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A UNIFIED APPROACH TO DRIVER ASSISTANCE SYSTEMS BASED ON ARTIFICIAL POTENTIAL FIELDS

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ABSTRACT

This paper presents an approach to vehicle control based upon the paradigm of artificial potential fields. Using this method, the dynamics of the vehicle are coupled with the environment in a manner that ensures that the system exhibits safe motion in the absence of driver inputs. The driver remains in control of the vehicle, however, with the control systems presenting a predictable and safe set of dynamics. With the control approach presented here, integration of various assistance systems can be easily achieved through simple superposition of individual potential and damping functions. A simple example of a combined lanekeeping and stability system demonstrates how this can be accomplished. Preliminary simulation results suggest that both safety and driveability are achievable with such a system, prompting further investigation.

NOMENCLATURE

C_f Front Cornering Stiffness (61595 N/rad)
C_r Rear Cornering Stiffness (61595 N/rad)
l Wheelbase (2.7 m)
a Distance from c.g. to Front Tire (1.3 m)
b Distance from c.g. to Rear Tire (1.4 m)
d Track width (1.5 m)
m Vehicle mass (1670 kg)
I Moment of Inertia (2100 kg m^2)
s Distance Along Roadway
e Lateral Position
ψ Yaw Angle
U_x Longitudinal Velocity
U_y Lateral Velocity
r Yaw rate
u_d Vector of Driver Commands
F_{bd} Driver Braking Force
F_{ad} Driver Acceleration Force
δ_d Driver Steering Command
u_c Vector of Control Inputs
F_{br} Right Differential Braking Force
F_{bl} Left Differential Braking Force
δ_c Controller Steering Command
x Vector of Position States
$\dot{q}$ Vector of Velocity States
$V(x)$ Potential Function
$F_(x, \dot{q}, u_d)$ Damping Function

Introduction

For many people (including the authors), driving is a fun and enjoyable experience. Yet driving is not without its hazards. Objects in the environment, whether fixed or moving, are generally unforgiving in a collision and the vehicle, in the absence of control, possesses no tendency to avoid such collisions. The work presented here envisions vehicle control as a means of fundamentally altering these dynamic relationships to enable the driver to operate in a nominally safe vehicle/environment system. Instead of viewing driver assistance as a collection of individual functions, we view it as a redesign of the driving experience. Ultimately, a successful redesign should make this experience safer, more fun and tunable to individual driving styles or preferences.

The paradigm chosen for this new relationship is that of an artificial potential field. First proposed by Khatib (1986) for robotic manipulator control, potential fields have seen considerable application to obstacle avoidance and mobile robots. In the automotive realm, Reichardt and Schick (1994) proposed an electric field interpretation for autonomous vehicle control based upon a risk map. The risk map assigned a value corresponding to the relative hazard to every point in a two-dimensional description of space. This hazard at each point, interpreted as a charge, exerted a force on the vehicle (interpreted as an electron) with the resultant force from all charges in the environment determining the path of the autonomous vehicle. Reichardt (1996) merged lanekeeping, obstacle avoidance and traffic sign recognition into the construction of the risk map. Hennessey *et al.* (1995) used a spring analogy to define "virtual bumpers" in 2D collision avoidance strategies. In this manner, they also characterized the vehicle's environment by potential fields.

In this paper, we propose an interpretation of driver assistance systems as potential fields and generalized damping functions added to the existing vehicle dynamics and driver inputs. By leaving the driver in the loop, high-level tasks such as path planning remain the province of the driver, thereby avoiding the difficulties of local minima which can arise with arbitrarily designed potentials. The combination of potential fields and damping serves as a means of sensor fusion, a method of weighting multiple control objectives (such as lanekeeping, stability, obstacle avoidance or convenience features like intelligent cruise control) and a generator of restoring forces. Viewed within the language of impedance control, the potential fields and damping turn the environment into an admittance, providing restoring forces which move the vehicle towards safer regions of the state space. The controller does not attempt to interpret driver intent, but merely presents a safe, predictable dynamic response to the driver.

