RULE-BASE REDUCTION FOR A FUZZY HUMAN OPERATOR PERFORMANCE MODEL

W. R. Norris, Q. Zhang, R. S. Sreenivas

ABSTRACT. *This article presents a general procedure of reducing the number of fuzzy rules needed to perform a human-in-the-loop (HIL) design process using a virtual environment design tool. This HIL design process is created for designing an adaptive steering controller to achieve optimal vehicle maneuverability regardless of operator's driving behaviors. In this design process, a dynamic model of an articulated off-road vehicle is implemented to determine the vehicle steering maneuverability via real-time simulation, and a virtual operator model is used to generate steer actions to guide the vehicle traveling on a predetermined path. Due to the complicated nature of steering an articulated vehicle, a high degree of granularity was required to cover all possible combinations of operating conditions. In order to meet real-time simulation requirements, a hierarchical fuzzy relations control strategy (FRCS) has been developed to reduce the size of the virtual operator's rule-base. Using the developed hierarchy, the fuzzy steering controller could effectively incorporate the reduced size rule-base. Validation simulation showed that this hierarchical approach could reduce the size of the rule base by over 98% without affecting the performance of the virtual operator.*

Keywords. *Human-in-the-loop design process, Fuzzy human operator performance model, Fuzzy control strategy, Fuzzy rule reduction.*

To improve the performance and efficiency of off-road vehicles, steer-by-wire technology has been recently introduced. While steering an articulated off-road vehicle, an operator's driving behavior will unavoidably affect the vehicle's maneuverability. To incorporate the human driving behaviors in vehicle steering controller design, the authors have proposed an innovative control system design method, the human-in-the-loop (HIL) interactive control system design tool (Norris et al., 2003). This HIL control system design tool is based on a virtual design technology that allows a new design to be tested and then improved in a virtual testing environment before building a prototype; therefore it is both technically and economically attractive (Jarayam et al., 1997; Durstewitz et al., 2002; Li et al., 2003; Meliopoulos and Cokkinides, 2004). To make the HIL control system design tool applicable in actual design processes, there are a number of obstacles to overcome. One of the most challenging obstacles is the lack of an adequate procedure for modeling or incorporating human behaviors into the interactive design process (Bautsch et al., 1997; Fales et al., 2003). The proposed virtual design tool constitutes a structural topology for incorporating a human operator or human operator model in the system design process. This method closes the loop for qualitative open-loop system design by composing several user-designed modular components, either removable or replaceable, depending on the design objectives (Norris, 2001).

An essential component in the virtual design tool is the human operator performance model (HOPM). The HOPM is a human perception-based model (Norris et al., 2002) developed for evaluating the steering performance of a wheel-type articulated off-road vehicle along an SAE test course (*SAE Standards*, 1994). This model integrates a virtual road (VR, a model of desired vehicle path defined according to SAE articulated vehicle test course), a virtual trainer (VT, an on-line learning tool for training a human-like decision-making model), and a virtual operator (VO, a steering command generating element for creating steering signals to guide the vehicle) to generate consistent human-like steering commands to control an electrohydraulic steering system of the vehicle to aid in the development of adaptive and optimal solutions for qualitative design (Norris et al., 2003). This autonomous control algorithm would simulate sub-optimal human performance with consistent decision-making and exhibit a variety of driving styles. A fuzzy logic approach was selected for representing the steering control rules in this HOPM. The suitability of fuzzy controllers was based on their applicability to nonlinear systems with uncertainty and on their capability to incorporate human knowledge in terms of heuristic rules (Liu and Wu, 1993; Hodge and Trabia, 1999; Zhang 2003; Kuravaki et al., 2004).

The basic requirements for the HOPM include the capability of performing real-time simulation and the capability of representing vehicle response characteristics with various driving behaviors. Incorporating the number of inputs required to steer a vehicle with different driving behaviors in evaluating a steering controller performance in a virtual-aided design process, it requires a massive computa-

Submitted for review in February 2005 as manuscript number IET 5784; approved for publication by the Information & Electrical Technologies Division of ASABE in March 2006.

The authors are **William R. Norris, ASABE Member,** Sr. Engineer, Deere & Company, Moline, Illinois; **Qin Zhang, ASABE Member,** Associate Professor, Department of Agricultural and Biological Engineering, and **Ramavarapu S. Sreenivas,** Associate Professor, Department of General Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois. **Corresponding author:** Qin Zhang, Dept. of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, 1304 W. Pennsylvania Ave., Urbana, IL 61801; phone: 217-333-9419; fax: 217-244-0323; e-mail: qinzhang@uiuc.edu.

