{\dot{e}}{cos\psi} - \frac{U_x\psi}{cos\psi}}{U_x} = \frac{\dot{e}}{U_x} - \psi \tag{11}$$

$$r = \dot{\psi} \tag{12}$$

Thus the total aligning moment can be expressed in terms of the states as

$$\tau_{align} = -k_a(\frac{\dot{e}}{U_x} - \psi + \frac{\dot{\psi}a}{U_x} - \frac{\theta}{s_r} - \delta_{pf}) \tag{13}$$

3.5 Lanekeeping Assistance Force

The force feedback based on the lanekeeping assistance is proportional to the force being applied to the vehicle from the potential field. Thus it is simply a function of the lateral and heading errors and the potential field parameters k and x_{la}:

$$\tau_{pf} = k_{pf}(ke + kx_{la}\psi) \tag{14}$$

The potential field derived force feedback is always acting in the direction the user should steer to move towards the minimum of the potential.

4. MODEL OF COMBINED SYSTEM

To examine the response of the system in the absence of driver steering, we first assume the torque applied to the handwheel by the driver is zero, so the handwheel is moving purely in response to the force feedback torque. The angle of the road wheels will be a combination of the handwheel angle and the angle commanded by the lanekeeping controller, and here we assume that the roadwheel angle can respond to these commands. For the steer-by-wire system in this vehicle this is a valid assumption for reasonable speeds of movement commanded, up to about 900deg/s at the handwheel. Thus if the force feedback system is not causing gross instability, the roadwheel angle will track the combination of handwheel and controller commands. An additional assumption is that the vehicle remains in the linear

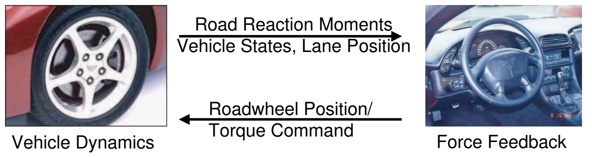

Fig. 3: Interconnection of force feedback and SBW systems

region of operation, with small slip angles. Again this is true if the combined system is operating in a stable manner.

Figure 3 shows schematically the interconnection between the force feedback and vehicle systems. Any force feedback that moves the handwheel will affect the command given to the steering system and, in turn, the aligning moment estimate and the lane position of the vehicle. This interconnection is shown mathematically in the linear state space formulation for the combined system:

$$\dot{x} = Ax \qquad x = \begin{bmatrix} e \\ \dot{e} \\ \psi \\ \dot{\psi} \\ \delta \\ \dot{\delta} \end{bmatrix} \tag{15}$$

where the A matrix is given by

$$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{2k}{m} & \frac{-(C_f+C_r)}{mU_x} & \frac{(C_f+C_r)-2kx_{la}}{m} & \frac{(-aC_f+bC_r)}{mU_x} & \frac{C_f}{ms_r} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{-2ka}{I_z} & \frac{(-aC_f+bC_r)}{I_zU_x} & \frac{(aC_f-bC_r)-2kx_{la}a}{I_z} & \frac{-(a^2C_f+b^2C_r)}{I_zU_x} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \multicolumn{6}{c}{(\tau^{vec}_{damp} + \tau^{vec}_{align} + \tau^{vec}_{pf})/(I_{add} + I_s)} \end{bmatrix}$$

where

$$\tau^{vec}_{align} = k_a \begin{bmatrix} \frac{k}{C_f} & \frac{1}{U_x} & \frac{kx_{la}}{C_f-1} & \frac{a}{U_x} & \frac{-1}{sr} & 0 \end{bmatrix} \tag{16}$$

$$\tau^{vec}_{damp} = k_{damp} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \tag{17}$$

$$\tau^{vec}_{pf} = k_{pf} \begin{bmatrix} k & kx_{la} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{18}$$

Thus each of the vectors in the above equations is inserted into the system matrix if that force feedback is active. The exact values depend on the gain used for each type of force feedback (k_{damp}, k_a, k_{pf}).

5. ROOT LOCI

Because of the complicated coupling between the vehicle and handwheel subsystems and the multiple types of force feedback being considered, it is useful to examine the system pole locations as a function of the gain on the various force feedback sources. This allows identification of force feedback gains which are stable, and provides intuition into the effect each of the gains has on combined system stability.

