A Design Tool for Operator–Adaptive Steering Controllers

W. R. Norris, Q. Zhang, R. Sreenivas, J. C. Lopez–Dominguez

Abstract. *One of the major deterrents of designing a control system for interactive use with an operator is the lack of a systematic procedure for modeling and incorporating human behavior directly into the design process. In many cases, direct operator feedback is difficult for qualitative design without a costly, full–scale physical prototype. The objective of this article is to present a modular framework, known as virtual design tools, to design the electrohydraulic steering system of off–road vehicles. The aim was to adapt the electromechanical interface between the operator's command signal and the fixed control and dynamic systems. The adaptation was performed with the intent of modifying the system performance to be more acceptable to the operator without altering the control system or vehicular components. This conceptual design tool was studied via a computer simulation for designing an operator–adaptive steering controller for an articulated off–road vehicle. The simulation results indicated that this "operator–in–the–loop" design method could successfully incorporate human behavior in the controller design process using the virtual design tool.*

Keywords. *Fuzzy logic, Neural networks, Operator–in–the–loop, Virtual design, Virtual machine, Virtual operator, Virtual trainer.*

This article presents an innovative control system design tool, the operator–in–the–loop (OIL) interactive control system design tool. This interactive OIL design tool is capable of incorporating human performance behaviors in the controller design process to make steering controllers adaptive to operator's driving habits for realizing optimal steering performance. This OIL design process is based on a virtual design technology that allows a new design to be tested and improved in a virtual environment before the building of a prototype. Therefore, it is both technically and economically attractive (Purschke et al., 1998). To make the OIL design process applicable in an industrial control system design process, there are a few obstacles to overcome. The first obstacle is to provide a satisfactory virtual design environment. This requires packaging the control dynamics and control interfaces with the operator to provide a video–like realistic and dynamic graphical design environment. The second obstacle is the need for a trainable real–time model to represent human operator performance consistently. The third obstacle is the need for an appropriate adaptive algorithm that adjusts the control system parameters automatically for realizing optimal machine performance.

This article introduces the fundamental concepts of a novel control system design method that incorporates human operator behaviors in the design process. To effectively present these concepts, an introduction of the topology design and operation principles of the OIL design tool is presented. The next section describes the major components of the OIL design tool. System integration and simulation evaluation of the OIL design tool are then illustrated. The illustrative application shows the design of a steer–by–wire control system for an articulated off–road vehicle.

Topology of the OIL Design Tool

The OIL control system design tool consists of a learning loop and a design loop. Figure 1 illustrates the system topology of the OIL control system design tool developed to design the steer–by–wire control system for an articulated off–road vehicle. The core loop of the OIL design tool consists of a virtual operator, a virtual vehicle, and a virtual road. The virtual operator is designed to create different driving behaviors of human operators in an attempt to drive an articulated off–road vehicle along a desired path. The virtual vehicle consists of a steering controller and a vehicle dynamics model to represent the responses of the vehicle to the operator's driving behavior. The virtual road is a predefined desired path for the vehicle. Switches S1 and S2 (fig. 1) can either be set to train the virtual operator using the steering error between the virtual vehicle and the virtual road or to engage the virtual designer to optimize the steering controller based on the steering error and the virtual operator's driving behavior. The virtual trainer is a machine–

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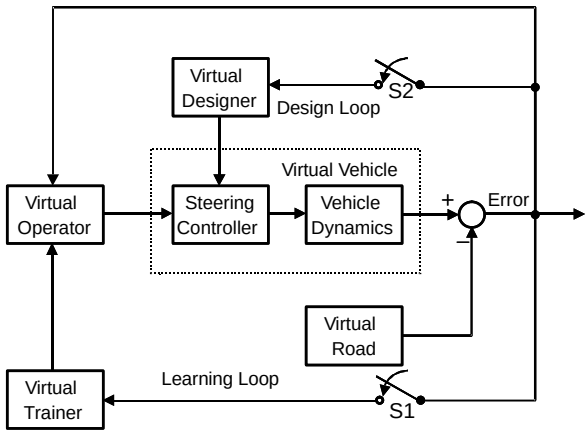


Figure 1. System topology for the operator–in–the–loop control system design tool developed for an off–road articulated vehicle steering control system.

learning algorithm designed to train the virtual operator to distinguish the steering pattern of a particular driver based on the characteristics of a feedback steering error. The virtual designer is an automated steering control optimizer that tunes the steering controller adaptively according to the operator's driving behavior. This OIL design tool is illustrated using the design process of an electrohydraulic steering controller for an articulated off–road vehicle, and it can be used for designing control systems for other applications by replacing the virtual vehicle and virtual road with appropriate plant and evaluation models.

The OIL design tool uses training, design, and implementation to perform the required functions. In the training phase, switch S1 is closed, switch S2 is open (fig. 1), and the virtual designer is disconnected from the loop. Therefore, the virtual vehicle (mainly the steering controller) is fixed in this phase. The feedback steering error (based on vehicle position, orientation, and trajectory) is determined by the differences between the outputs from both the virtual vehicle and the virtual road. The steering error is sent to both the virtual trainer and the virtual operator as the training sample to train a human decision–making model (HDMM), the core of the virtual operator. After being trained, the HDMM will be capable of providing a consistent steering pattern to represent certain driving behaviors of a human operator.