  ISSN 0883−8542

tional capability to perform a real-time design simulation for a vehicle with four-degree-of-freedom. Therefore, reducing the size of the rule base to describe the driving behaviors without loss of its capability to cover all required conditions is desirable for effectively implementing a HOPM-base design process. This article will introduce a general method for reducing the size of the HOPM rule-base. To present the relevant information completely, this article is constituted of wheel-type articulated vehicle steering model, human operator performance model, hierarchical rule-based reduction strategy, and HIL simulation validation and discussion.

Wheel-Type Articulated Vehicle Steering Model

The vehicle steering model was used to analyze the vehicle turning performance in the HIL virtual design environment during the interactive design process. Accomplishing this goal requires the model containing only the necessary details of the vehicle turning dynamics to make the real-time virtual simulation comparable to actual turning performance and maintain enough complexity to provide useful information to support the HIL design. A typical wheel-type articulated off-road vehicle consists of an engine-end frame (EEF) and non-engine end frame (NEEF) connected by an articulate joint (AJ). A wheel-type front-end loader is an example of such a vehicle. As shown in figure 1, a wheel-type loader is a four-wheel, single bucket, one-pin joint articulated vehicle. To complete a turn, two hydraulic cylinders adjust the orientation of both the EEF and NEEF in reference to the AJ.

To construct this HOPM, a wheel-type articulated vehicle sub-model (Pauling and Larson, 1988), an electrohydraulic steering system sub-model (Qiu et al., 2001) and a Pacejka tire sub-model (Stotsky and Hu, 1997) were used. To meet the requirements for satisfying real-time simulation, three sub-models were finalized with the following characteristics: (1) a two-dimensional model of two symmetric rigid bodies with a revolute joint; (2) a low traveling speed with the lateral slip neglected; (3) an unloaded vehicle; and (4) incorporated dry friction and rolling resistance. The following equations were derived from three supporting sub-models used in the virtual design simulation analysis (Norris, 2001).

Figure 1. A typical wheel-type articulated front-end loader.

$$x_F = x + CG_R \cos\theta_R + CG_F \cos(\theta_R + \theta_F) \tag{1}$$

$$y_F = y + CG_R \sin\theta_R + CG_F \sin(\theta_R + \theta_F) \tag{2}$$

$$\dot{\theta}_A = K_V C_d A_V \sqrt{\frac{2(P_2 - P_T)}{\rho}} \tag{3}$$

$$F_{Ci} = D_C \sin\left\{C_C \tan^{-1}\left[B_C\beta_T - E_C(B_C\beta_T - \tan^{-1}(B_C\beta_T))\right]\right\} \tag{4}$$

$$F_{Ai} = D_A \sin\left\{C_A \tan^{-1}\left[B_A\beta_T - E_A(B_A\beta_T - \tan^{-1}(B_A\beta_T))\right]\right\} \tag{5}$$

where

x_F and y_F = the displacements of the NEEF center of mass

x and y = the displacements of the EEF center of mass

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

CF_F and CG_R = the distances of the NEEF and the EEF frames to the articulate pin

$\dot{\theta}_A$ = the steering rate of vehicle

K_V = the geometric gain of the steering cylinders of the articulated vehicle

P_2 and P_T = steering cylinder pressure and hydraulic tank pressure, respectively

C_d = the steering control valve orifice coefficient

A_V = the steering control valve flow passing area

β_T = the slide slip angle of the tire

B_A, C_A, D_A, E_A and B_C, C_C, D_C, E_C = constants for cornering force and self-aligning force calculation.

Human Operator Performance Model

As indicated earlier, the HOPM provides an essential means to present the influence of human driving behavior in steering control to support the interactive HIL virtual design process. More specifically, the HOPM creates appropriate steering signals corresponding to various driving behaviors of human operators in controlling an electrohydraulic steering system that actuates two steering cylinders to complete the turning function. In the interactive design process, the HOPM is implemented in real-time simulation, and required to retain sufficient details to represent steering performance under different driving conditions but to contain only necessary complicity to simply the reasoning process. The formulation of the HOPM has been reported separately (Norris et al., 2002).

As shown in figure 2, the three main components of HOPM were a virtual road, an error interpreter, and a human decision-making model (HDMM). The virtual road provided a required vehicle path in terms of a series of equally spaced global coordinates. Those coordinates were presented in a format of piecewise continuous mapping of the planned

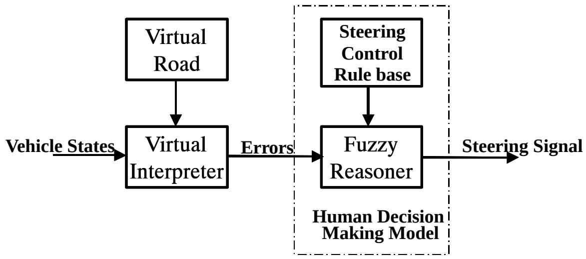

Figure 2. The main components of the human operator performance model (HOPM): a virtual road, a virtual Interpreter, and a human decision-making model (HDMM).

vehicle trajectory. The error interpreter determined five vehicle trajectory errors including distance (ε_d), front angle (ε_θ), orientation (ε_ϕ), look-ahead-heading ($\varepsilon_\varphi - \varepsilon_{\theta_a}$) and look-forward-heading ($\varepsilon_\varphi - \varepsilon_{\theta_f}$) errors based on the differences between the vehicle position, orientation and the planned trajectory from the virtual road as defined in figure 3. Those errors were supplied to HDMM to generate appropriate steering signals corresponding to the vehicle states.