To illustrate this general concept, a combined lanekeeping and yaw control application is presented. The potential field description of lanekeeping and the damping interpretation of yaw control can simply be added together to produce a system with nominally safe behavior. While it is easily established that the new system has nominally safe dynamics, performance and driver acceptance are not clear. To examine these issues, simulations of vehicle performance in a lane change maneuver are presented. The results suggest that a driver can intuitively drive in the potential field framework and integration of various control functions can be achieved in the proposed manner. A brief summary of the future directions suggested by these preliminary results concludes the paper.

Basic Approach

Robotic control using artificial potential fields was originally motivated by the desire to move some of the responsibility for collision avoidance from a high-level (and consequently slow) planning task to the lowest (and fastest) level of control (Khatib 1986). By directly coupling sensing to certain types of actuation, fast environmental hazards could be handled instinctively, rather than by high-level planning. This analogy transfers well to driver assistance systems. By keeping the driver in the loop, human capacity for high-level planning remains central to the driving experience while advanced control systems provide added convenience or faster response to hazards.

The unifying principle behind this approach is to consider each vehicle control system as assessing some penalty, or level of hazard, on different regions of the state space. The potential function is determined by summing the hazard assessed by each system on the position variables. The damping function, in turn, penalizes velocity variables. The controller (or controllers, when multiple systems are involved) then provides a level of restoring force corresponding to the gradient of the potential function (referred to as the potential field) along with the artificial damping. The vehicle therefore exhibits a natural tendency to return to areas of the state space with low levels of hazard, assisting the driver with low-level control tasks. With this approach, sensor fusion is captured systematically by the creation of the potential and damping functions and coordination among different actuators is embodied in the generation of the restoring force.

The following examples serve to better explain this concept of an artificial potential field defined by degree of hazard. Figure 1 illustrates a cross section of the environmental hazards seen by the car in the right lane in the manner envisioned by Reichardt (1996). Should the driver drift so that lane departure or a collision with the other vehicle becomes likely, the potential hazard would increase and the controller would provide a greater restoring force to move the vehicle to a safer region (in this case, the center of its lane). Interactions among safety and convenience systems can be easily viewed in such a context. For example, knowledge of the road curvature may allow a car's on-center feel to be associated with proper lane tracking as opposed to straight-line motion.

Expressing AVCS systems in terms of potential and damping functions offers several insights. First, since artificial potential fields represent a complete redesign of the dynamic relationship between a system and its environment, this view opens up new possibilities for design of the driving experience. One extremely simple example of this is relating on-center feel to lane tracking, as previously mentioned. Second, the superposition property of potential functions allows for better analysis and design of interactions among control systems. This is especially true for interactions between systems that react primarily to environmental stimuli (like collision avoidance or lanekeeping) and those which react primarily to the vehicle state (such

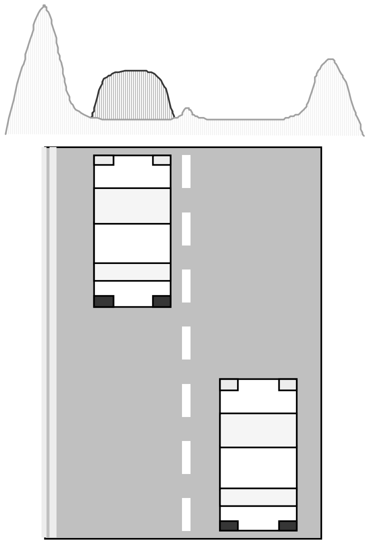

Figure 1. CROSS SECTION OF POTENTIAL FUNCTION

as stability control). While such systems have been developed separately, it is not hard to envision interactions involving, for instance, a choice between skidding and lane departure (this is particularly true if the scope is extended to heavy trucks with multiple trailers). Third, the level of assistance provided can be adjusted by simple scaling of the potential function. Increasing the “height” of the potential function peaks relative to the valleys creates a greater restoring force in response to a given hazard, thus providing a higher level of assistance (or intrusiveness).

It is important to note that under this interpretation of the artificial potential functions (where the gradient determines the “drift vector” as viewed by the driver), it is only necessary to calculate the gradient at the current location of the vehicle. Factors such as a preview distance or time-to-line-crossing could conceivably be built into the analysis by proper construction of the potential function (Krogh 1984). Nor is exact tracking of the gradient required, as in certain interpretations of artificial potential fields for mobile robots (Guldner and Utkin 1995). The only control task required is for the actuators to act in concert to produce the restoring force dictated by the potential field at the current location.