In the design phase, switch S1 is open, and switch S2 is closed. This deactivates the virtual trainer to provide a consistently trained virtual operator and activates the virtual designer to optimize the steering controller adaptively according to the detected operator's driving behavior. During the optimization process, the virtual designer will adjust the parameters in the steering controller according to the input steering signal from the virtual operator and the resulting errors in vehicle trajectory based on the current set of controller parameters. To incorporate human driving behaviors in the controller design process, an adaptive algorithm was used to adjust a valve modulation curve (VMC) of the electrohydraulic steering control system (Norris et al., 2002).

In the implementation phase, switch S1 is open, and switch S2 is closed, as in the design phase. The main differences between the design and implementation phases are that the virtual operator is replaced by a human operator, and the virtual designer is used to tune the controller parameters adaptively to a human operator's driving habit. This is done to accomplish the predefined steering operation in the implementation phase. During implementation, the virtual designer will continuously optimize the VMC in accordance with the operator's driving behavior and steering error.

Core Components of the OIL Design Tool

As discussed in the previous section, the core components of the OIL design tool include a virtual vehicle, a virtual road, a virtual operator, a virtual trainer, and a virtual designer. The following section introduces the principles and the design of these core components.

The Virtual Vehicle

The virtual vehicle consists of a steering controller and a vehicle dynamics model. The vehicle dynamics model provides vehicle trajectory responses to different steering inputs via simulation. The basic requirements for this model were to make it simple enough to perform real–time simulation but maintain necessary complexity to provide sufficient information for steering control optimization. A typical articulated off–road vehicle normally consists of four wheels, two separate frames, and an articulation joint (AJ) to link these frames. Because the engine in this type of vehicle is normally installed on one frame and its implement on another, the frame with the engine is often referred to as the engine–end–frame (EEF), and the other frame is often referred to as the non–engine–end–frame (NEEF). Two hydraulic cylinders are used to adjust the orientation of the NEEF and the EEF to steer this type of off–road vehicle.

The articulated vehicle steering dynamics model consists of a vehicle model, an electrohydraulic steering system model, and a tire dynamics model (Norris, 2001). With the constraints of performing the real–time simulation, the vehicle dynamics model was designed to exhibit the following characteristics: (1) the vehicle was modeled as two rigid bodies with a revolute joint, (2) the model was two–dimensional, (3) the vehicle was unloaded, (4) lateral slip was neglected, (5) the effects of dry friction and rolling resistance were incorporated, (6) cornering forces and moments were determined using Pacejka tire models (Bakker at el., 1987), (7) the hydraulic system model consisted of an electrohydraulic control valve and two hydraulic actuating cylinders, and (8) the steering system was assumed to be symmetric.

Figure 2 shows a top view of the articulated vehicle model, presented in free body diagrams in a global coordinate system. From Newton's laws, the sum of forces and moments were derived to represent the linear accelerations of the vehicle in the x and y directions. Based on a force analysis on both NEEF and EEF (Norris, 2001), the constraint equations arising at the pin (articulation joint) were expressed as:

$$x_F = x + CG_R \cos\theta_R + CG_F \cos(\theta_R + \theta_F) \quad (1)$$

$$y_F = y + CG_R \sin\theta_R + CG_F \sin(\theta_R + \theta_F) \quad (2)$$

where

x_F and y_F = position coordinates of the NEEF center of mass

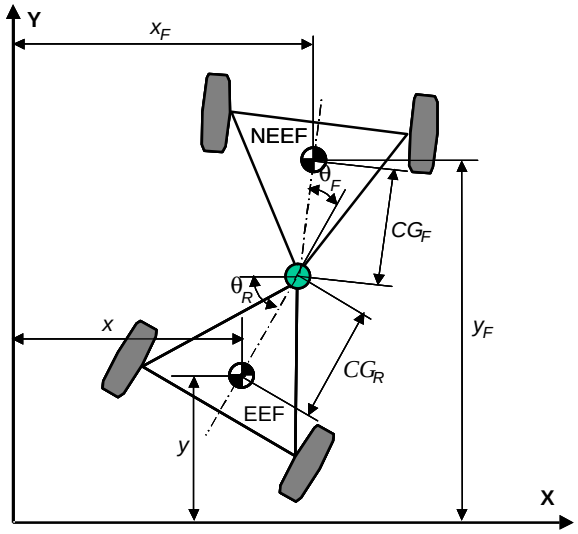


Figure 2. A top view of an articulated vehicle in a global coordinate system.

x and y = position coordinates of the EEF center of mass

θ_F and θ_R = orientations of the NEEF and the EEF frames in the global coordinate system

CG_F and CF_R = distances of the NEEF and the EEF frames to the articulation pin.