The HDMM was the core element in HOPM. The main functions of the HDMM were to attain an operator-like steering behavior and to generate a steering control signal according to the attained behavior for a given condition to implement the HIL design simulation. The design objective of the HDMM was to minimize the tracking error with minimal steering correction when steer an articulated vehicle in following a predefined path by various operators with different driving behaviors. An error interpreter was used for assessing path-tracking error in this HDMM. Human decision-making for control tasks was based primarily on the judgment gained from experience. The detailed design of the HDMM has been reported separately (Norris et al., 2003).

To develop the HOPM to incorporate human operator judgment, a fuzzy logic approach was used. By this approach, the steering control decision rules were presented in the format of Mamdani type fuzzy rules (Ying, 2000). Mimicking a human's reasoning process, those rules searched for appropriate steering decisions based on detected five defined vehicle trajectory errors in terms of distance (ε_d), front angle (ε_θ), orientation (ε_ϕ), look_ahead_heading ($\varepsilon_\varphi - \varepsilon_{\theta_a}$) and look_forward_heading ($\varepsilon_\varphi - \varepsilon_{\theta_f}$). The amplitudes of the distance, the orientation and the look_forward_heading errors were expressed using five linguistic variables of

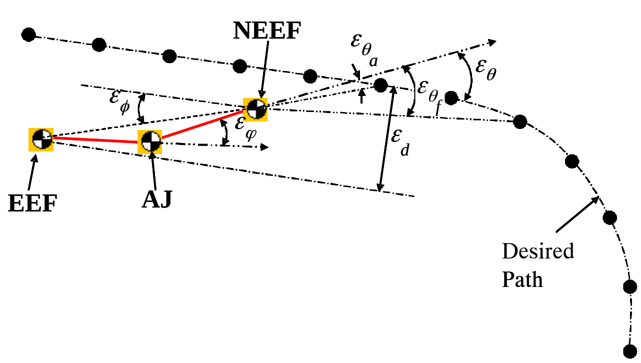

Figure 3. Definition of vehicle trajectory errors.

far_left, close_left, zero, close_right and far_right, and the amplitudes of the front angle and the look-ahead-heading errors were expressed using seven linguistic variables of far_left, near_left, close_left, zero, close_right, near_right and far_right in the HDMM.

The steering control rules were derived based on heuristic knowledge using the defined input variables. The rules were derived based on a common sense approach using all applicable input variables. The procedure of hierarchical derivation of those rules is presented in the next section.

To reduce the computational load without sacrificing the capability of handling the ambiguity of the linguistic variables used in the derived fuzzy rules, trapezoidal fuzzy membership functions (some cases with Z and S shoulders) were used (fig. 4). The defuzzification method used in this HDMM was the Center of Maximum (Von Altrock, 1995). The steering actions were defuzzified using the symmetric linguistic variables of hard_right corresponding to a controller output of 1.0 (hard_left = -1.0), moderate_right = 0.6667 (moderate_left = -0.6667), soft_right = 0.3333 (soft_left = -0.3333) and zero = 0.0.

Hierarchical Rule-Base Reduction Strategy

This HDMM used a hierarchical fuzzy rule creation technique to derive the steering control rules. The hierarchy was determined according to the importance of each input variable in achieving the steering control objectives and in creating appropriate steering signals to bring and/or maintain the vehicle along the desirable path from any initial position and/or orientation with minimal corrections under different conditions. The relative position errors of an articulated vehicle to the desired path can be defined by (1) the distance of the vehicle to the centerline of the desired path; (2) the location of the vehicle related to the centerline (on left or right side); and (3) the direction of the vehicle related to the centerline. Figure 5 illustrates a few representative positions. In order to incorporate the information, a fuzzy relations control strategy (FRCS) was developed for the derivation of appropriate fuzzy steering rules. Based on this FRCS, a steering control action is determined in terms of only the relevant input variables. The following example illustrates a derivation process of fuzzy steering rules for the vehicle based on the FRCS.

