Development of a Haptic Feedback Transition Algorithm for Lane Changes

Using Neuromusculoskeletal Modeling

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Overview

1. Introduction
2. Problem Statement & Research Questions
3. Our Approach
4. Cybernetic Model
5. Results, Accomplishments & Conclusions
1. Introduction

Road Safety Systems
Haptic Feedback
Lane Keeping Support System
Key Research Questions
Road Safety Systems

Improving Road Safety

- Passive safety systems (seatbelts & airbags)
- Active safety systems (ABS & ESC)
  - Task automation (ACC)
  - Response automation (LDWS)
Current Active Safety Systems

Disadvantages

- Task automation systems:
  Driver is taken out of the control-loop.

- Response automation systems:
  - discrete warnings [1]
  - reliability issues [2]


Active Safety System that provides Haptic Feedback
Guidance via the Sense of Touch

- Driver always stays in control.
- Decrease of visual demand.
- Increase of performance.

Haptic Feedback Modalities [4]
Guidance via the Sense of Touch

- Torque Feedback ($T_t$)
- Stiffness Feedback ($K_s$)

Lane Keeping Support System [4]

- Supports lateral control of cars.
- Provides continuous haptic feedback.

Intelligent Driver Support System

Present & Future

- Present support: lane keeping
- Future support: lane changing & obstacle avoidance
What is Haptic Feedback?
An Application Currently under Development

- Haptic Steering Wheel Guidance
  - Lane keeping assist
- Continuous Haptic Feedback

Salucchi & Gray (2004); Land & Lee (1994)
The Problem

- Continuous Haptic Steering Wheel Guidance
  - Lane keeping assist

- What happens when you want to change lanes???
The Problem

- Continuous Haptic Steering Wheel Guidance
  - Lane keeping assist

- What happens when you want to change lanes???

- Lane keeping and lane changing are two mutually exclusive tasks
  - But we want to be able to provide continuous haptic feedback
Key Research Questions

- How can the haptic feedback algorithm be designed such:
  - that it doesn’t restrict drivers in making lane changes,
  - while preventing safety degrading lane deviations?

- Can the current LKSS be extended such that the haptic guidance transitions smoothly from one supporting task to another?
Our Approach

- **Lane Keeping Support**
  - Traces lane center
- **Lane Change Support**
  - "reroutes" the lane center
Our Approach: Lane Change Algorithm

Intelligent Driver Support System

Car States & Position

Lanes

LCA

Reference Lane

Future Lane

vdr(t) [m] +

Car States & Position

Current Lane

Reference Lane

Current Lane

T_{idss}
Research Approach

- Human-centered approach: development of the LCA taking the driver into account (neuromusculoskeletal modeling).

- 3-step design cycle [5]

2. Cybernetic Model

- Why is it needed?
- What does it comprise?
- Obtaining Model Parameters
- Simulations
Why is the cybernetic model needed?

Need & Requirement

• Need:
  • To assess the haptic support algorithm.
  • To learn how haptic support affects the driver steering behavior.

• Requirement:
  • The model should include interactions between:
    • Driver
    • Steering Wheel Dynamics
    • Car Dynamics
    • IDSS (LKSS & LCA)
Cybernetic Model
Cortical Control

Driver Model

- Preview controller [6] that minimizes the error of the car w.r.t. a reference path: $U_{ssi} = f(e_{ref})$.
- Can perform two tasks: lane keeping & lane changing.

Virtual Desired Reference [7]
Cortical Control Model

\[ v_{dr}(t) = -\frac{d_y}{2\pi} \sin\left(\frac{2\pi}{t_{lc}} t\right) + \frac{d_y}{t_{lc}} t \]
\[ a_{cc}(t) = \frac{2\pi d_y}{t_{lc}^2} \sin\left(\frac{2\pi}{t_{lc}} t\right) \]
\[ j_{erk}(t) = \frac{4\pi^2 d_y}{t_{lc}^3} \cos\left(\frac{2\pi}{t_{lc}} t\right) \]

- Lateral acceleration < 2 m/s²
- Lateral jerk < 2.5 m/s³

Neuromusculoskeletal Model [8]  

Driver Model  

- Models the physiological properties of the human arms.  
- It is modeled as an endpoint admittance.

Steering Wheel Dynamics

Car Model

- Mass-spring-damper system
- The constant stiffness represents the centering behavior of the steering wheel.

\[ H_{adm}^{sw}(s) \]
Vehicle Dynamics

Car Model

- 2 DOF bicycle model
- Linear tire dynamics

\[ H_{\theta_{sw}, V_y}(s) = \]

\[ H_{\theta_{sw}, \psi}(s) = \]
Parameters of the NMS Model

How are these obtained?

