A Control Architecture for Rendering Passive and Active Whole-body Coordination in Driving Tasks

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I. Introduction

The development of vehicle and driver-assistance technology have motivated the high-fidelity modeling of humans for driving tasks. Such realistic simulations of passive and active driver behavior when maneuvering a vehicle not only enhances the understanding of driver's limitation and preference in various driving scenarios but also contributes to the improvement of the usability and intelligence of the driver-assistance system, as well as the vehicle's ergonomics and safety. Previous research on mathematical modeling of the human driver has investigated the neuromuscular dynamics of the human arm when holding a steering wheel, and proposed a closed-loop control framework for rendering multi-joint coordination in steering control for path following [1], [2]. Further in [3], neuromusculoskeletal dynamics was incorporated in this control framework to address the muscle reflex dynamics for disturbance rejection. In addition to driving task reasoning and driver/vehicle motion control, a mathematical human model may also account for a driver's cognitive behavior and performance according to psychological principles and insights. In [4], a hierarchical framework was proposed as a cognitive architecture that incorporates a driver model with the components for vision-based vehicle control, environment monitoring, and vehicle maneuver decision making.

This paper focuses on rendering a driver's passive and active motion in response to the dynamics of the vehicle under maneuver. For many driving tasks, a driver needs to coordinate the motion for gas/braking pedaling with steering control, which results in complex motion response ranging from passively maintaining body posture to actively maneuvering the vehicle according to traffic and road condition. So far, there is limited investigation on the whole-body coordination that involves both passive and active motion reflex/control. In [5], the whole-body coordination was studied for complex balancing tasks [6], yet it is still unclear how to render the active maneuver motion control in response to the environment. In this paper, we propose an integrated control framework for rendering whole-body coordination in physical interaction between human driver and the vehicle in typical driving scenarios. The aim of this study is to understand how the human motor control system coordinates the torso, upper and lower limbs when maneuvering a vehicle (i.e. steering wheels and pedals respectively) in normative driving scenarios. The contribution of our work include: (1) integrating OpenSim human model [7] to realistically simulate human dynamics, and (2) developing hierarchical closed-loop motion control to realistically simulate the driver's passive and active whole-body coordination.

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II. The Proposed Framework for Human Driver Model

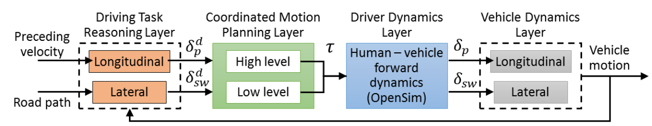

Fig. 1: Control framework for whole-body driver control in driving tasks

This study aims to model human driver's reactive motions with high-fidelity in normative driving scenarios. Such reactive motions are rendered by two interactive controllers: one for controlling longitudinal and lateral motions of the vehicle for the scenarios (i.e., lane following, braking, turning, etc) and the other for controlling the dynamic simulation of human driver behaviors in current scenario. In our proposed model (see Fig. 1), these two controllers are integrated into a four-layer framework. The **driving task reasoning layer** computes the desired pedal angles δ_p^d for longitudinal motion control and the steering wheel angle δ_{sw}^d for lateral motion control [8], while the **coordinated motion planning layer** computes the corresponding joint torques τ in the whole-body coordination. The **driver dynamics layer** uses OpenSim whole-body musculoskeletal model to simulate the human driver's forward kinematics and dynamics, and the resulted maneuver motions. It also estimates the muscle-level actuation, which can be used to analyze the comfort/potential injury resulted from the driver's reactive motion. The driver's commanded pedals δ_p and steering wheel δ_{sw} angles, resulted from the maneuver motions computed in the driver dynamics layer, are feed to the vehicle dynamics layer.

OpenSim Driver and Vehicle Cockpit Model: To investigate the dynamics in the interaction of driver and vehicle, we integrate a whole-body human musculoskeletal model (37 DOFs) with a vehicle cockpit model in OpenSim. The human model is integrated with OpenSim models for the neck, lumbar spine, and upper and extremities. The vehicle cockpit model is also converted from a finite element (FE) model of a passenger vehicle [9]. The Pelvis part of the driver model was mounted on the seat cushion of vehicle cockpit model with a ball joint. Contact interfaces were defined on the top surface of pedals, seats, and floor as well as feet, leg, buttock, and torso of the human driver.