Vehicle and Environment Models

The vehicle model used in this study (Figure 2) is a simple yaw plane representation with three degrees of freedom (Koepele and Starkey 1990).

$$m\dot{U}_x = [F_{xr} + F_{xf}\cos\delta - F_{yf}\sin\delta + mrU_y] \quad (1)$$

$$m\dot{U}_y = [F_{yr} + F_{xf}\sin\delta + F_{yf}\cos\delta - mrU_x] \quad (2)$$

$$I_z\dot{r} = [aF_{xf}\sin\delta + aF_{yf}\cos\delta - bF_{yr}] \quad (3)$$

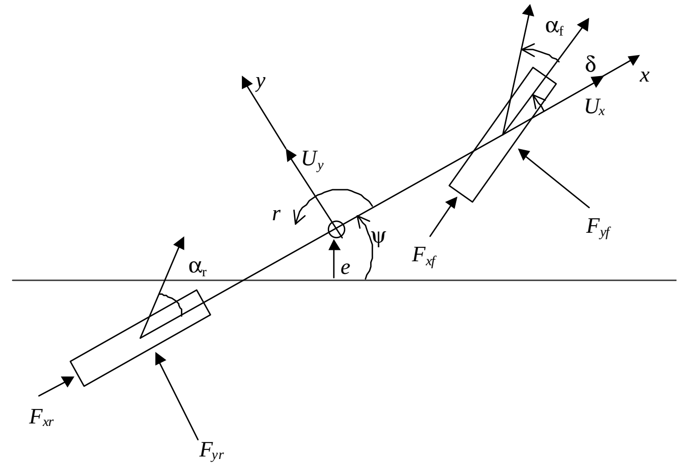

Figure 2. PLANAR MODEL OF VEHICLE DYNAMICS

In this paper, we make small angle assumptions and ignore higher powers of δ, giving

$$\alpha_f = \delta - \frac{ra + U_y}{U_x} \quad (4)$$

$$\alpha_r = \frac{r_b - U_y}{U_x} \quad (5)$$

With the further assumption of a linear tire model for cornering:

$$F_{yf} = C_f\alpha_f \quad (6)$$

$$F_{yr} = C_r\alpha_r \quad (7)$$

Equations 1 through 3 become

$$m\dot{U}_x = mrU_y + F_b + F_{ad} + C_f\left(\frac{ra + U_y}{U_x}\right)\delta \quad (8)$$

$$m\dot{U}_y = C_r\left(\frac{rb - U_y}{U_x}\right) - C_f\left(\frac{ra + U_y}{U_x}\right) - mrU_x + C_f\delta \quad (9)$$

$$I_z\dot{r} = -aC_f\left(\frac{ra + U_y}{U_x}\right) - bC_r\left(\frac{rb - U_y}{U_x}\right) + aC_f\delta + \frac{d}{2}F_{br} - \frac{d}{2}F_{bl} \quad (10)$$

In this convention, brake forces are taken as negative and the total brake force, F_b, is the combination of driver command and differential braking:

$$F_b = F_{bd} + F_{br} + F_{bl} \quad (11)$$

Similarly for the steering:

$$\delta = \delta_c + \delta_d \tag{12}$$

This can be written as:

$$M\ddot{q} + D(\dot{q}) = B_c(\dot{q})u_c + B_d(\dot{q})u_d \tag{13}$$

where

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_z \end{bmatrix}; B_d = \begin{bmatrix} 1 & 1 & \frac{ra+U_y}{U_x}C_f \\ 0 & 0 & C_f \\ 0 & 0 & aC_f \end{bmatrix}$$

$$B_c = \begin{bmatrix} 1 & 1 & \frac{ra+U_y}{U_x}C_f \\ 0 & 0 & C_f \\ \frac{d}{2} & -\frac{d}{2} & aC_f \end{bmatrix}$$

$$D = \begin{bmatrix} -mrU_y \\ -C_r(\frac{rb-U_y}{U_x}) + C_f(\frac{ra+U_y}{U_x}) + mrU_x \\ aC_f(\frac{ra+U_y}{U_x}) + bC_r(\frac{rb-U_y}{U_x}) \end{bmatrix}$$

The driver input vector is given by $u_d = [F_{ad}\ F_{bd}\ \delta_d]^T$, corresponding to acceleration forces from the engine, brake forces and the steering angle. The control input vector is $u_c = [F_{br}\ F_{bl}\ \delta_c]^T$, which assumes that differential braking and the application of an additional steer angle through a steer-by-wire system are possible. For simplicity, we assume all drive and brake torques act on the rear wheels.