- The parameters are obtained with a System Identification and Parameter Estimation (SIPE) analysis.
- Data sets from experiments conducted at DUT are used, where drivers performed classical tasks behind a steering wheel.

- Classical tasks:
  - Position Task
  - Relax Task
  - Force Task

SIPE Results

\[ VA F = \left(1 - \frac{\sum_{k=1}^{N} |y(t_k) - \hat{y}(t_k)|^2}{\sum_{k=1}^{N} |y(t_k)|^2}\right) \times 100\% \]
Human-car Model
Simulating an Unsupported Lane Change

![Graph showing simulated lane change](image-url)
Human-car Model with LKSS
Simulating a Lane Change with LKSS support
3. Lane Change Algorithm

Philosophy
Modules
Simulations
Recapitulation

• Lane Keeping Support System provides haptic support for lane keeping (LK).

• The Lane Change Algorithm should make it possible to have a smooth transition of haptic support.

• The Lane Change Algorithm should be designed such that it extends the current LKSS.
LCA Philosophy

Behind the LKSS

- Advantage: freedom to manipulate the haptic guidance directly
- Disadvantages: It is complex to merge two haptic guidance signals.
LCA Philosophy

In Front of the LKSS

- Advantage: straightforward approach.
- Disadvantage: haptic guidance cannot be manipulated directly.
LCA Modules

- Lane module determines the current lane and when a LC has been completed.
- TLC module predicts in which amount of time the car is leaving the current lane and gives a flag when, TLC < T_{lcm}.
- Reference lane module adds a VDR to the current lane when a LC occurs (TLC < T_{lcm}).
Cybernetic Model Simulation Result

Supported Lane Change

- \( K_{sw} \) [Nm/rad]
- \( T \) [N]
- \( \theta_{sw} \) [deg]
- \( Y_o \) [m]
- \( TLC_{flag} \) [Hz]
Unsupported vs. Supported
Required Steering Input from the Driver
4. Proposed IDSS investigated in more detail

Effect of LCA on the LK support function?

Effect of different NMS settings on IDSS effectiveness?
Accomplishments

• A cybernetic model has been constructed that can be used to design haptic feedback support systems

• A haptic transition algorithm has been developed that smoothly transitions the haptic feedback from LK to LC and vice versa.

• The developed LCA allows the driver to make lane changes while still letting the LKS function properly
Accomplishments after Graduation

• Fixed-base driving simulator experiment

Conclusions

• Simulations indicate that during a supported lane change the required steering torque is higher in the beginning (up to 15%)
  • Confirmed in driving simulation experiment
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  - No change observed in driving simulation experiment
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  - The algorithm sometimes did not properly anticipate the driver’s behavior
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- The LCA is compatible with different NMS systems, which indicates that it is compatible for different drivers
  - The LCA did not significantly change the execution path of the lane change
Questions
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System Identification

**SIPE**

- Obtain a non-parametric frequency response function (FRF).
- Choose a model (NMS model) to fit on the FRF.

ARMAX estimation averaged over eight subjects

Raw spectral estimation averaged over eight subjects
Influence of LCA on the Lane Keeping Support Work Domain

- IDSS supports lane change when TLC < T_{lcm}.

\[ K_0 = 4.2 \text{ [Nm/rad]} \]
\[ K_t = 1 \text{ [-]} \]
\[ K_{\psi, future} = 0.3 \text{ [rad/m]} \]
\[ K_{\psi, present} = 0.3 \text{ [rad/ rad]} \]
\[ K_{\psi, present} = K_0 \text{ [Nm/rad/m]} \]
Influence of Different NMS Model Parameters on IDSS Effectiveness

Compliant Driver

Less Compliant Driver

Magnitude

Magnitude

\( y_g \) [m]

\( \alpha_y(t) \) [m/s^2]

\( j_y(t) \) [m/s^3]
Parameter Estimation

SIPE

- Minimizing the error between the parametric transfer function and the non-parametric FRF:
  - Lsqnonlin() in Matlab, is used.
  - Initial parameter values chosen randomly.
  - Constraints: (initial) parameter > 0.

- Obtained parameters values were comparable to an independent study, [9].

Chosen LCA Philosophy

In Front of the LKSS

• Initiated based on the time to line crossing (TLC), [10].
• In order to initiate the LCA and to keep it activated: TLC < $T_{lcm}$.
• Two values of the threshold $T_{lcm}$ are used: DI on/off.
• VDR is chosen for a five-second lane change.