In order to steer the vehicle back to the desired path as quickly as possible when the vehicle is offset to its desired path, this FRCS applied a human-like reasoning process to determine an optimal steering action. It will first check if the vehicle is far away from the desired path. Two distance error classes of far_left and far_right are used to define the offset of the vehicle from the centerline. In both cases, the steering priority is given to find a "straight-line approach" for minimizing the distance error regardless if the vehicle is in parallel with the desired path or not. Consequently, it only needs two input variables: the distance error and the front-angle error, to support the decision-making using the following example rule:

IF Distance is far_left, AND Front-Angle is far_left, THEN Steering Action is hard_right.

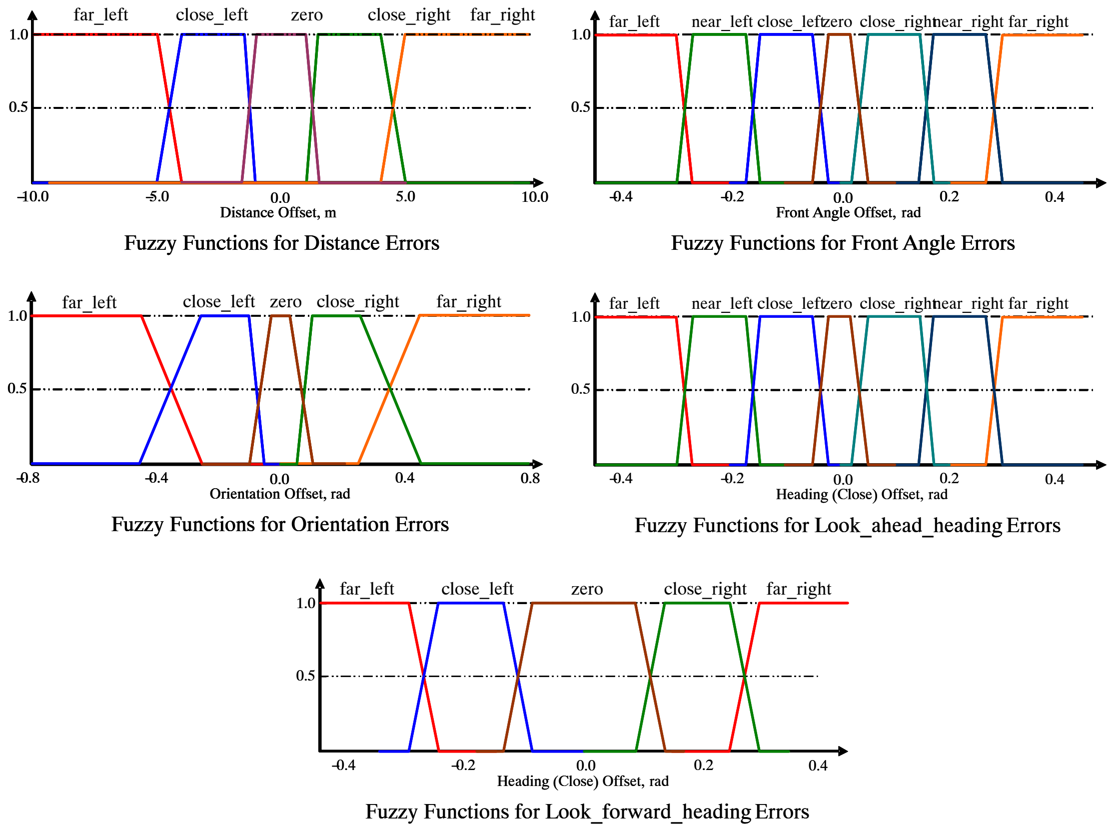

Figure 4. Definition of fuzzy membership functions for input variables of the fuzzy steering rules.

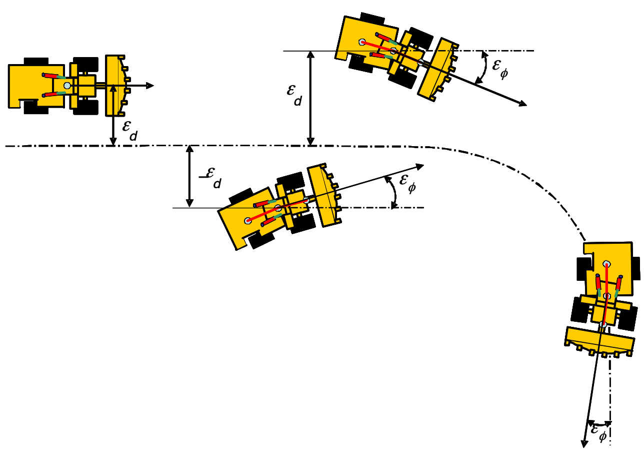

Figure 5. Illustration of sample relative positions involved with interpreting trajectory errors.

