Data-Driven Hardware-in-the-Loop Plant Modeling for Self-Driving Vehicles

Hannah Grady Nicholas Nauman Md Suruz Miah

Department of Electrical and Computer Engineering
Bradley University, Peoria, Illinois, 61625, USA

Sponsor: AutonomouStuff | https://autonomoustuff.com/
306 Erie Avenue, Morton, IL 61550
Telephone: 309-291-0966, email:info.as.ap@hexagon.com

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Outline

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Applications of Autonomous Vehicles

- Autonomous vehicles are being developed by many companies for commercial and personal use
- Modeling different subsystems (such as, steering, brake, acceleration, ...) for autonomous vehicles is a challenging task
- Models for autonomous vehicle subsystems must be very accurate due to safety factors

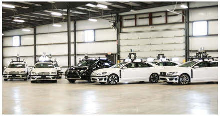

Figure 1: AutonomouStuff Vehicle Fleet[a]

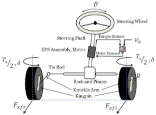

Figure 2: Autonomous Vehicle Steering System[b]

[a] https://hexagonpositioning.com/pi-brands/autonomoustuff

[b] https://www.autonews.com/article/20181105/OEM10/181109921/delphi-s-pace-award-winning-e-steer-an-autonomous-vehicle-building-block

Problem Statement

Given input-output data of different subsystems, such as steering, acceleration, brake, shift, speed, and speed control, of an autonomous (self-driving) vehicle:

- Develop mathematical and/or block diagram models of these subsystems
- Develop machine learning-based models for the major subsystems of Lexus self-driving vehicle

Problem Statement

Given input-output data of different subsystems, such as steering, acceleration, brake, shift, speed, and speed control, of an autonomous (self-driving) vehicle:

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Proposed Solution

- Use state-space modeling techniques based on input and output data
- Use system identification modeling techniques
- Use machine learning (neural network) based modeling techniques

Outline

Existing Solutions

- Use of System Identification Toolbox in MATLAB to create models from data [1]
  - Offers a variety of model choices
  - Needs a large amount of raw data to produce an accurate model
- Third order ARMAX model creates models using traditional methods of analysis [2]
  - Allows the use of traditional analysis methods to create a model
  - More room for error during calculations
- Steer-By-Wire method as a system model [3]
  - Can model systems with small non-linearities
  - Mechanical components replaced by electrical components
- Authors in [4] illustrate identification of multiple-input single-output model for maximum power point tracking of photovoltaic system.
  - Fourth order ARX model ended up giving the best fit

Outline

System Identification Preliminaries

Preliminary Work

- Documentation on MATLAB's System Identification Toolbox and tutorials
- Literature Review
- Data Collection for steering, braking and acceleration subsystems

MATLAB Example: Dealing with Multi-Variable Systems: Identification and Analysis

- Learned how to create an iddata object from a given data set
- Created a state space model and compared it to the validation data
- Tried creating submodels for some of the channels in order to try and get a better fit
- Then created a MISO model and learned how to merge the two SISO models that were created earlier

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System Architecture

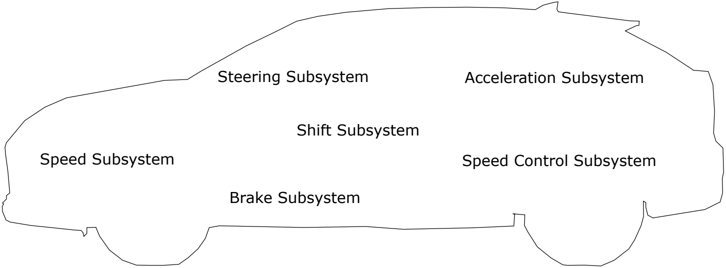


Figure 3: Lexus Vehicle with Subsystems

System Architecture

System Architecture

The overall system architecture of this project consists of six subsystems:

- Steering
- Acceleration
- Brake
- Shift
- Speed
- Speed control

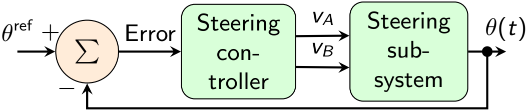


Figure 4: Steering subsystem block diagram.

