Virtual Vehicle Systems Simulation

“A Modular Approach in Real-Time”

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Computer technology adds tools to engineering.
Virtual reality for arcade, movie and as a design tool in engineering.
Imagine driving in a virtual realistic vehicle with full feedback.
An engineer can design and modify a subsystem, and analyze the vehicle ride performance immediately.
No knowledge or expertise is required for evaluating vehicle subsystems on full-vehicle simulation.
Implementing a vehicle ride control systems must be a drag and drop exercise.
Networked simulation environment allows for remote simulation subsystems and hardware in the loop
Modularity provides capability for distributed simulation and improved computational performance.
Contents

• Objective and Applications
• Vehicle Model & Tire Model
• Modularity and Real-Time
• Implementation of UI in MATLAB/Simulink
• Conclusions
• Many industry activities involve design and testing of automotive systems.

• ITT : ABS, TACOM : Leader-following, suspension, collision warning

• Simulation could be used to replace certain test-track experiments.

• Many simulation packages have black-box dynamics models, are expensive and are not flexible to fit any specific purpose.

• Collaborative online simulation exploit capabilities of internet
Applications

• Design of vehicle sub-systems (interactive)
• Analysis of vehicle sub-systems (state-access)
• Subjective validation of concept designs
• Facilitate testing of prototype systems
• Benchmark hazardous scenarios
• Education for drivers and customers
• Instrumentation for in-the-loop mechatronics studies
Laboratory Setup

Virtual Reality Immersion
  Video Projection
  Audio Projection
  Perspective Tracking

Driver
  Quantitative Performance
  Qualitative Performance
  Human Factors

In-The-Loop Hardware Components
  Driving Cab Accessories
  Mechatronics Hardware Prototype

Real-Time Animation/Visualization
  Automotive Driving Visualization
  Concept Component Visualization

Motion Base Shaker and Force Feedback
  6 Degrees of Freedom
  Hydraulics Table

Real-Time Function Simulation
  Automotive Dynamics Simulation
  Mechatronics Virtual Prototype
Virtual Vehicle System

State Space Formulation:

\[ \dot{x} = Ax + Bu + \eta(x,u) \]
\[ y = Cx + Du + \zeta(x,u) \]
Vehicle Model - Free Body

\[
\sum_{i}^{4} \left( F_{\text{defl},i} + F_{\text{susp},i} + \omega \bar{W} \right) = M^{-1} a + \frac{\omega}{s} v + \frac{\omega}{s} \bar{x}
\]

Sum of Forces:

\[
F = \sum_{i=1}^{4} \left( F_{\text{slip},i} + F_{\text{defl},i} + F_{\text{roll},i} \right) + F_{\text{wind}}
\]

Integration

\[
\bar{v}_k = \bar{v}_{k-1} + \frac{1}{2} \Delta t M_v^{-1} \left( F_{k-1} + F_k \right)
\]

\[
\bar{x}_k = \bar{x}_{k-1} + \frac{1}{2} \Delta t \left( \bar{v}_{k-1} + \bar{v}_k \right)
\]
Vehicle Model - Free Body

Sum of Torques:

\[ T = \sum_{i=1}^{4} \left( ^\circ C_i \times \overline{F}_{slip,i} + ^\circ A_i \times \overline{F}_{defl,i} + ^\circ A_i \times \overline{F}_{roll,i} \right) \]

Angular Body Accelerations:

\[ ^c \dot{\Omega} = \left( ^c T - ^c \Omega \times (I ^c \Omega) \right)I^{-1} \]

Roll, Pitch, Yaw:

\[ ^c \dot{\Theta} = \begin{bmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \theta \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{bmatrix} ^c \Omega \]
Vehicle Model - Suspension

Suspension and Tire deflection spoke model

\[ \delta_T = L_T - [^o B_i - ^o Isect(^o B_i, \sigma)] \]
\[ \delta_S = L_S - [^c B_i - ^c A_i] \]
\[ z_w = L_S - \delta_S \]

Equation of motion:

\[ M_w s^2 z_w + \cos \sigma \left( D_T + K_T \frac{1}{s} \right) s \delta_T + \left( D_S + K_S \frac{1}{s} \right) s \delta_S = -F_z(s) \]
Tire Dynamics Model

• Existing tire models are either
  - not related to physical parameters
  - based on lookup tables
  - derived from velocities; requires minimum velocity

• New tire model is introduced, based on two analytical models and physical parameters.