From this example case, the control rule applies only two errors out of all five defined ones. It indicates that based on the FRCS approach, the optimal steering action can be derived in using only the relevant errors. Omitting the irrelevant errors can significantly reduce the computational load. Furthermore, the front-angle error is used only to provide the sign of the distance error. For example, a far_right front-angle error will never occur with a far_left distance error in a normal path tracking operation, and vise verse. Based on the FRCS approach, it is also permissible to exclude those cases in the rule base to further reduce its size.

After the vehicle approaching to the desired path, the primary objective of steering control is to attain a smooth approach to the path and then follow it with a minimum overshoot. Paralleling the vehicle to the path becomes a secondary control objective. The corresponding distance error is classified as close_left or close_right. Also, under such circumstances, the vehicle heading should be determined according to the path heading and is defined as orientation error to replace the front-angle error in steering control rules. Consequently, the front-angle error and other errors can be ignored in steering control rule:

IF Distance is close_left, AND Orientation is far_left, THEN Steering Action is hard_right.

When the distance error is in the acceptable range (in the zero region), the orientation error is deemed the primary metric for incorporating the control strategy. In such cases, the smoothness of the vehicle merging into the desired path becomes a priority, and the look_ahead_heading error is then used as an important factor to determine the appropriate steering control actions. Under this priority, the steering control rules can be represented as the following example:

IF Distance is zero, AND Orientation is close_left, AND Look_Ahead_Heading is far_left,

THEN Steering Action is hard_right.

Once both the distance and the orientation errors are within their acceptable levels, the heading errors (both look_ahead_heading and look_forward_heading) become the primary concerns in the control decision-making. In this case, a look-ahead/forward aspect is necessary to ensure the operator could prepare for large perturbations in the path. An example steering control rule is illustrated as follows:

IF Distance is zero, AND Orientation is zero, AND Look_Ahead_Heading is close_left, AND Look_Forward_Heading is far_left, THEN Steering Action is soft_right.

Using the FRCS and the overall objective to minimize the steering error, the hierarchy of each fuzzy relations control variables (FRCV) can be determined based on their global influence: (1) the distance error is defined globally and minimizing the distance error has the highest priority; (2) the orientation error resumes the second highest hierarchy and the steering control goal is to minimize the orientation error when the distance error is within the classes of either "close" or "acceptable;" (3) the goal for minimizing the look_ahead_heading error becomes the priority when both the distance and the orientation errors are within either "close" or "acceptable" level; (4) to minimize the look_forward_heading error has the next priority after all the distance, orientation, and look_ahead_heading errors are within either "close" or "acceptable" range; and (5) the steering action of minimizing the front angle error is implemented only when all other errors are under control. A summary of the hierarchical influence based on the relative strategic value of the FRCV is represented in table 1.

One-half of the symmetric rule-base using the developed FRCS is summarized in table 2. The blank spaces in the table represent rules irrelevant to the control strategy ("do not care" rules) and are excluded from the rule base. Based on this FRCS approach, it requires only 81 steering decision-making rules, compared to 6125 ($5 \times 7 \times 5 \times 7 \times 5$) rules based on the conventional way of rule derivation, to cover all possible steering actions applicable to driving an articulated vehicle in following an SAE test course. It represents an over 98% reduction in the total number of rules by applying the FRCS approach in deriving a steering control rule-base without scarifying the completeness of the controllable region.

The fuzzy inference engine of the HDMM was implemented using a C program automatically generated using a commenrcial fuzzy logic application software named FuzzyTECH^{TM} (Inform Software Corporation, Chicago, Ill.). The error interpreter and path planner were written in C. The code for the virtual operator was implemented in user-code block diagram within MATRIXx SystemBuild (National Instruments, Austin, Tex.). A series of vehicle steering operations was simulated using the developed vehicle model and HDMM. It took 20 s to complete the simulation analysis for a 90-s steering operation at a 50-Hz sampling rate on an HP C180 workstation. The system satisfied the timing requirement for real-time simulation.

HIL Simulation Validation and Discussion

A series of simulation tests were performed to evaluate the effectiveness of using the HOPM approach to design a fuzzy steering controller adaptive to the operator driving behaviors. The simulation study was planned so that the steering controller under the design process should be able to steer the vehicle to follow a steering performance evaluation course for an articulated off-road vehicle with various driving behaviors as defined by an SAE standard (SAE standard J1511, SAE, 1994). The criterion for passing the test is that all the tire tracks of the vehicle should remain within the boundaries of the test course while the vehicle is traveling at a constant speed of 16±2 km/h. The human operator's driving behaviors were input in a form of time-series steering angle of a steering joystick with different turning rates.