The electrohydraulic steering system in an articulated vehicle uses two hydraulic cylinders to control the articulation rate of the EEF and NEEF rotating around the AJ to accomplish the turning operation. The vehicle's articulation rate is controlled by regulating the direction and rate of the hydraulic flow to the steering cylinders. The steering actuating force is determined using a control volume approach. The following piston motion equations were used as the governing equations for the hydraulic steering system control (Norris, 2001):

$$\dot{P}_1 = \left(\frac{\beta_M}{V_1 + V_L}\right)\left(Q_{IN} + \dot{x}_{C1}A_2 - \dot{x}_{C2}A_1\right) \quad (3)$$

$$\dot{P}_2 = \left(\frac{\beta_M}{V_2}\right)\left(Q_{OUT} - \dot{x}_{C1}A_1 + \dot{x}_{C2}A_2\right) \quad (4)$$

$$Q_{OUT} = C_d A_V \sqrt{\frac{2(P_2 - P_T)}{\rho}} \quad (5)$$

where

A_1 and A_2 = piston head–end and rod–end areas, respectively

P_1 and P_2 = high and low cylinder pressures, respectively, dependent on the cylinder motion direction

P_T = tank pressure

V_1 and V_2 = volume of hydraulic fluid in the steering cylinders

V_L = volume of hydraulic fluid in the lines

β_M = bulk modulus of the hydraulic fluid

ρ = density of the hydraulic fluid

x_{C1} and x_{C2} = positions of cylinders 1 and 2, respectively

Q_{IN} and Q_{OUT} = flow rates entering and bleeding from the hydraulic cylinders

A_V = hydraulic control valve orifice area

C_d = orifice coefficient.

The tire dynamics of the articulated vehicle were determined based on the Pacejka tire model (Bakker at el., 1987; Norris, 2001). The following equations were used to determine the cornering force and tire self–aligning force for each tire on the articulated vehicle:

$$F_{Ci} = D_C \sin\{C_C \tan^{-1}[B_C\beta_T - E_C(B_C\beta_T - \tan^{-1}(B_C\beta_T))]\} \quad (6)$$

$$F_{Ai} = D_A \sin\{C_A \tan^{-1}[B_A\beta_T - E_A(B_A\beta_T - \tan^{-1}(B_A\beta_T))]\} \quad (7)$$

where β_T is the slide slip angle of the tire, and B_A, C_A, D_A, E_A and B_C, C_C, D_C, E_C are constants for cornering force and self–aligning force calculation.

The dynamic model of the articulated vehicle was implemented using MatrixX (Norris, 2001). It took 15 s to perform a 90 s vehicle maneuvering simulation with a 50 Hz sampling rate on an HP C180 workstation, which satisfied the real–time simulation requirement.

The steering controller in the virtual vehicle is represented using an adaptive VMC (fig. 3) of the E/H steering control valve for this illustrative application. The VMC converts the steering signal, generated either by a human or virtual operator, into the electrical control signal to actuate the solenoid valve drivers to implement the steering action. With on–line tuning using the virtual designer, the steering controller could be personalized to adaptively tune the VMC

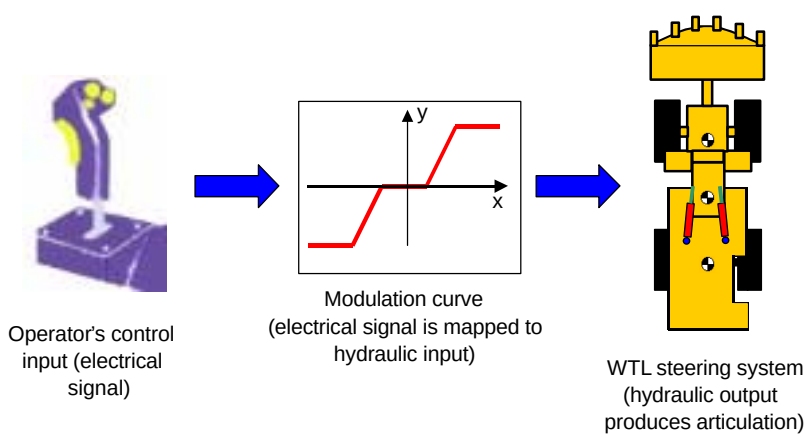


Figure 3. The valve modulation curve (VMC) commonly used for electrohydraulic steering control systems of off–road articulated vehicles.

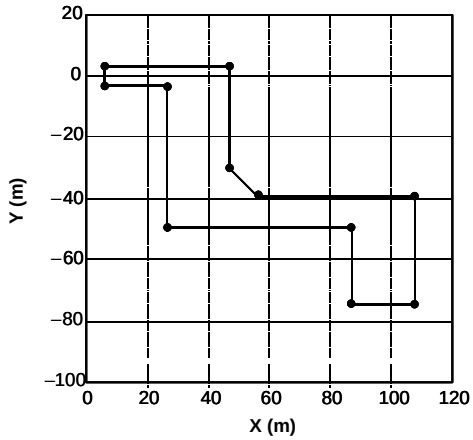


Figure 4. Steering performance test course for off–road rubber–tire vehicles as defined in SAE Standard J1511.

according to the human operator's steering style, resulting in optimal vehicle maneuvering performance.

The Virtual Road

The core of the virtual road is a predefined path for an articulated off–road vehicle to follow. The path is determined based on an SAE standard (SAE, 1994) steering test course for off–road rubber–tired machinery. Based on the predefined test path (fig. 4), the virtual road will generate a desired trajectory for the articulated vehicle to follow. Since the SAE standard requires the test course be made on a compacted or paved surface with a maximum grade of 3% in any direction, it is reasonable to ignore the effect of side slide in the determination of the desired trajectory.