The Motion Control for Human Driver Model: The proposed driver model uses two controllers to simulate the the low-level and high-level human motion control. Our two-level control architecture is proposed based on the following hypotheses on human motor system: (1) human motions are realized by blending the decentralized PD control and centralized control signals in a provably stable way; and (2) a switching between decentralized to centralized control will occur in the transition between tasks that requires different driving skills — for example, a switching from decentralized to centralized control will be triggered in the transition from lane following to turning at the intersection. In the two-level control architecture, the low-level motion control was represented with a decentralized proportional-derivative (PD) controller in joint space. It minimizes the differences between desired and commanded joint angles and rotational velocities, so the driver can reach to and stabilize at the desired body posture, as if in set point tracking control. At runtime, the distributed controller continues to balance the body posture against perturbation and disturbances to the vehicle.

The high-level controller is essentially a task-based centralized controller, which intends to track desired hand/foot trajectories according to the desired pedal angles and steering wheel angle that the driving task reasoning layer commands. As in Eq. (1) the centralized control will joint torque τ via the coefficients K_p and K_D for whole body dynamics.

$$\begin{aligned} \tau &= M(q)[J(q)^{-1}(a_x - \dot{J}(q)\dot{q})] + C(q,\dot{q})\dot{q} + N(q) + J_c^T F_c \\ a_x &= -K_P(x - x^d) - K_D(\dot{x} - \dot{x}^d) + \ddot{x}^d \end{aligned} \quad (1)$$

In Eq. (1), q is the state variables in joint space, x is the state variables in task space, x^d is the desired position in task space, M is the inertia matrix, J represents the system Jacobian matrix, C is the Coriolis matrix, N is the matrix for gravity forces, J_c is the contact Jacobian, F_c captures the contact forces, K_P and K_D are constant gain matrices.

For higher computational efficiency, we propose to apply decomposition approaches or cascade control structure to the high-dimensional human models. Depending on the nature of driving tasks, the whole-body human model can be considered as a cascaded structure of upper and lower body and therefore decoupled in control. Leveraging the different control approach and model decomposition, we may improve simulation fidelity at lower computational cost. We may also consider decoupling the control of the driver's passive and active upper and lower body motions if they are not highly correlated. For instance, in acceleration/deceleration along a straight road, we may decouple the control for gas pedaling and for balancing of driver body at a safe and comfortable posture by holding steering wheel.

III. Preliminary Results

Our preliminary work has implemented the distributed controller for maintaining human body posture when maneuvering the vehicle to follow another vehicle on a straight road. The driver's responsive motion, with and without the distributed control are compared in OpenSim simulation ($t = 3$ sec). In our simulation, the commanded pedal angles was determined using simple linear time delay model as in [8]. A decentralized PD controller (i.e., the lower-level controller) for the human driver body was implemented to maintain the driver's initial posture under the disturbances caused by vehicle motion. Shown in Fig. 2, the 7th cervical vertebra in the un-controlled model deviated from it's initial position in the lateral direction (the z-direction of the model), while the controlled model could keep up the 7th cervical vertebra to its initial position. Full simulation result can be obtained through the link: `https://goo.gl/t851y8`. In future work, we will implement centralized controller and study the mechanism between decentralized and centralized control. We will also investigate methods for task-based modeling decomposition and decoupled control to improve computational efficiency.

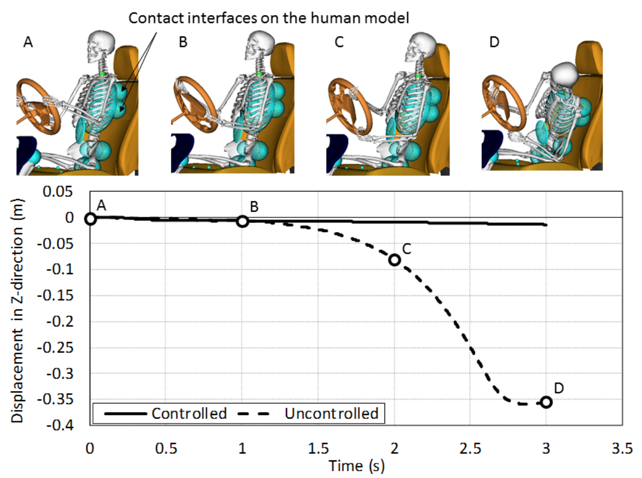

Fig. 2: Displacement of center of mass of the 7th cervical vertebra in the z-direction with and without distributed PD controller.

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