Real-Time and High-Fidelity Simulation Environment for Autonomous Ground Vehicle Dynamics

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<td>Briefing Charts</td>
<td>05-07-2013 to 03-08-2013</td>
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Introduction

Ground Vehicle Research Simulation Tradeoffs

• Fast but low physical fidelity
  – Block that slides on the ground

• High physical fidelity but slow
  – Highly detailed model

Goal of Research

• Construct a ground vehicle simulation that is fast with good physical fidelity
  – Real-time
  – Full suspension, wheel-soil interaction, navigation, and control
ROAMS Background

ROAMS

- The JPL DARTS lab team has been involved in vehicle modeling and simulation for over 20 years
- Many key JPL/NASA missions require high-fidelity simulations
  - Spacecraft missions (Cassini, MER, MSL)
  - Planetary rovers (Pathfinder, MER, MSL, research rovers)
- The DARTS lab team created ROAMS for ground vehicle simulations of planetary rovers (http://dartslab.jpl.nasa.gov)
Example ROAMS Vehicles
ROAMS Simulation Models

- Encoders
- IMU
- Sun sensor

Sensor devices

- Rover Vehicle & Arm
- Dynamics and Kinematics

Motor Control Controllers

- Battery
- Solar panels
- Power models

Vision/Nav. Sensors

- Cameras

Contact model

- Compliance model

Goal Commands

- Way-Point Generation

Visualization

- Dspace

Navigation

- Locomotion & Haz. Avoidance
- Stereo Vision

- Terrain data
- DEM, Mesh

- Science Instruments

- Terrain data

DARTS
Rigid/Flexible Real-Time Multibody Dynamics Engine

Recipient of the NASA Software of the Year Award.


* DARTS solves equations of motion for flexible multi-body system based on the dynamics properties of the bodies in the system and the forces applied to those bodies. Based on Spatial Operator Algebra state-of-the-art algorithms.
• Kinematics and Dynamics of rigid/flex multibody systems
• Uses minimal DOF, **internal coordinate** formulation – eliminates constraints, is an **ODE** approach, and has superior numerical properties;
• Implements highly efficient **O(N)** recursive multibody dynamics algorithm in contrast with the more commonly used **O(N^3)** algorithm
• Based on **Spatial Operator Algebra** mathematical framework for multibody dynamics.
• General purpose with model data driven interface
• Models **multi-flexible** body systems and captures nonlinear rigid/flex nonlinear coupling

The more common and traditional approach uses a DAE formulation

**Pros**
- Full descriptor formulation
- Ability to handle any arbitrary constraint
- Diagonal mass matrix
- Conceptually easy to understand

**Cons**
- Computationally expensive
- Inexact constraint satisfaction
- Numerical issues of DAEs - stability and non-physical oscillations, convergence, singularity
Wheel/Soil Terramechanics

- Contact forces and torques on a six-wheel rover are statically indeterminate
  - $6 \times (6 \text{ wheels}) = 36$ unknowns
  - 6 equations (+3 for rocker/bogey)

- Wheel/soil interaction model
  - Lumped model for wheel/soil interaction (Bekker/Terzaghi)
  - Use Hunt/Crossley spring/damper models for normal forces at each wheel
  - Traction model to detect when in slippage regime – uses 2D tangent plane, 2 DOF spring/damper compliance model for contact point.
  - Tune model parameters based on empirical data

We chose to simulate the HMMWV vehicle

- Representative military vehicle
- Complex suspension
- U.S. Army interest as sensor platform
- Vehicle parameters from existing ADAMS model
HMMWV Quarter-Car Model

- Complex suspension model for each wheel
  - 5+ bodies (including chassis) in closed chain
  - revolute and ball joints
- Double “A-arm” suspension on each wheel
  - 2 A-arms (tan)
  - Spring-damper (green)
  - Wheel mount (pink)
  - Rider arm / steering linkages (purple)
- Not modeled: revolute joint bushings, drive train
Modeling Closed Chains

- Modeling multi-body systems with “closed chains” is inefficient.
- Tree topologies can be modeled using efficient recursive techniques to model body forces and motions.

internal closed loop
Modeling Closed Chains

- Fully Augmented (FA) model (DAE)
  - Non-minimal coors + constraints
  - Simple setup

- Tree Augmented (TA) model (DAE)
  - Minimal tree coors + constraints
  - Better for large loops

- Constraint Embedding (CE) model (ODE)
  - Minimal coors
  - Optimal for small loops
Comparison of multi-body modeling efficiency for HMMWV model

<table>
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<tr>
<th>Method</th>
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<th>No. of constraints</th>
<th>Augmented size</th>
<th>Sim time ratio</th>
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<td>15</td>
<td>0</td>
<td>15</td>
<td>1</td>
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<td>TA</td>
<td>45</td>
<td>30</td>
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<td>FA</td>
<td>216</td>
<td>201</td>
<td>417</td>
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Urban Simulation Environment (1km x 2km)

- Created using CityEngine
  - Combines high-rise section (middle) and “sub-urban” (outer)
  - Straight and curved roads
- Extracted surface height map for wheel-soil models
Off-Road terrain created with Height Map Editor and added textures
HMMWV Simulation in Urban Environment

GPS: (34.007666, -118.997819)

LIDAR Simulation
HMMWV Simulation in Urban Environment (autonomous)

- GPS Output
- LIDAR sim (live)
- Navigation based on waypoint following
- Obstacle avoidance
- Driver’s View (live)
- Data Logging/plotting
Lane Change Maneuver

- Speed up to 20 m/s (72 kph)
- Change lanes at 30s
- Maintain lane for 20s
- Change back to original lane

Normal forces acting vertically on wheels by the soil
Lane Change Maneuver Plots

- Roll degrees
- Pitch degrees
- Yaw degrees

Time (s)

Velocity (m/s)
- Longitudinal Velocity m/s
- Lateral Velocity m/s

Time (s)

Rate (deg/s)

Time (s)

Acceleration (m/s²)

Time (s)
Off-road simulation

Simulated control of HMMWV on off-road using teleoperation (joystick for driver steering and gas/brake)
Conclusions

• Demonstrated high-fidelity HMMWV model
  – Full multi-body dynamics model of front and rear suspension, and steering
    • Significant advantages using constraint-embedding approach
  – Sensor models (LIDAR, GPS, cameras)
  – Navigation and control
  – Operates at ½ real-time (without optimization)

• Useful for HMMWV modeling simulations
  – Sensor simulations, vehicle design, etc
  – Being deployed at ERDC with VANE

• Techniques could be applied to other types of military vehicles
Potential Future Work

• Potential areas to improve suspension model
  – Anti-sway bar
  – Bushings
  – Drive train
  – Steering column dynamics

• Validation against real vehicle data