In this research, the virtual road applied a series of equally segmented points to indicate the trajectory (fig. 5). There are two approaches that can be used to generate the trajectory in this virtual road: (1) recording an actual vehicle trajectory while driven by a human operator, and (2) generating an artificial trajectory using a trajectory planning model, as follows (Norris, 2001):

$$\theta_A = \sin^{-1}\left(\frac{L}{2r}\right) \tag{8}$$

$$y(n) = y(n-1) \pm L\sin(n\theta_A) \tag{9}$$

$$x(n) = x(n-1) \pm L\cos(n\theta_A) \tag{10}$$

where

θ_A = angle between the vehicle traveling direction and the road segment centerline

L = length of the road segment

r = radius of the curvature segment

n = number of road segments in the curvature from the vehicle

$x(\ )$ and $y(\ )$ = location of the vehicle in the global coordinate system.

The Virtual Operator

The virtual operator is a steering signal generating element that provides consistent steering signals representing certain driving behaviors to support the OIL control system design. The virtual operator is formulated using an error interpreter and an HDMM.

The error interpreter is designed to identify the position and orientation errors of the vehicle compared to the desired trajectory. Here, the vehicle is represented using two interconnected line segments with checkerboard circles indicating the locations of the AJ and the centers of gravity for EEF and NEEF (fig. 6). The identified errors will be transferred to the HDMM to determine appropriate steering control actions. By this approach, the vehicle model uses four degrees of freedom to identify four errors — offset (distance), orientation, heading angle (immediate), and heading angle (near) — used to describe vehicle position and orientation errors.

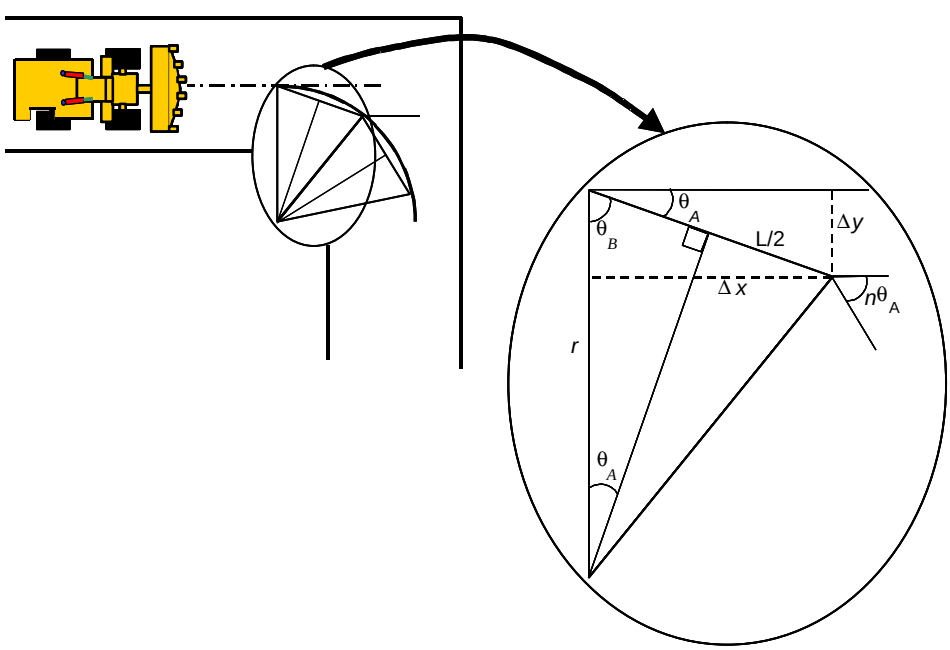


Figure 5. Variables and techniques used by the trajectory planner to generate the desired path.