• Fuzzy logic is used for supervisory decision on the actuation of the models, based on the state of the vehicle.
Tire Dynamics - Dugoff

Slip coefficient:

\[ \mu \]

Slip ratio: 
\[ s = \frac{v_{wheel} - v_{vehicle}}{v_{wheel}} \]
Tire Dynamics - Dugoff

\[ \pm \mu \]

\( V_v \) (vehicle speed)

Forward

\( V_w \) (wheel speed)

Braking

Traction

Reverse

Traction
Problem: Dugoff model does not incorporate stick friction
Solution: Introduce additional friction component, based on Fuzzy logic supervisory control.
Tire Stick Friction Model

Stick Friction Force:

\[
\bar{F}_{St} = \begin{bmatrix}
D_{stick}(v_{v,x} - v_w) + K_{stick}\frac{1}{s}(u_{v,x} - u_w) \\
D_{stick}v_{v,y} + K_{stick}u_{v,y} \\
0
\end{bmatrix}
\]
Tire Model - Fuzzy Switch

Membership functions for the fuzzy tire model

\[ \mu_{St} = \frac{1}{1 + e^{4|\lambda - \delta|}} \]

\[ \mu_{Fr} = 1 - \frac{1}{1 + e^{4|\lambda - \delta|}} \]

\[ \delta = \nu_w - \nu_v \]
Tire Dynamics Model
Hardware Implementation

Simulation Platform Integrated Network Environment (SPINE)
SPINE is the communication backbone for the VVSS. The simulation software for each module communicates through a DLL with the VVSS. The VVSS serves a pool of shared memory to the modules through SPINE.
Modularity - State Indexing

Implicit Bilinear Approximation:

\[ x_{1,k+1} = \ddot{x}_{1,k} + a h u_k \]
\[ x_{2,k+1} = \ddot{x}_{2,k} + b \frac{h}{2} \left( \ddot{x}_{1,k+1} + \ddot{x}_{1,k} \right) \]
\[ x_{3,k+1} = \ddot{x}_{3,k} + c \frac{h}{2} \left( \ddot{x}_{2,k+1} + \ddot{x}_{2,k} \right) \]
Modularity - Integration

Implicit Bilinear Approximation:

\[
\begin{align*}
    x_{1,k+1} &= \tilde{x}_{1,k} + ahu_k \\
    \tilde{x}_{2,k+1}^1 &= \tilde{x}_{2,k} + b \frac{h}{2} \left( \tilde{x}_{1,k+1} + \tilde{x}_{1,k} \right) \\
    x_{3,k+1} &= \tilde{x}_{3,k} + c \frac{h}{2} \left( \tilde{x}_{2,k+1} + \tilde{x}_{2,k} \right)
\end{align*}
\]

Forward Euler Approximation:

\[
\begin{align*}
    x_{1,k+1} &= \tilde{x}_{1,k} + ahu_k \\
    \tilde{x}_{2,k+1}^1 &= \tilde{x}_{2,k} + bh\tilde{x}_{1,k} \\
    x_{3,k+1} &= \tilde{x}_{3,k} + ch\tilde{x}_{2,k}
\end{align*}
\]

Explicit Bilinear Approximation:

\[
\begin{align*}
    x_{1,k+1} &= \tilde{x}_{1,k} + ahu_k \\
    \tilde{x}_{2,k+1}^1 &= \tilde{x}_{2,k} + bh\tilde{x}_{1,k} + ab \frac{h^2}{2} u_k \\
    x_{3,k+1} &= \tilde{x}_{3,k} + ch\tilde{x}_{2,k} + bc \frac{h^2}{2} \tilde{x}_{1,k} + abc \frac{h^3}{4} u_k
\end{align*}
\]

At Some: \( t = kh \)
Modularity - Timing

Slide 22

Oakland University
Intelligent Vehicle Dynamics and Control
Real time - Simulation time