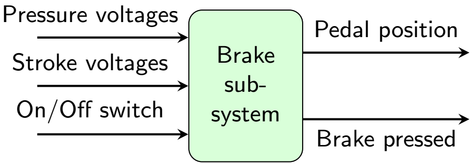


Figure 5: Brake subsystem block diagram

System Architecture

Subsystems

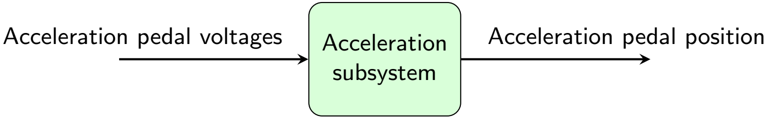


Figure 6: Acceleration subsystem block diagram

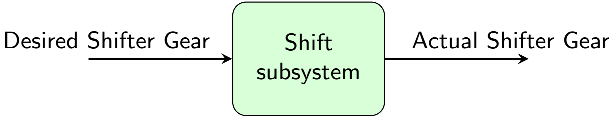


Figure 7: Shift subsystem block diagram

System Architecture

Subsystems

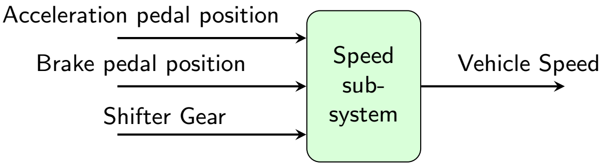


Figure 8: Speed subsystem block diagram

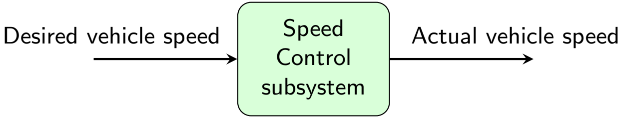
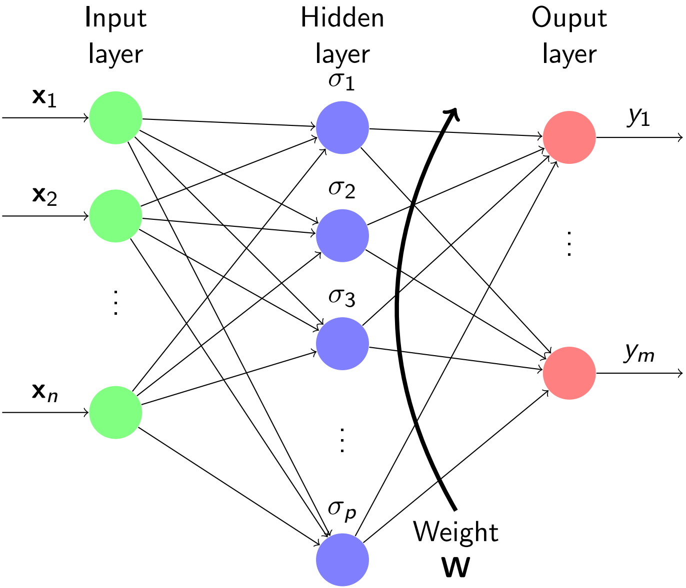


Figure 9: Speed Control subsystem block diagram

Outline

Modeling using Neural Networks



Therefore, approximated output signal can be written as:

$$\mathbf{y} = \mathbf{W}^T \boldsymbol{\sigma}(\mathbf{x}), \tag{1}$$

where $\boldsymbol{\sigma} : \mathbb{R}^n \rightarrow \mathbb{R}^p$ with components of weight matrix $\mathbf{W}$ shown in Fig. 10 are given by

$$\mathbf{W} = \begin{bmatrix} w^{1,1} & w^{1,2} & \dots & w^{1,m} \\ w^{2,1} & w^{2,2} & \dots & w^{1,m} \\ \vdots & \ddots & \dots & \vdots \\ w^{p,1} & w^{p,2} & \dots & w^{p,m} \end{bmatrix}.$$

Now take η data points and form the set of linear equations as:

$$\begin{aligned} \boldsymbol{\sigma}^T(\mathbf{x}_k)\mathbf{W} &\approx \left(\mathbf{y}_k^{[d]}\right)^T \\ \boldsymbol{\sigma}^T(\mathbf{x}_{k+1})\mathbf{W} &\approx \left(\mathbf{y}_{k+1}^{[d]}\right)^T \\ &\vdots \\ \boldsymbol{\sigma}^T(\mathbf{x}_{k+\eta-1})\mathbf{W} &\approx \left(\mathbf{y}_{k+\eta-1}^{[d]}\right)^T \end{aligned}$$