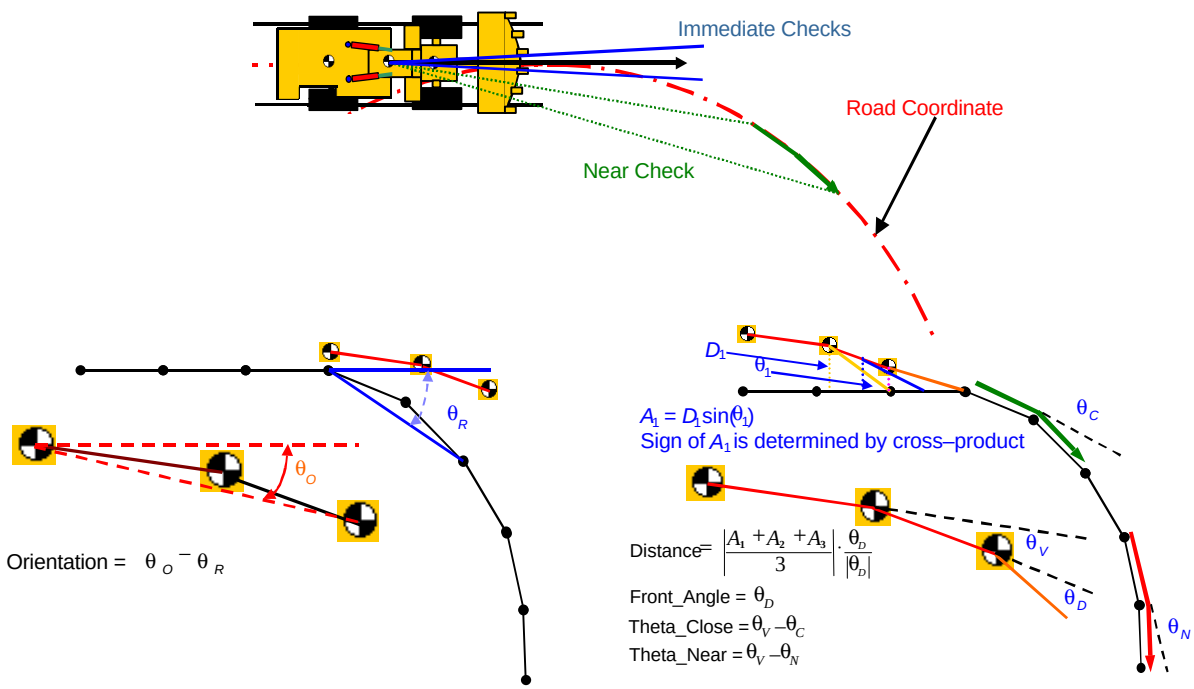


Figure 6. Illustration of the immediate check and the near check in error interpretation.

The offset error (E) is the average distance from the vehicle's AJ and CG positions to their corresponding positions on the reference segment along the required trajectory, defined as follows:

$$E = \left|\frac{A_1 + A_2 + A_3}{3}\right| \frac{\theta_D}{|\theta_D|} \tag{11}$$

where $A_i = D_i \sin(\theta_i)$ and $i = 1, 2, 3$ are vehicle offset errors at the AJ, the CGs at EEF, and NEEF, and θ_D is the front angle error between the NEEF center line and the desired path segment, as defined in figure 6.

The orientation error (O) is defined as the difference between the vehicle orientations related to global coordinates, as shown in figure 6, using the following equation:

$$O = \theta_O - \theta_R \tag{12}$$

where θ_O is the angle between the global x axis and the connecting line between EEF CG and NEEF CG, and θ_R is the angle between the global x axis and the connecting line between AJ and NEEF CG.

The heading angle (immediate) error (theta_close, H_C) is defined as the difference between the vehicle's articulation angle and the angle between contiguous road segments. The heading angle (near) error (theta_near, H_N) is gauged by the required change in the articulation angle to match the curvature further along the trajectory:

$$H_C = \theta_V - \theta_C \tag{13}$$

$$H_N = \theta_V - \theta_N \tag{14}$$

where

θ_V = articulation angle between EEF and NEEF

θ_C = relative angle between the referenced segment and the next segment in the trajectory

θ_N = relative angle between two contiguous road segments a distance away from the segments referenced by θ_C.

The HDMM is the core of this virtual operator and is developed based primarily on the judgment gained from the experience of a human operator. Therefore, a fuzzy estimation approach was applied in developing the HDMM. A Mamdani–type fuzzy reasoning process was employed to derive appropriate steering control actions in terms of a set of IF–THEN rules. Those rules represent the judgment laws for determining the importance of detected vehicle position and orientation errors related to the steering control goal, and optimal ways for minimizing the errors and keeping the vehicle on the desired path. For example, the distance error was selected as the primary factor for deriving steering actions. A few fuzzy reasoning rules were derived based on common sense knowledge to determine the appropriate steering actions, as follows:

IF offset is far left AND front angle is near left, THEN steer to right all the way.

IF distance is close left AND orientation is close left, THEN steer to right more.

IF distance is zero AND orientation is far left AND heading (immediate) is far left, THEN steer to right all the way.

Similarly, steering control reasoning rules were derived for all possible conditions of vehicle maneuvering. All the rules were derived based on heuristic knowledge that was drawn from the controller strategies. The objective for the fuzzy control reasoning rules was to steer the vehicle properly to bring and/or maintain the vehicle parallel to and at a minimum distance from the desired trajectory.

In developing these fuzzy reasoning rules, some colloquial terms were used to describe if an error is "acceptable," "close," or "far away" from an objective based on experience. Such daily language terms are defined as the linguistic variables in the fuzzy reasoning rules, and these linguistic variables contain some degree of uncertainty since it is very difficult, if not impossible, to measure what is "acceptable"

and "close." As the standard for Mamdani–type fuzzy systems, the HDMM used the MIN–MAX operation–based inference mechanism to support the decision making. The defuzzification method was the center of area with singletons for reducing the required computation effort with smooth outputs (Norris et al., 2001).

The Virtual Trainer

The virtual trainer was developed to tune the HDMM in the virtual operator based on a set of training data to formulate a consistent human–like vehicle maneuvering behavior. The training data were obtained by recording human operators' maneuvering patterns while driving the articulated vehicle. The training process for this application involved manually tuning the fuzzy membership functions for all linguistic variables used in HDMM fuzzy reasoning rules. The criterion for tuning the fuzzy membership functions was to minimize the output from the error interpreter. The fuzzy linguistic variables in this OIL design tool were mainly used to classify the vehicle position and orientation errors, such as *far left*, *close left*, *zero*, *close right*, and *far right*.