Time to compute overhead and $n$ integration steps must be smaller than frame size:

$$t_0 + nt_s < T_f$$

The time that is simulated per frame must match the real time laps of the frame:

$$h_s = \frac{T_f}{n}$$

The minimum sub-sample integration time must meet the requirement:

$$h_s > \frac{t_0 + nt_s}{n}$$
Real timing

Real Time Integration Step Size for Various Frame Rates

Integration step size (s) vs. Subsampling (n) for different frame rates.
Implementation in MATLAB

Virtual Vehicle Systems Simulation

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General Dynamics Laboratory
Implementation in MATLAB
Implementation in MATLAB

Block Parameters: Left Front Suspension Length

- WSS Receive module (mask)

The output of the WSS Receive Module represents the value of the scalar that belongs to the WSS index.

Parameters

- WSS Index
  
  212

[OK] [Cancel] [Help] [Apply]
### Implementation in MATLAB

#### Indexes for vehicle chassis

<table>
<thead>
<tr>
<th>Scalar indexes</th>
<th>Vector Indexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 Throttle angle</td>
<td>00 Position</td>
</tr>
<tr>
<td>02 Brake angle</td>
<td>01 Wheel spin acceleration</td>
</tr>
<tr>
<td>03 Steering angle</td>
<td>02 Wheel spin velocity</td>
</tr>
<tr>
<td>10 Traction</td>
<td>03 Wheel spin angle</td>
</tr>
<tr>
<td>11 Lateral Acceleration (read only)</td>
<td>04 Steering angle</td>
</tr>
<tr>
<td>12 Forward Velocity (read only)</td>
<td>04 Wheel angle rate</td>
</tr>
<tr>
<td>50 Sprung mass</td>
<td>05 Instantaneous Angle Rate</td>
</tr>
<tr>
<td>998 zoom</td>
<td>06 Instantaneous Angle Accel.</td>
</tr>
<tr>
<td>999 azimuth</td>
<td>50 Inertia (about x, y, z)</td>
</tr>
<tr>
<td>90 Center of Gravity</td>
<td>90 Location</td>
</tr>
</tbody>
</table>

**SPINE communication accepts the following variables from the MATLAB workspace:**

- `title = <string>`: The name of the application
- `host = <string>`: The VVSS server hostname
- `Ts = <scalar>`: The integration sampling interval

#### Indexes for vehicle corners

- Right Front (RF) corner: 100 to 199
- Left Front (LF) corner: 200 to 299
- Right Rear (RR) corner: 300 to 399
- Left Rear (LR) corner: 400 to 499

#### Scalar indexes

- 00 Wheel spin acceleration
- 01 Wheel spin velocity
- 02 Wheel spin angle
- 03 Steering angle
- 04 Tire deflection acc
- 05 Tire deflection rate
- 06 Tire deflection
- 07 Tire deflection constant
- 08 Tire damping coefficient
- 10 Suspension deflection acc
- 11 Suspension deflection rate
- 12 Suspension deflection
- 13 Suspension spring constant
- 14 Suspension spring damping
- 50 Wheel (unsprung mass)
- 51 Wheel (spin) inertia
- 52 Tire-Road slip coefficient (u)
- 60 Brake Torque
- 61 Drive Torque
- 62 TTRC Torque

#### Vector Indexes

- 00 Location A
- 01 Location B
- 02 Location C
- 05 Vehicle Velocity
- 10 Anchor Location
- 11 Anchor Location CG
- 49 Additional Susp. force
- 50 Suspension force
- 51 Tire deflection force
- 52 Slip force
Real Timing
Driver Environment
Conclusions

- Developed a Vehicle Simulation Environment (VVSS) and a real-time based simulation network (SPINE).
- Facilitate a plug-and-play ready to use simulation environment in familiar popular Matlab/Simulink.
- Fully interactive audio/motion feedback stereo-vision human driver environment.
- Easily configure any driving scenario and terrain configuration through separate datafile.
- Still unsolved problem for P&P calibration ...
Virtual Vehicle Systems Simulation

“A Modular Approach in Real-Time”

Fine.
Systems Engineering

Math

Science

Technology

Engineering