Simulations were performed using both a controller with full-set fuzzy rules and a controller with reduced-set fuzzy rules. As the rule-base was changed during the simulations, the membership functions of all the defined linguistic variables were kept unchanged after being tuned to one set of specific driving behaviors. As shown in figure 6, the three lines in the left plots represent two tire trajectories (two outside lines) and the trajectory of the center of gravity of the vehicle NEEF (the center line). The simulated trajectories using the controllers with a full-set of fuzzy rules and with a reduced-set of fuzzy rules were almost identical due to the fact that the reduced-set rule-base removed only the duplicated fuzzy rules and those fuzzy rules were never applicable in normal path tracking operations. However, the total simulation time for a complete test cycle (a 90-s test course using a real vehicle) was reduced from over 30 min with the full-set rule-base (contained a total of 6125 fuzzy rules) to less than 20 s when switched to the reduced-set rule-base (contained only 81 fuzzy rules).

To evaluate the effectiveness using a reduced set of fuzzy rule-base in improving the performance of steering control in tacking a desired path, a comparison simulation study was conducted. In this study, the vehicle path tracking performance was simulated while the vehicle was controlled using a fixed gain steering controller and using a HOPM-based adaptive steering controller supported by the reduced-set of fuzzy rules. Figure 6 presents the results. As one can find on

Table 1. Summary of the hierarchy fuzzy relations control strategy and the appropriate fuzzy relations control variables.

	Metric for FRCS Classification						
			Distance = (Acceptable)				
					Orient = (Acceptable)		
FRCVs	Distance (Far)	Distance (Close)	Orient (Far)	Orient (Close)	Look_Ahead (Far)	Look_Ahead (Close)	Look_Ahead (Acceptable)
Distance	Priority 2	Priority 2	Priority 2	Priority 3	Priority 3	Priority 4	Priority 4
Front Angle	Priority 1	N/A	N/A	N/A	N/A	N/A	N/A
Orientation	N/A	Priority 1	Priority 1	Priority 2	Priority 2	Priority 3	Priority 3
Look_Ahead	N/A	N/A	N/A	Priority 1	Priority 1	Priority 2	Priority 2
Look_Forward	N/A	N/A	N/A	N/A	N/A	Priority 1	Priority 1

Table 2. Half of the symmetric rule-base incorporating the hierarchical technique.

IF					THEN
Distance	Front Angle	Orientation	Look_Ahead	Look_Forward	Steer Command
far_left	far_left				hard_right
far_left	near_left				moderate_right
far_left	close_left				soft_right
far_left	zero				zero
close_left		far_left			hard_right
close_left		close_left			moderate_right
close_left		zero			soft_right
close_left		close_right			soft_right
close_left		far_right			soft_right
zero		far_left	far_left		hard_right
zero		far_left	near_left		hard_right
zero		far_left	close_left		hard_right
zero		far_left	zero		moderate_right
zero		far_left	close_right		moderate_right
zero		far_left	near_right		moderate_right
zero		far_left	far_right		soft_right
zero		Close_left	far_left		hard_right
zero		Close_left	near_left		moderate_right
zero		Close_left	close_left		moderate_right
zero		Close_left	zero		soft_right
zero		Close_left	close_right		soft_right
zero		Close_left	near_right		soft_right
zero		close_left	far_right		soft_right
zero		zero	far_left	far_left	hard_right
zero		zero	far_left	close_left	hard_right
zero		zero	far_left	zero	moderate_right
zero		zero	far_left	close_right	moderate_right
zero		zero	far_left	far_right	soft_right
zero		zero	near_left	far_left	hard_right
zero		zero	near_left	close_left	hard_right
zero		zero	near_left	zero	medium_right
zero		zero	near_left	close_right	soft_right
zero		zero	near_left	far_right	soft_right
zero		zero	close_left	far_left	hard_right
zero		zero	close_left	close_left	moderate_right
zero		zero	close_left	zero	soft_right
zero		zero	close_left	close_right	soft_right
zero		zero	close_left	far_right	soft_right
zero		zero	zero	far_left	soft_right
zero		zero	zero	close_left	zero
zero		zero	zero	zero	zero

the right side of the simulation results, the steering actions (in terms of the articulation angles) generated from the HOPM-based adaptive controller was considerably gentler than that from the fixed gain controller. As a result, the simulated trajectories from a fixed-gain controller presented some oscillations in the vehicle trajectory (the upper set in the figure). A much smoother trajectory was obtained from a HOPM-based adaptive controller with reduced-set of fuzzy rules (the lower set in the figure). While both controllers could steer the vehicle following the desired path, quantitative analyses on steering actions indicated that the steering correction could be over 50° with a few zigzags to ensure the vehicle following a desired path with a fixed-gain steering controller. As a comparison, it needed less than 10° of steering corrections to steer the vehicle following the desired path with a HOPM-based adaptive controller.