In this OIL design tool, Π, *Z*, and *S* type fuzzy membership functions (Lin and Lee, 1996) were chosen for various linguistic variables. The following are, respectively, the definition of Π, *Z*, and *S* type fuzzy membership functions:

$$\Pi(x,\alpha,\beta,\psi,\zeta)=\begin{cases} 0 & x\le\alpha \\ \dfrac{x-\alpha}{\beta-\alpha} & \alpha<x\le\beta \\ 1 & \beta<x<\psi \\ \dfrac{\zeta-x}{\zeta-\psi} & \psi\le x<\zeta \\ 0 & x\ge\zeta \end{cases} \tag{15}$$

$$S(x,\alpha,\beta)=\begin{cases} 0 & x\le\alpha \\ \dfrac{x-\alpha}{\beta-\alpha} & \alpha<x\le\beta \\ 1 & x\ge\beta \end{cases} \tag{16}$$

$$Z(x,\alpha,\beta)=\begin{cases} 1 & x\le\alpha \\ \dfrac{\beta-x}{\beta-\alpha} & \alpha<x\le\beta \\ 0 & x\ge\beta \end{cases} \tag{17}$$

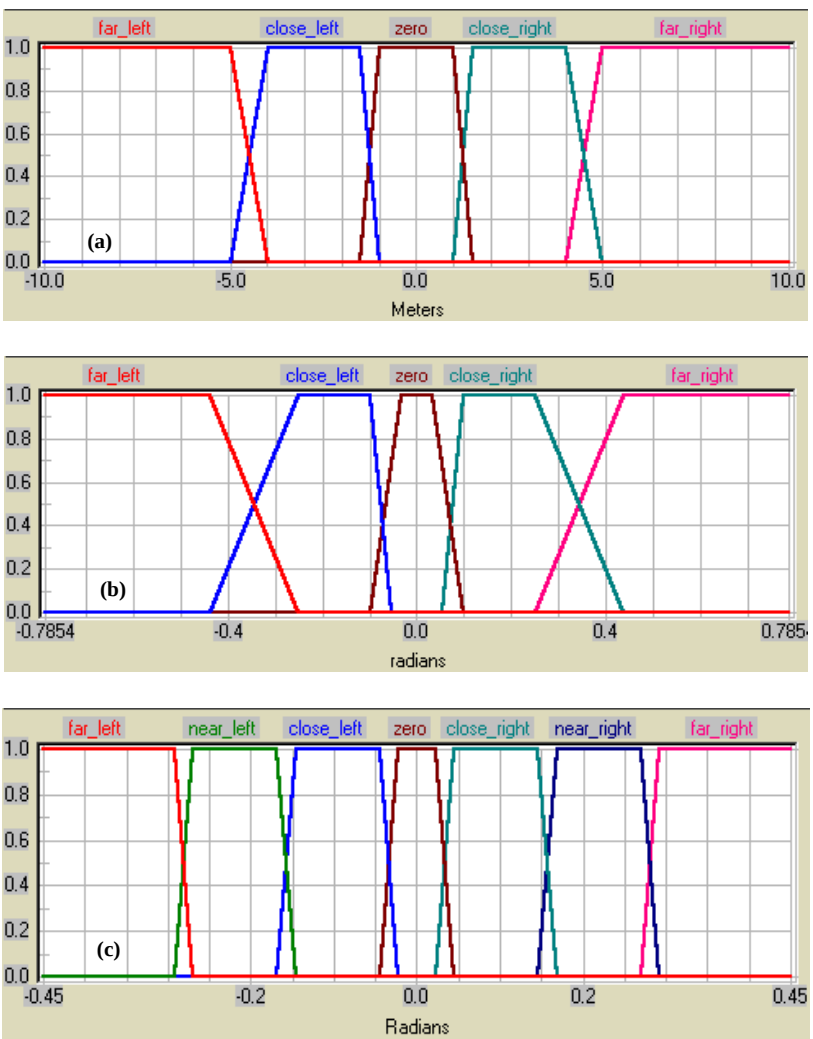


Figure 7. Defined domains of fuzzy membership functions for (a) distance error, (b) orientation error, and (c) heading (immediate) error.

where x is the real value of the independent variable, and α, β, ψ, and ζ are real–valued boundaries corresponding to linguistic values.

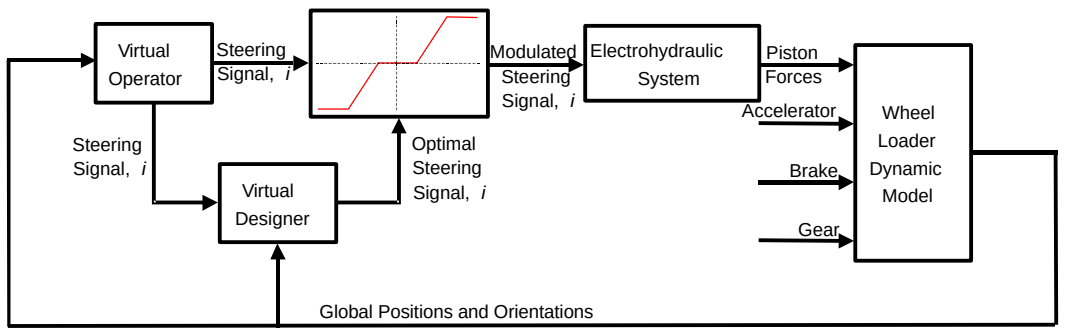
The intrinsic use of the Π, Z, and S type membership functions are to reduce the computational load. The quantity of pertinent rules can be significantly reduced when one or more inputs fall within the flat region of their respective Π, Z, and S type membership functions. The membership function parameters were tuned manually to minimize the maximum distance variation from a given trajectory (Norris et al., 2001). Figure 7 shows the tuned membership functions for the input variables and their interpretations.