For this paper, we consider a straight section of roadway with the position vector $w = [s\ e\ \psi]^T$ representing the location of the vehicle cg in the environment. The state vector of the system is therefore given in terms of the position variables, w, and the velocity vector, $\dot{q}$. Transformation between the environmental and body fixed systems can be achieved through:

$$\frac{\partial \dot{w}}{\partial \dot{q}} = \frac{\partial w}{\partial q} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{14}$$

Control Law

The general form of controller discussed here adds a conservative force derivable from a potential function and a general damping term to the existing vehicle dynamics. The control law is therefore of the form:

$$u_c = B_c^{-1}(\dot{q}) \left[-\frac{\partial V}{\partial w}\frac{\partial w}{\partial q} + F(w, \dot{q}, u_d) \right] \tag{15}$$

where $V(w)$ is the potential function describing the overall hazard in the system and $F(w, \dot{q}, u_d)$ is a generalized damping term. This term can be any vector function that satisfies

$$\dot{q}^T F(w, \dot{q}, u_d) \leq 0 \tag{16}$$

With a differentiable potential function, $V(w)$, and a damping function that satisfies Equation 16, the system will exhibit a nominally safe behavior.

Proposition 1.1 (Nominally Safe Behavior). *If the potential function $V(w)$ is interpreted as a level of hazard applied to system states, then in the absence of driver input, the system hazard is bounded by:*

$$V_{max} = \frac{1}{2}\dot{q}(0)^T M \dot{q}(0) + V(w(0))$$

where $w(0)$ and $\dot{q}(0)$ are the values at the initial time $t = 0$.

Proof. Defining an effective energy by

$$E = \frac{1}{2}\dot{q}^T M \dot{q} + V(w)$$

the rate of change of energy is:

$$\begin{aligned} \dot{E} &= \dot{q}^T M \ddot{q} + \frac{\partial V}{\partial w}\frac{\partial w}{\partial q}\dot{q} \\ &= \dot{q}^T [-D(\dot{q}) + B_c(\dot{q})u_c] + \frac{\partial V}{\partial w}\frac{\partial w}{\partial q}\dot{q} \\ &= \dot{q}^T \left[-D(\dot{q}) - \frac{\partial V}{\partial w}\frac{\partial w}{\partial q} + F(w, \dot{q}, 0) \right] + \frac{\partial V}{\partial w}\frac{\partial w}{\partial q}\dot{q} \\ &= -\dot{q}^T D(\dot{q}) + \dot{q}^T F(w, \dot{q}, 0) \end{aligned}$$

From the equations of motion:

$$\begin{aligned} \dot{q}^T D(\dot{q}) = \frac{1}{U_x} &\left[(C_f + C_r)U_y^2 + 2(aC_f - bC_r)rU_y \right. \\ &+ \left. (a^2 C_f + b^2 C_r)r^2 \right] \end{aligned}$$

From Sylvester's Criterion, this quadratic form is positive when $l^2 C_f C_r > 0$. Hence, the vehicle always contributes to damping (an intuitive result and similar to that obtained by Chen and Tomizuka, 1996, for articulated vehicles). Since the controller also contributes to damping by Equation 16, the effective energy cannot increase and

$$V_{max} \leq E_0 = \frac{1}{2}\dot{q}(0)^T M \dot{q}(0) + V(w(0))$$

bounds the hazard experienced by the system.

A Lanekeeping and Yaw Control System

To demonstrate the coupling of environmental and vehicle states in this paradigm, we consider the simple example of a combined lanekeeping and stability control system. This example is intended to highlight some of the functionality that can be achieved by simply adding a potential field and generalized damping to the vehicle dynamics; it is not intended to represent an ideal choice of parameters for either system. Indeed, in this paper, lanekeeping is achieved solely through the potential field while stability control functionality follows from the damping term alone. As noted later, coupling may be desirable.