In compact form:

$$\mathbf{\Sigma W} \approx \mathbf{U}^{[d]}, \qquad \text{with}$$

$\mathbb{R}^{\eta \times p} \ni \mathbf{\Sigma} = [\mathbf{\Sigma}_0, \mathbf{\Sigma}_1, \ldots, \mathbf{\Sigma}_{\eta-1}]^T$ with $\mathbf{\Sigma}_\kappa = \boldsymbol{\sigma}^T(\mathbf{x}_{k+\kappa})$ and $\mathbb{R}^{\eta \times m} \ni \mathbf{U}^{[d]} = [\mathbf{U}_0, \mathbf{U}_1, \ldots, \mathbf{U}_{\eta-1}]^T$ with $\mathbf{U}_\kappa = (\mathbf{y}_\kappa)^T$ for $\kappa = 0, 1, \ldots, \eta - 1$.
Let $\mathbf{\Sigma W} \equiv \hat{\mathbf{U}}$, sum-of-squared error, δ can be written as:

$$\delta = \frac{1}{2} \| \mathbf{U}^{[d]} - \hat{\mathbf{U}} \|^2$$

Weight matrix $\mathbf{W}$ can then be found minimizing the sum–of–square error δ defined by

$$\delta = \frac{1}{2} \| \mathbf{U}^{[d]} - \mathbf{\Sigma W} \|^2 = \frac{1}{2} \mathrm{Tr} \left[(\mathbf{U}^{[d]} - \mathbf{\Sigma W})^T (\mathbf{U}^{[d]} - \mathbf{\Sigma W}) \right].$$

Taking the derivative of δ with respect to $\mathbf{W}$ yields

$$\frac{\partial \delta}{\partial \mathbf{W}} = -\mathbf{\Sigma}^T \mathbf{U}^{[d]} + \mathbf{\Sigma}^T \mathbf{\Sigma W} \tag{2}$$

Setting $\frac{\partial \delta}{\partial \mathbf{W}}$ to zero yeilds

$$\mathbf{W} = \left(\boldsymbol{\Sigma}^T \boldsymbol{\Sigma}\right)^T \boldsymbol{\Sigma}^T \mathbf{U}^{[d]}.$$

- Hidden layer to output layer weight is updated at each policy iteration $r = 0, 1, \ldots$ using gradient descent approach as:

$$\begin{aligned} \mathbf{W}^{(r+1)} = \mathbf{w}^{(r)} - \ell \frac{\partial \delta}{\partial \mathbf{W}} = \mathbf{W}^{(r)} - \ell \left(-\boldsymbol{\Sigma}^T \mathbf{U}^{[d]} + \boldsymbol{\Sigma}^T \boldsymbol{\Sigma} \mathbf{W}^{(r)}\right) \\ = \mathbf{w}^{(r)} - \ell \boldsymbol{\Sigma}^T \left(\boldsymbol{\Sigma} \mathbf{W}^{(r)} - \mathbf{U}^{[d]}\right) \quad (3) \end{aligned}$$

Modeling using Neural Networks

- Used MATLAB's Neural Network Time Series App
- All models generated using the Bayesian Regularization Algorithm
- Models trained using collected log data

Outline

Specifications

Proposed vehicle subsystem models are expected to fulfill requirements listed below:

- Resulting plant model will consist of reasonably accurate subsystem models
- Subsystems can be used to create a HIL testbench
- Steering model can handle very small changes in steering angles
    - smooth out any non-linear discontinuities that would normally be measured by the steering motor, especially for small changes in the steering angle, depicted in 11.