The Virtual Designer

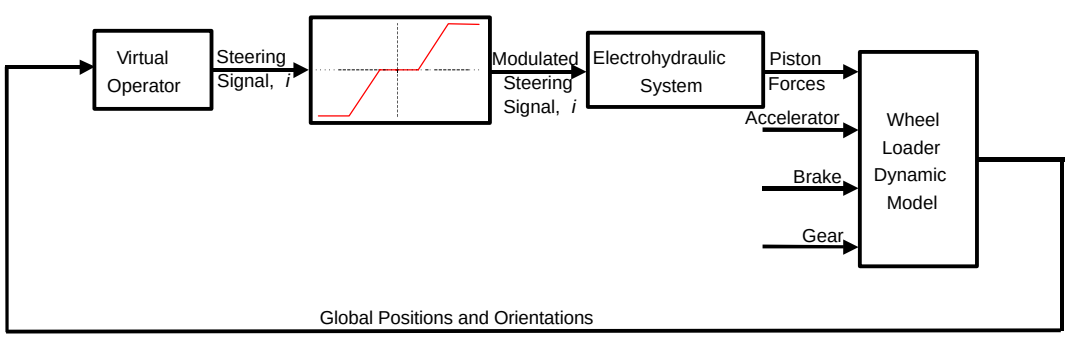
The OIL control system design tool is intended to provide, by practical means of design, a "personalized" steering controller for an articulated vehicle in order to achieve consistent and optimal steering performance regardless of the operator. This goal was accomplished by adjusting the VMC for the steering controller adaptively according to the operator's maneuvering habit.

The virtual designer was used to tune an augmented VMC (fig. 8). In this OIL design tool, the VMC used was parameterized as a two–dimensional and piece–wise continuous curve, mapping between the input electric steering signal and the steering actuating rate. The core algorithm of this virtual designer is a neural network emulator for performing the adaptive adjustment of the "personalized" VMC for the steering controller (Norris et al., 2002). The inputs to the neural network emulator include the steering command provided by the virtual operator, vehicle position, and orientation errors provided by the error interpreter. The emulator was trained off–line using steering commands and its corresponding error data (errors: offset, orientation, and heading angles) identified by the virtual operator. The trained emulator was capable of predicting future distance, orientation, heading angle (immediate), and heading angle (near) errors on–line.

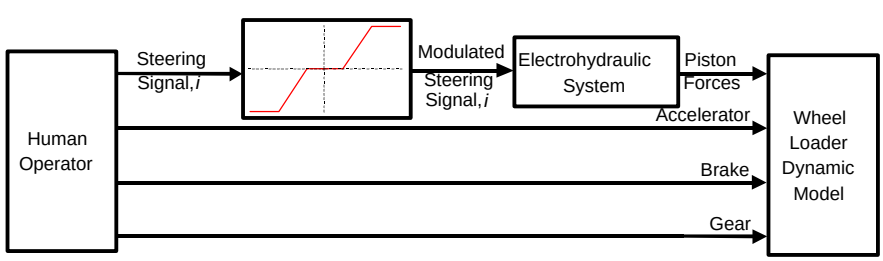
After being fully trained, the emulator was coupled with a global minimization function to determine the optimal VMC by means of evaluating alternative steering patterns through simulation. Steering signals created by the VMC would be evaluated using the emulator in simulation analysis. The virtual designer would adjust the VMC according to the simulation results for realizing minimum errors in both vehicle position and orientation.



(a) Training process



(b) Design process



(c) Implementation process

Figure 8. System structures of the virtual designer in different processes.

Integration and Validation of the OIL Design Tool

All core components described in the previous section were linked according to the topological scheme of the OIL control system design tool, as shown in figure 1. The essential integration tool to make the OIL design tool accomplish its goal is a human operator performance model (HOPM). The HOPM integrates the virtual road, virtual trainer, and virtual operator to provide consistent human–like steering signals to control the electrohydraulic steering system of the vehicle (Norris et al., 2002). Validation of the OIL design tool evaluated the capability of the HOPM to generate appropriate control signals of different steering styles to steer the articulated vehicle smoothly along the SAE test course. The criterion for passing the SAE course is that the HOPM can steer the vehicle along the test course at 16 ±2 kph without noticeable oscillation after completing the turns (SAE, 1994).