Potential Field Design

As we have formulated the problem, it is not hard to develop the control law or to guarantee that the system tends to move towards "safer" states (as defined by the potential function) in the absence of inputs. In a vehicle system, the following criteria should also hold:

1. The hazards defined by the potential fields between lanes should be calibrated in such a way to prevent lane crossing in the presence of disturbances.
2. The dynamics in the center of the lane should be those of the uncontrolled vehicle.
3. The driver should be able to change lanes in a manner qualitatively similar to the uncontrolled system.

The first two of these can be met analytically in the development of the potential fields. The third is evaluated through simulation with a driver model. The potential function chosen for the lanekeeping task is solely a function of lateral error, e, and is illustrated in Figure 3. This corresponds to a highway with two lanes travelling in the same direction and lane centers at $e = 0$ and $e = 3.5m$. For information on the position in the lane and lane curvature, we assume the use of a GPS system coupled with a precision map (Wilson *et al.* 1998). The potential function is much greater for road departure than for lane crossing, consistent with intuition. Furthermore, the potential function is flat in the center of the lane to give the driver the opportunity to maneuver without intrusion.

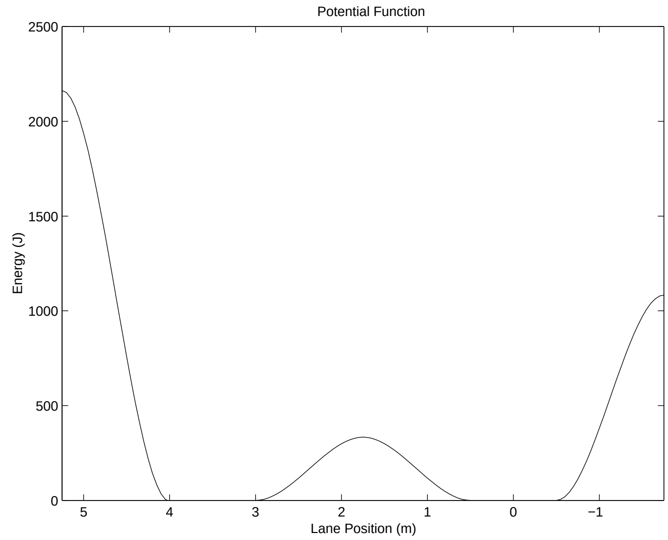

Figure 3. SECTION OF LANEKEEPING POTENTIAL FUNCTION

This design involves several criteria on the potential function. First, the gradient should be zero at the point exactly between the lane centers (1.75 m) to prevent a discontinuous change in the system dynamics at this point. Secondly, the peak value of the field in each section should correspond to the energy required to overcome the field.

Choice of Damping Values

To achieve a stability control function, we would like to be able to alter the vehicle's yaw rate when we sense that it is different from that commanded by the driver. Based upon steady handling results, we define the desired yaw rate in terms of the driver's steering command:

$$r_{des} = \frac{U_x}{L + K{U_x}^2}\delta_d \qquad (17)$$

The yaw rate controller used here is simply:

$$M_{yaw,des} = \gamma(r_{des} - r) \qquad (18)$$

Figure 4 conceptually divides this controller into six regions, labeled understeer, oversteer and reverse steer. In the oversteer and reverse steer cases, the desired yaw moment always acts in the opposite direction as the yaw rate, making the damping nature of the controller quite clear. In the understeer case, however, the stability controller increases the yaw rate. If we do not compensate for the effect of the differential braking terms on the longitudinal motion, however, the overall system exhibits damping.