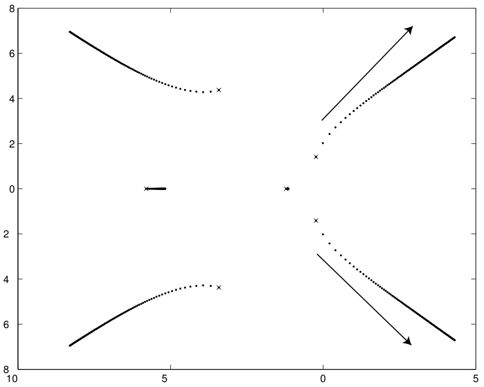

Fig. 4: System Pole Locations with Increasing Potential Field Force

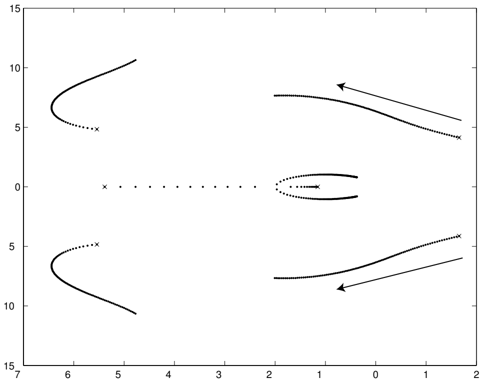

Fig. 5: System Pole Locations with Increasing Aligning Moment

Figure 4 shows the pole locations with increasing k_{pf}, the gain on the force feedback derived from level of potential field force (Equation 14), with all other force feedback gains set to zero. As expected, too much feedback based on relative lane position causes too much handwheel motion, leading to instability of the vehicle. Although the system is stable at very low levels of potential field force feedback, these are much too small to effectively communicate with the driver (only about 10mNm at 1 meter lateral error).

One way to stabilize the vehicle is to add force feedback based on the aligning moment. Figure 5 shows pole location with increasing k_a, the gain on the aligning moment force feedback. Here the potential field force feedback is set to a value that results in about 1-2Nm when enough steering is applied to leave the lane. With increasing aligning moment on the handwheel the system does get more stable, as the aligning moment tends to return the handwheel to center.

Another way to stabilize the vehicle and allow higher levels of potential field force feedback is to simply add damping and inertia to the handwheel. Figure 6 shows pole locations with increasing damping on the handwheel (increasing k_{damp}), with enough added inertia to match the stock Corvette

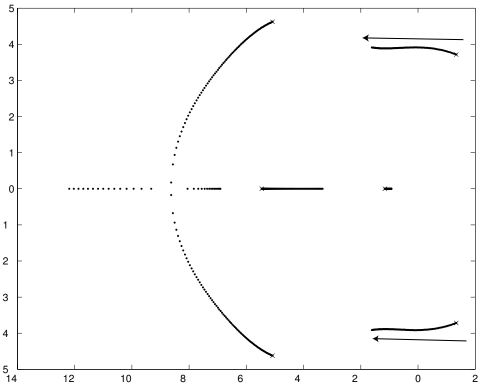

Fig. 6: System Pole Locations with Increasing Damping

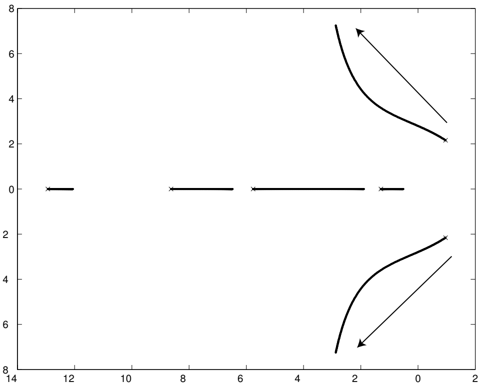

Fig. 7: System Pole Locations with Increasing Lookahead distance

steering system. This effectively stabilizes the system, but can lead to an overly heavy steering feel if too much damping is applied.

Although the potential field gain must be determined to keep the vehicle in the lane in the absence of driver inputs, the lookahead distance can be selected from a range of stable values. For this reason it is useful to examine the effect of increasing lookahead on the stability of the system. Figure 7 shows that the system poles stabilize with more lookahead. This is because the lookahead tends to counteract any large vehicle motions the handwheel would otherwise command.