In the validation simulation, the virtual operator was tasked to steer the vehicle to pass the SAE course. Real–time simulations were performed using the MatrixX environment after the virtual designer was trained, and the virtual vehicle model was validated against vehicle test data. In the validation study, a 90 s vehicle steering implementation procedure on the SAE course was simulated at a 50 Hz sampling rate. It took 10.1 s to complete the validation simulation for the 90 s steering cycle, which satisfied the requirement for real–time simulation. In this validation, a minimization function ran the emulator neural network in forward mode, which adjusted the augmented VMC until the resulting vehicle position error was within a predefined error limit. The simulation analysis results indicated that the OIL design tool could quickly train the virtual operator, and the

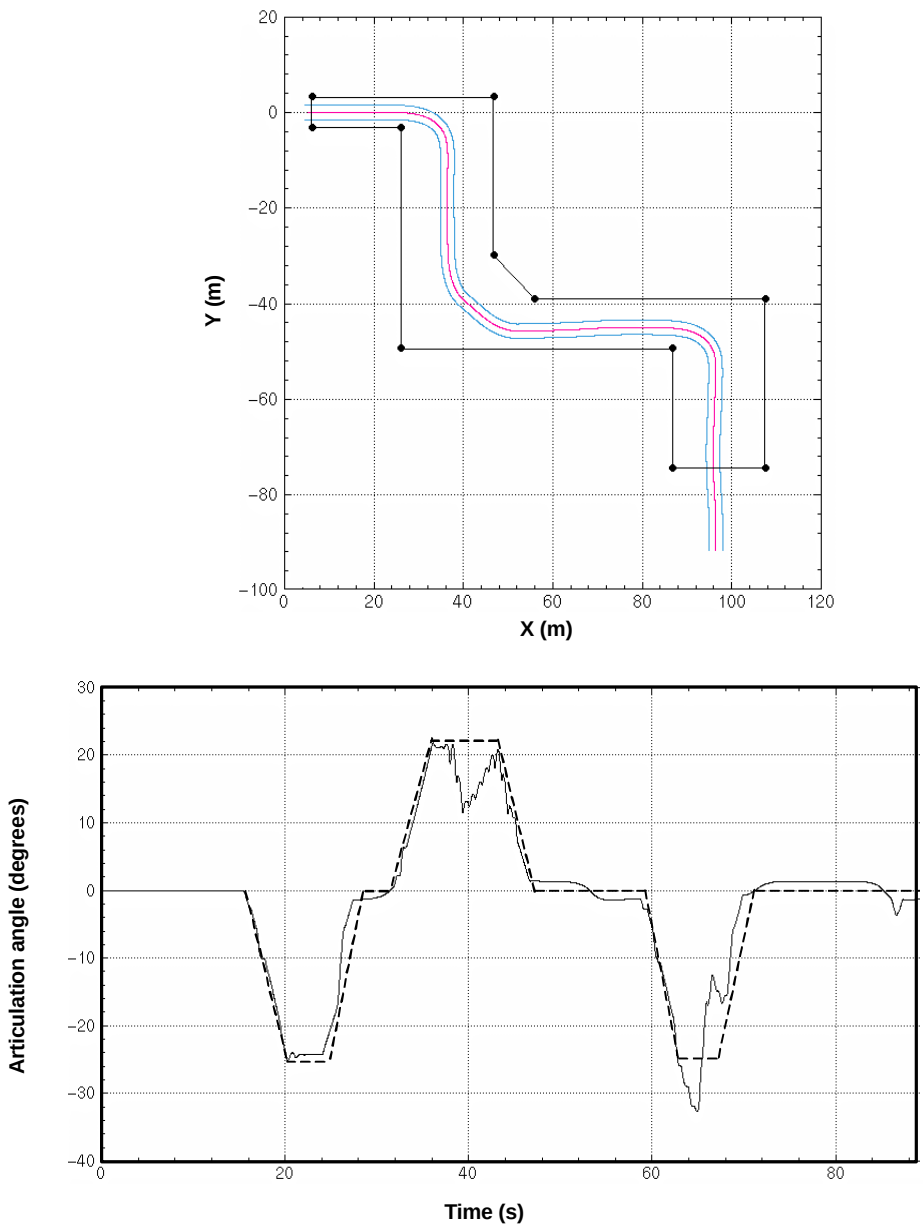


Figure 9. The virtual operator steering the vehicle through the SAE standard steering evaluation course with the corresponding vehicle articulation angles.

trained virtual operator could satisfactorily steer the articu–lated vehicle (fig. 9). It also proved that the HOPM was capable of tuning the steering controller adaptively to the driver's steering habits to realize a consistent steering performance on an articulated vehicle.

The validation was performed via real–time simulation analysis because the goal of this OIL design technology was to evaluate control system performance during the design process. The dynamic responses obtained from simulation analysis should be sufficient to assess the controller performance corresponding to different steering styles.

Conclusion

A virtual design tool framework has been developed for designing control systems for the electrohydraulic steering of articulated vehicles. All parameters of the vehicle system could be configured dependently in simulation analysis. The simulation results demonstrate that the framework has the capacity to capitalize on the full potential of virtual environments. A few possible application areas include rapid prototyping of vehicle system designs, autonomous vehicle research, the study of human controllability issues, and "operator–in–the–loop" design techniques. The virtual design tool framework, along with the flexibility inherent in mechatronic and electromechanical systems, will provide a better control system design strategy, employing performance characteristics desired by a human operator.

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