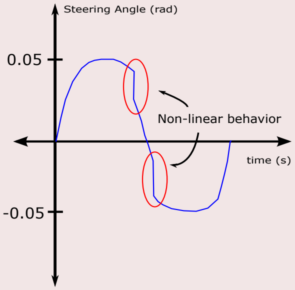


Figure 11: Steering Non-linear Behavior

Outline

Manual Mode

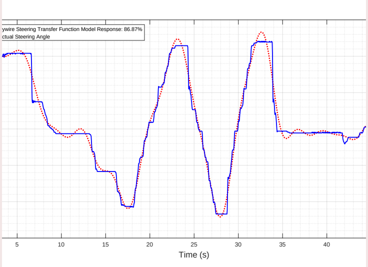


Figure 12: Output of Estimated Manual System Model

By-Wire Mode

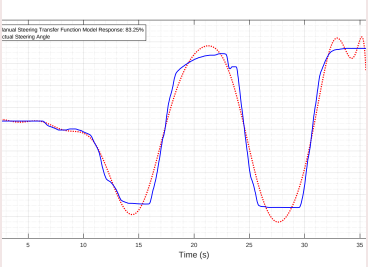


Figure 13: Output of Estimated By-Wire System Model

Manual Mode

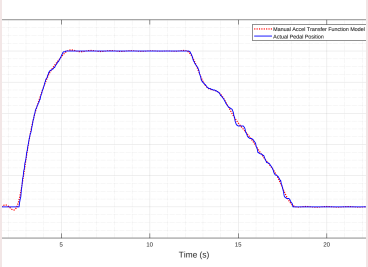


Figure 14: Output of Estimated Manual System Model

By-Wire Mode

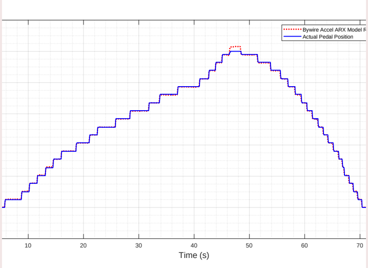


Figure 15: Output of Estimated By-Wire System Model

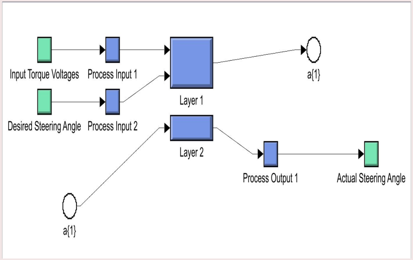
Transfer Function Modeling

Brake System Simulation

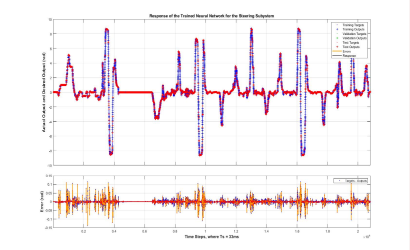
- Only manual models were considered
- There were no transfer function models that could satisfy both the best fit and error requirements

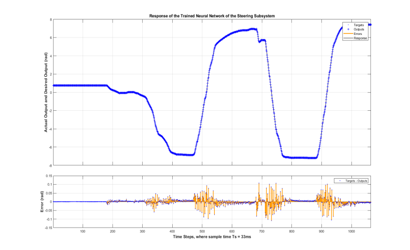
Neural Network Modeling

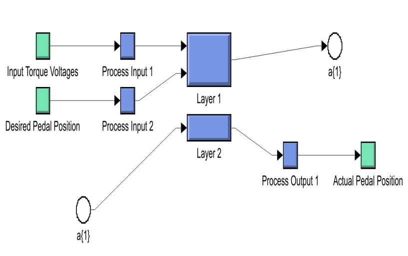
Steering System Simulation



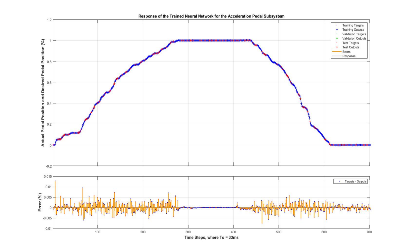
- Only a few samples are just outside of the accuracy requirements
- Transfer function model did not meet the accuracy requirements

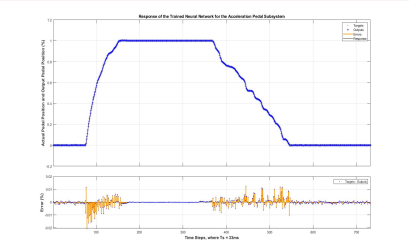






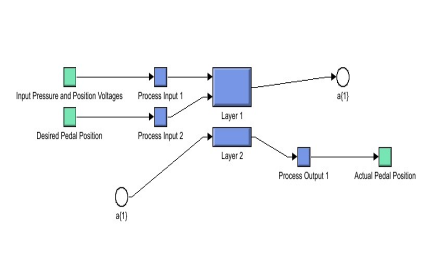
- All samples within 2% of the actual output
- Transfer function model did not have the same accuracy bounds
- Fewer concerns about connections in Simulink



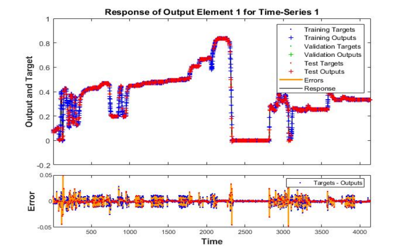


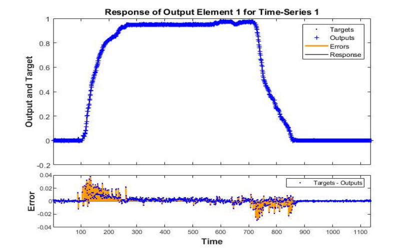
Neural Network Modeling

Brake System Simulation



- With this model, the error is kept below 5%
- Able to easily track model performance
- Provides better results than the transfer function model