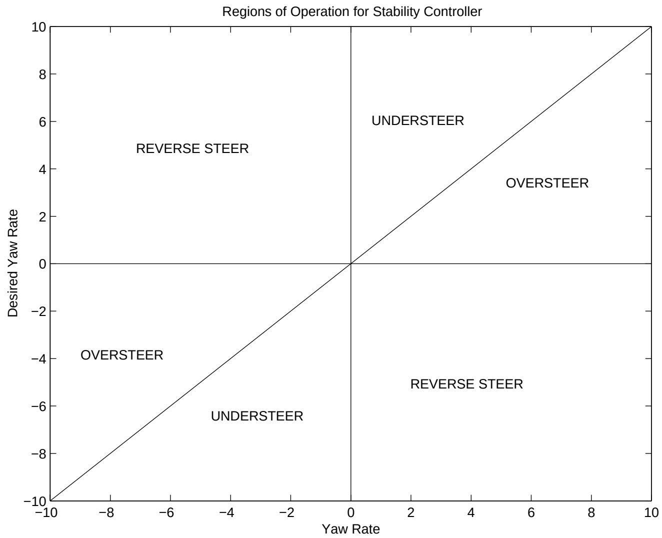

Figure 4. STABILITY CONTROL REGIONS OF OPERATION

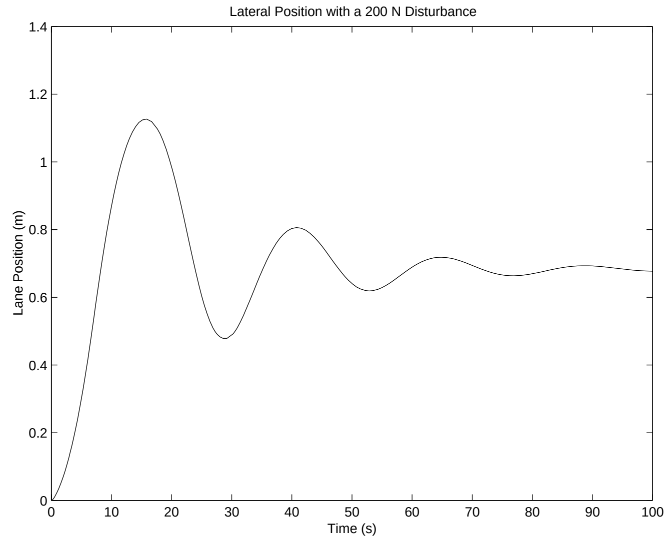

Figure 5. RESPONSE WITH SIDE WIND DISTURBANCE

Therefore, defining the damping function, F by

$$F(w,\dot{q},u_d) = \begin{bmatrix} \frac{2}{d}\gamma|r_{des}-r| \\ 0 \\ \gamma(r_{des}-r) \end{bmatrix} \quad (19)$$

$$\dot{q}^T F(w,\dot{q},u_d) = r\left[\gamma(r_{des}-r)\right] - 2\frac{U_x}{d}\gamma|r_{des}-r| \quad (20)$$

This expression is less than zero whenever the vehicle is operating in the oversteer or reverse steer regions described above or when the vehicle is operating in the understeer region with:

$$|r| \leq \frac{2U_x}{d} \quad (21)$$

Physically, this corresponds to an instantaneous turning radius greater than half of the track width. Cases where the vehicle is understeering the desired yaw rate while achieving a turning radius of less than half of the track are, to say the least, rare. From a mathematical standpoint, the controller can be shut off under these conditions to guarantee damping; from a practical standpoint, such a modification will not impact the stability control at all.

While omitted here for simplicity, more realistic features for a stability control system can be added in this framework. Among such enhancements are braking of the front wheels, a threshold level of mismatch between r and r_{des} before the system activates and ensuring that the system does not attempt to track values of r_{des} that cannot be achieved under the current friction conditions (Alberti and Babbel 1996). Additional stabilization based upon the vehicle sideslip angle can also be added within this framework, since counteracting sideslip is comparable to damping on U_y.

Simulation Evaluation

Although the system presented here is quite straightforward to design, there is no evidence that the resulting dynamics can easily be controlled by a driver. To examine this, we investigated both the response of the system to a disturbance (with no driver input) and the performance in two different lane change maneuvers. The simulation model included the nonlinear trigonometric terms in the vehicle equations of motion, though maintained the linear tire model and ignored the lateral/longitudinal coupling of tire forces.

Disturbance Rejection

Figure 5 shows the system response for a step disturbance of a 200N lateral force applied to the vehicle. This disturbance corresponds to a side wind of about 20mph acting at the vehicle cg. As can be seen from the plot, the vehicle remains within the lane with this disturbance. The response shows a very slow oscillation due to the flatness of the potential function in the lane center and the lack of damping in the potential fields. Such an oscillation could easily be corrected by the driver, though damping could also be added to remove energy from the vehicle while it is in the potential field. This choice is ultimately one of driver acceptance.