Figure 8 shows how increasing speed (U_x) effects the system poles. With increasing speed any movement of the handwheel more immediately effects the vehicle position and heading, leading to the higher frequency poles in the figure. The vehicle modeled is inherently somewhat understeering, so it is perhaps not surprising that the system damping decreases with speed.

These root loci show the significant effect changes in force feedback or lanekeeping controller gains can have on the stability of the system.

	Stable	Unstable	units
Inertia Added	0.009	0.009	kgm^2
Damping Added	0.344	0.052	Nm/rad/s
P.Field FF	25	25	mNm/kN
Aligning Moment	0	0	Nm/deg
Potential Field Gain	2000	2000	N/m
Lookahead Distance	20	20	m

Table 1: Force Feedback and Lanekeeping Parameters

6. EXPERIMENT

The setup described in section 3.1 along with the experimental lanekeeping setup described in [4] enables validation of the linear model and a qualitative feel for this force feedback. Testing on the west ramp and parallel at Moffett Federal Airfield allows safe testing at highway-like speeds. For each test the vehicle is accelerated to a steady speed (maintained by cruise control) of about 20m/s, with the force feedback inactive and the steering wheel away from center. In this way the vehicle reaches a steady state deviation from the center of the lane due to the steering angle. At the beginning of the data set shown, the force feedback is switched on, immediately applying a torque to the handwheel. Table 1 shows the amount of each type of force feedback used for the stable experiment shown. Specifically here the inertia has been augmented to match the steering system of a stock Corvette, and artificial damping has been applied to stabilize the system. Similar gains with less damping are also shown in the table. These gains feel similar when driving the vehicle, but result in a wildly unstable response.

Figure 9 shows an experiment with the stable gains that result in a smooth return to lane center for the vehicle. The smoothness of the trajectory in Figure 9 is comparable to that of the vehicle without force feedback. The experiment deviates from the model due to the coulomb friction in the system mentioned in section 3.2. The handwheel exhibits more damping than the simulation predicts, and

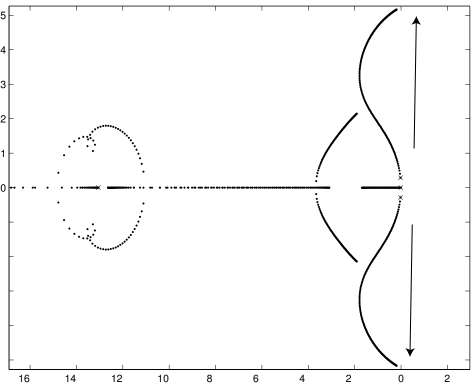

Fig. 8: System Pole Locations with Increasing Speed

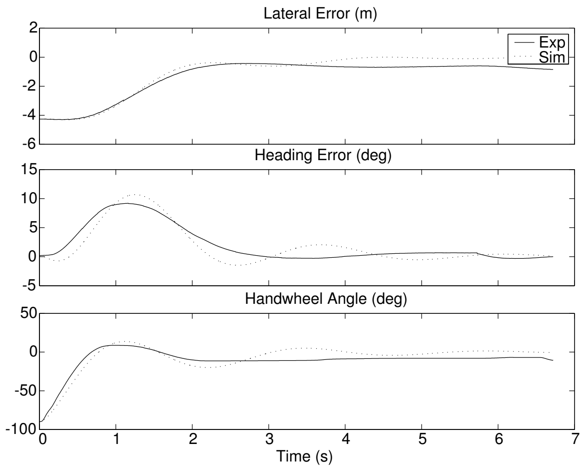

Fig. 9: Experiment and Simulation with Stable Force Feedback Gains

never returns exactly to center, because of this unmodeled friction. However the underlying dynamics of the system are captured by the model, demonstrating the value of the linear analysis.

7. CONCLUSIONS

An examination of stability is critical for any application of force feedback to an assistance system. A system designed for good driver feel can very easily be unstable in the absence of driver inputs, and at the same time stability does not ensure good driver feel. This work provides a framework for the simultaneous design of force feedback and assistance systems. This analysis shows that within a range of values that feel reasonable to the driver, changes to the lanekeeping controller or force feedback can have marked affects on the response of the vehicle.

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