Outline

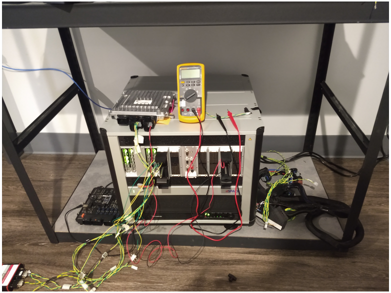
Software and Hardware

- Software
  - MATLAB's System Identification Toolbox
  - MATLAB's Neural Network Time Series Toolbox
  - DSpace/Control Desk
  - Vector CANAlyzer
- Hardware
  - Laptop
  - PACMod ECU
  - CANCase
  - CAN bus

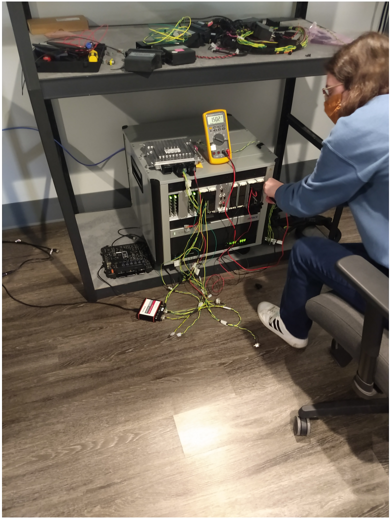
Control Method

- Manual Mode
  - Vehicle is not autonomous
  - Torque voltages are sent by the vehicle ECU
- By-Wire Mode
  - Vehicle is autonomous
  - Torque voltages are sent by the PACMod ECU
  - Torque voltages sent from the vehicle ECU are discarded by open-circuiting the motors

Figure 16: Autonomous Vehicle Data Collection Setup



- HIL Bench
- Measuring output voltages to confirm results



- Testing data points using Control Desk software

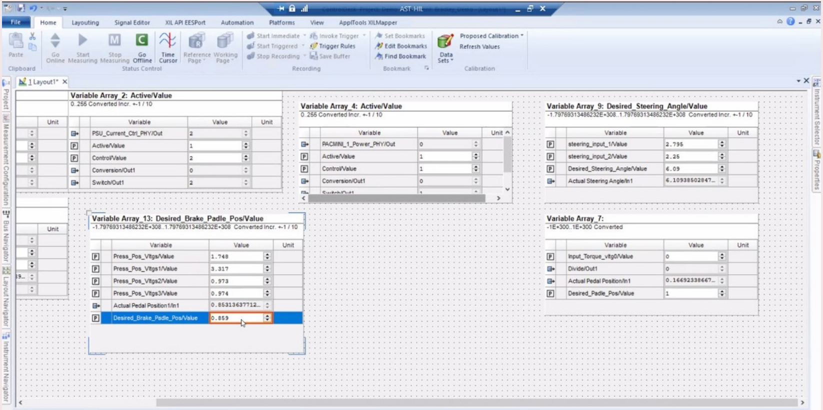


Figure 17: Model Validation Setup

Outline

Conclusions and Future Work

Conclusions and Challenges

- Conclusions
  - Switch from transfer function to neural network models
  - Neural network modeling worked best
- Challenges
  - Time constraints
  - Hardware constraints

Future Work

- Model shift, speed, and speed control subsystems
- Test models using Hardware-in-the-Loop
- Create new vehicle controllers

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Outline

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[1] R. Adnan, M. H. F. Rahiman, and A. M. Samad, "Model identification and controller design for real-time control of hydraulic cylinder," in *2010 6th International Colloquium on Signal Processing its Applications*, 2010, pp. 1–4.

[2] B. Li, R. Wang, Y. Zhang, and Z. Wang, "Modeling of steering system of high speed intelligent vehicle by system identification," in *Proceedings of the IEEE International Vehicle Electronics Conference (IVEC'99) (Cat. No.99EX257)*, 1999, pp. 243–246 vol.1.

[3] S. A. Saruchi, H. Zamzuri, S. A. Mazlan, M. H. M. Ariff, and M. A. M. Nordin, "Active front steering for steer-by-wire vehicle via composite nonlinear feedback control," in *2015 10th Asian Control Conference (ASCC)*, 2015, pp. 1–6.

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[4] M. Hussain, A. Omar, and A. Samat, "Identification of multiple input-single output (miso) model for mppt of photovoltaic system," in *2011 IEEE International Conference on Control System, Computing and Engineering*, 2011, pp. 49–53.