The simulation evaluation has demonstrated that the tuning of fuzzy membership functions for relevant linguistic variables adaptively to a human operator's driving behaviors can result in a much more gentle steering operation to complete the required turns more smoothly. Such a feature will lead to an excellent vehicle maneuverability that will allow less experienced human operators to achieve high performance and increased productivity.

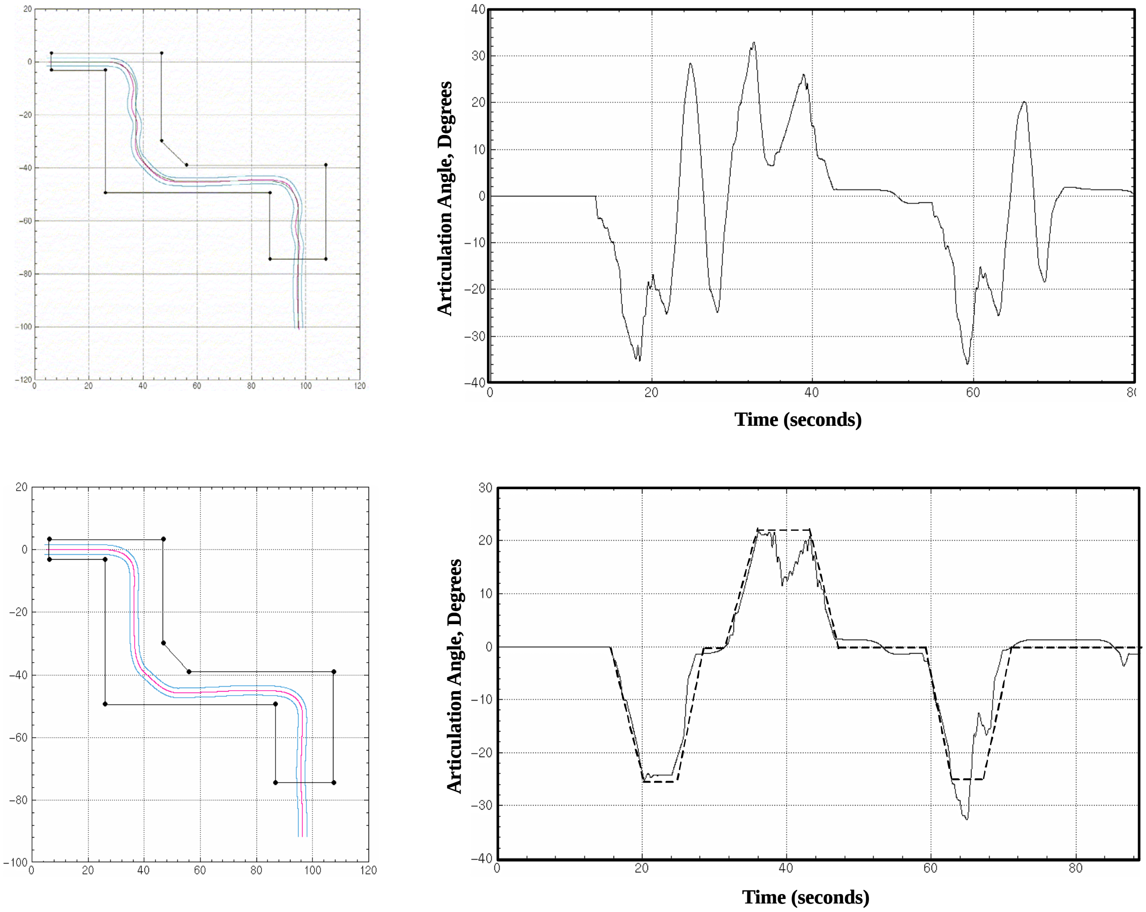

Figure 6. Simulation results of the articulated vehicle steering control performance using a human-in-the-loop (HIL) controller designer. The upper set was from an untrained steering controller and the lower set was from a trained controller using a reduced set of fuzzy rules.

CONCLUSION

A real-time HOPM for optimizing the performance of a fuzzy steering controller and an FRCS steering controller design tool for reducing the total number of fuzzy control rules needed to implement the fuzzy controller were developed in this research. The HOPM can provide a human-like error interpretation and a common sense approach to create control rules for an adaptive fuzzy steering controller. To reduce the complicity of the decision-making process, a hierarchical technique of FRCS could incorporate the priorities of relevant parameters with appropriate control strategy to build a minimal size rule base without loss of the completeness of the fuzzy controller operation range. Simulation analyses indicated that this HOPM could achieve the design objective of real-time adaptation to different driving behaviors of human operators despite a large degree of control interpretation granularity and a complex system model by using a HDMM. The methods developed in this research can be used to create a hierarchical rule base viable for many other applications for human performance studies, qualitative system design, and for autonomous equipment algorithm development.