Parameter	Symbol	Value
Gain	K_{drv}	0.035
Time delay	τ_d	0.2 s
Neuromuscular Lag	τ_n	0.2 s
Lead Constant	τ_1	10 s
Lag Constant	τ_2	0 s
Preview Time	T_p	0.5 s
Steering Ratio	K_{steer}	20.3

Table 1. DRIVER MODEL PARAMETERS

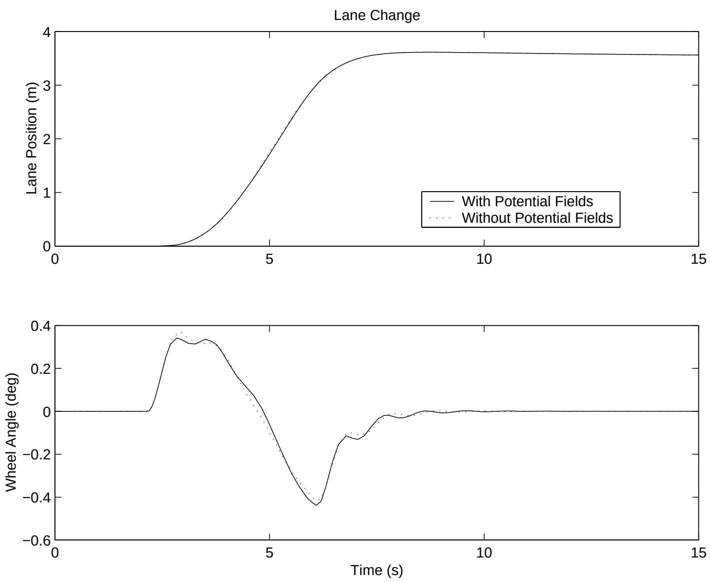

Figure 6. GENTLE LANE CHANGE RESPONSE

Lane Changes

The driver model used in this study was obtained from Cooke *et al.* (1996) and possesses the "cross-over model" form:

$$\Delta_d(s) = K_{drv}\left(\frac{\tau_1 s+1}{\tau_2 s+1}\right)\left(\frac{1}{\tau_n(s)+1}\right)e^{-\tau_d s} \qquad (22)$$

with the parameters in Table 1. To evaluate the driveability of the controlled system, a sinusoidal lane change trajectory was fed through the driver model at a speed of 20 m/s. Figure 6 compares the lateral position and driver input for the uncontrolled vehicle and the vehicle with potential fields added. The two responses are strikingly similar. This result is very encouraging, suggesting that driving in the potential field does not require or provoke a substantially different response from the driver (to the extent that the driver model incorporated here reflects a true human response). The trajectory is also quite similar, suggesting that a potential field capable of lanekeeping in the presence of disturbances is not overly obtrusive in normal driving. One issue not answered by these simulations, however, is the whether or not the force generated by the vehicle controller should in some manner be fed back to the driver through the steering wheel.