ACKNOWLEDGEMENTS

The material presented in this article was based upon work supported partially by Caterpillar Inc. and USDA Hatch Funds (ILLU-10-352 AE). The mentioned support is gratefully acknowledged. Any opinions, findings, and conclusions expressed in this publication are those of the authors and do not necessarily reflect the views of the University of Illinois, Caterpillar Inc., or the USDA.

REFERENCES

Bautsch, H. S., S. Narayanan, and M. D. McNeese. 1997. Development and evaluation of a cognitive model of human-performance in fighter aircraft. In *Proc. IEEE International Conference on Systems, Man and Cybernetics*, Vol. 3: 2109-2113. Piscataway, N.J.: IEEE.

Durstewitz, M., B. Kiefner, R. Kueke, H. Putkonen, P. Repo, and T. Tuikka. 2002. Virtual collaboration environment for aircraft design. In *Proc. 6th International Conference on Information Visualisation,* 502-507. Piscataway, N.J.: IEEE.

Fales, R. C., K. Chipperfield, and F. Wagner. 2003. Modeling and control of a construction machine with a human-in-the-loop assessment in virtual reality. In *Proc. Of Dynamic Systems and Control Division,* Vol. 72(1): 561-568. New York: ASME.

Hodge, N., and M. Trabia. 1999. Steering fuzzy logic controller for an autonomous vehicle. In *Proc. 1999 IEEE International Conference on Robotics and Automation*, Vol. 3: 2482-2488. Piscataway, N.J.: IEEE.

Jarayam, S., H. I. Connacher, and K. W. Lyons. 1997. Virtual assembly using virtual reality techniques. *CAD Computer Aided Design* 29(8): 575-584.

Kuravaki, I., L. V. Litvintseva, S. A. Panfilov, G. G. Rizzotto, K. Takahashi, I. S. Ulyanov, T. Haqivara, and A. V. Yazenin. 2004. Design of robust knowledge bases of fuzzy controllers for intelligent control of substantially nonlinear dynamic systems. I: Application of soft computing. *J. of Computer and Systems Sciences International* 43(4): 615-632.

Li, Q. M., F. C. Lee, and T. G. Wilson Jr. 2003. Design verification and testing of power supply system by using virtual prototype. *IEEE Transactions on Power Electronics* 18(3): 733-739.

Liu, T., and J. Wu. 1993. A model for a rider-motorcycle system using fuzzy control. *IEEE Transactions on Systems, Man & Cybernetics* 23(1): 267-76.

Meliopoulos, A. P. S., and G. J. Cokkinides. 2004. A virtual environment for protective relaying evaluation and testing. *IEEE Trans . on Power Systems* 19(1): 104-111.

Norris, W. R. 2001. A design framework for qualitative human-in-the-loop system development. Ph.D. diss. Urbana, Ill.: University of Illinois Urbana-Champaign, Department of Agricultural Engineering.

Norris, W. R., R. Sreenivas, and Q. Zhang. 2002. A real-time human operator performance model for performing adaptive control system design. In *Automation Technology for Off-Road Equipment*, ed. Q. Zhang, 297-306. St. Joseph, Mich.: ASAE.

Norris, W. R., Q. Zhang, R. Sreenivas, and J. C. Lopez-Dominguez. 2003. A design tool for operator-adaptive steering controller. *Transactions of the ASAE* 46(3): 883-891.

Pauling, P., and C. S. Larson. 1988. Simulation of an articulated wheel loader including model for earthmoving tires. SAE Technical Paper No. 88-0777. Warrendale, Pa.: SAE.

Qiu, H., Q. Zhang, J. F. Reid, and D. Wu. 2001. Modeling and simulation of an electrohydraulic steering system. *International Journal of Vehicle Design* 17(2/3): 259-265.

SAE Standards. 1994. J1511. Steering for off-road, rubber-tired machines (revised February 1994). Warrendale, Pa.: SAE.

Stotsky, A., and X. Hu. 1997. Stability analysis of robustly decoupled car steering system with nonlinear tire model. In *Proc. IEEE Conference on Decision and Control*, Vol. 5: 4750-4755. Piscataway, N.J.: IEEE.

Von Altrock, C. 1995. *Fuzzy Logic and Neurofuzzy Applications Expla*ined. Princeton, N.J.: Prentice Hall.

Ying, H. 2000. *Fuzzy Control and Modeling: Analytical Foundations and Applications*. New York: IEEE Press.

Zhang, Q. 2003. A generic fuzzy electrohydraulic steering controller for off-road vehicles. *J. of Automobile Engineering* 217(9): 791-799.