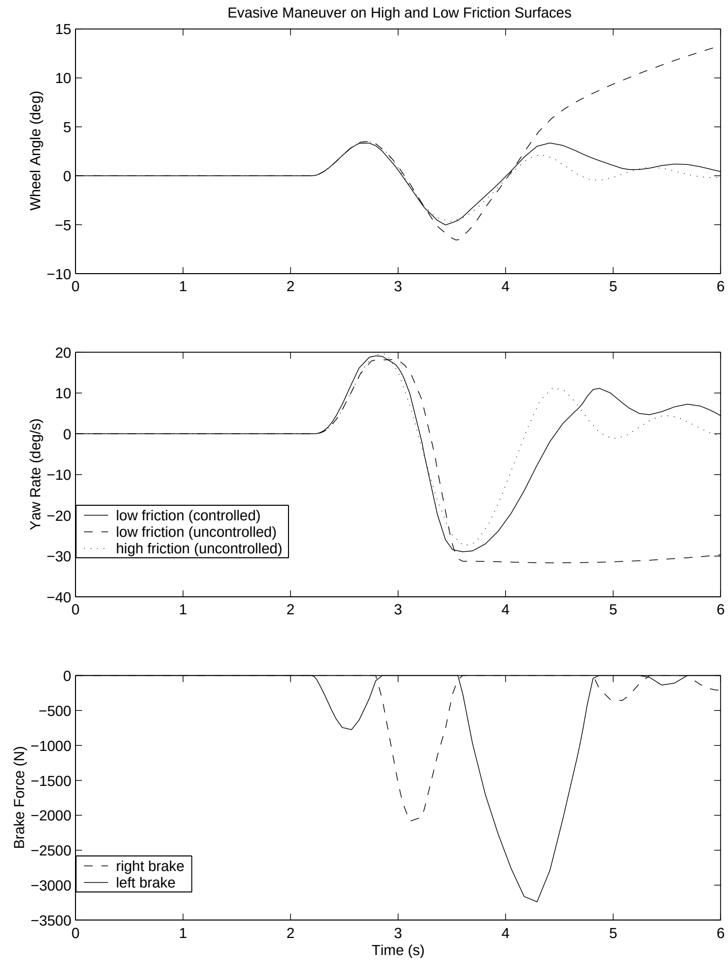

Figure 7. AVOIDANCE MANEUVER RESPONSE

To analyze the effect of the stability controller, an avoidance maneuver consisting of a double lane change was also examined. Figure 7 shows this maneuver under three sets of conditions. For a high friction road surface corresponding to a dry road, the driver is able to successfully execute the maneuver. When the friction is reduced to a peak value $\mu = 0.4$, however, the vehicle spins, as indicated by the constant yaw velocity of approximately -30 deg/s. With the addition of the stability controller, the driver is again able to successfully execute the avoidance maneuver. Comparison with published results (Alberti and Babbel 1996) shows that the controller response is indeed reasonable.

Conclusions

This paper outlines the rationale for, and a first application of, a unified approach to driver assistance based upon artificial potential fields. Such an approach offers an intuitive means of creating a nominally safe operating environment for the vehicle while keeping the driver in control. A key advantage is the ability to integrate vehicle control systems through simple addition of potential and damping functions. Early simulation results give encouragement that a balance between nominally safe behavior and driveability can be struck in such a system. Current work includes retention of nonlinear dynamic terms in the proof of nominally safe behavior, incorporation of more realistic tire dynamics and stability control objectives and extension to other vehicle states (such as roll).

REFERENCES

Alberti, V. and E. Babbel (1996). Improved driving stability by active braking of the individual wheels. In: *Proceedings of AVEC 96, Aachen University of Technology, June, 1996*. pp. 717–732.

Chen, C. and M. Tomizuka (1996). Passivity-based nonlinear observer for lateral control of tractor-trailer vehicles in automated highway systems. In: *Proceedings of the 1996 IFAC, San Francisco, CA*. pp. 273–278.

Cooke, R.J., D.A. Crolla and M. Abe (1996). Combined ride and handling modelling of a vehicle with active suspension. In: *Proceedings of AVEC 96, Aachen University of Technology, June, 1996*. pp. 1037–1053.

Guldner, J. and V.I. Utkin (1995). Sliding mode control for gradient tracking and robot navigation using artificial potential fields. *IEEE Transactions on Robotics and Automation* **11**(2), 247–254.

Hennessey, M., C. Shankwitz and M. Donath (1995). Sensor based 'virtual bumpers' for collision avoidance: Configuration issues. In: *Proceedings of the SPIE*. Vol. 2592.

Khatib, O. (1986). Real-time obstacle avoidance for manipulators and mobile robots. *International Journal of Robotics Research* **5**(1), 90–98.

Koepele, B. and J. Starkey (1990). Closed-loop vehicle and driver models for high-speed trajectory following. In: *Transportation Systems - 1990 ASME WAM, Dallas, TX*. pp. 59–68.

Krogh, B. (1984). A generalized potential field approach to obstacle avoidance control. In: *Proceedings of the SME Conf. Robotics Research, Bethlehem, PA*.

Reichardt, D. (1996). *Kontinuierliche Verhaltenssteuerung eines autonomen Fahrzeugs in dynamischer Umgebung*. PhD thesis. Fachbereich Informatik der Universitaet Kaiserslautern.

Reichardt, D. and J. Schick (1994). Collision avoidance in dynamic environments applied to autonomous vehicle guidance on the motorway. In: *Proceedings of the IEEE Intelligent Vehicles Symposium, Paris, France*.

Wilson, C.K.H., S. Rogers and S. Weisenburger (1998). The potential of precision maps in intelligent vehicles. In: *Proceedings of the IEEE Intelligent Transportation Systems Conference, Stuttgart, Germany*.