Real Time Simulation for Off-Road Vehicle Analysis

Dr. Pasi Korkealaakso
Mevea Ltd., May 2015
Contents

• Introduction

• Virtual machine model

• Machine interaction with environment and realistic environment behavior

• Interaction with real machine control system

• Conclusion
Mevea Ltd.

• Mevea has been founded in 2005 and during its history it has delivered more than 100 simulator models to almost 50 customers in 15 countries. Mevea has a close co-operation with several universities and research institutes in order to provide world class solutions to its customers.

• Mevea simulators are based on the experiences, software and hardware developed during the last 10 years. A customer specific Mevea simulator includes the specific machine models, environments, training scenarios and hardware integrated with original machine controls.

• Mevea innovations have been recognized e.g. by Innofinland prize in 2011 (see picture on right).

• For more information, go to www.mevea.com or contact sales@mevea.com

Tarja Halonen
The President of the Republic of Finland

The national Innofinland Prize of the President of the Republic was awarded to Mevea Ltd. on November 29th, 2011:

“New generation’s product development simulator. The solution reduces the need for prototypes as the products are developed to a greater degree of completion in a virtual environment.”
Why real-time simulation in product development?

- In traditional product development approach the simulations like structural analysis using Finite Element Method (FEM) are done “offline” – i.e. calculation may take hours, when the real life phenomenon takes place in milliseconds.

- In the real-time simulation computer model runs at the same rate as the actual physical system.

- There are many situations where offline-simulation is not enough to simulate the real life machine behaviour e.g.
  - Virtual prototype of the full system is needed: operator – control system – machine(s) – environment
  - Control system should be tested with machine or vice versa
  - Operator involvement and feedback is needed

- Real-time simulation offers several business benefits in product development compared to traditional approach e.g.
  - Faster time to market
  - Savings in engineering and testing costs
  - Savings in quality costs

- Real time simulation is a good extension to offline simulation
What is required for the accurate real time simulation in product development?

• The accurate real time simulation requires the following elements to be taken into account in simulation:
  1. Accurate virtual machine model
     - modelling of actuators (=force producing elements) like hydraulics and engine
     - modelling of mechanical structures like rigid / flexible bodies
  2. Machine interaction with environment and realistic environment behaviour
  3. Integration or simulation of the real machine control system (software / hardware)

• In the following pages we will explain each of the above areas in more detail in the scope of off-road construction vehicles.
Contents

• Introduction

• Virtual machine model

• Machine interaction with environment and realistic environment behavior

• Interaction with real machine control system

• Conclusion
Virtual machine model

- The foundation for accurate real time simulation is the virtual machine model including:
  - Rigid and flexible structures like cabin, frame, attachments etc.
  - Actuators like hydraulics and engine
  - Powertrain

- As the hydraulic is one of the main elements in the construction equipment it should be included into real time simulation with details like:
  - The amount of non-dissolving air in oil is taken into account as a function of pressure
  - The flexibility of hoses is taken into account as a function of pressure
  - Hydraulic pump causes load to engine
  - Valves and valve block internal spools are modelled depending on the valve type, e.g. pressure compensator spool, pressure reducing spools, shock spools, anti-cavitation spools and lock spools

- Also tires and their interaction with soil should be part of accurate virtual machine model

Examples of simplified wheel loader powertrain and hydraulics models in Mevea real time simulation
Mevea Solver - Overview

### Preprocessor
- Parser
- Initialization

### Solver
#### Solution methods
- **Augmented Lagrangian**
- Baumgarte
- Coordinate partitioning
- Penalty function
- Recursive method

#### Numerical solution
- Runge-Kutta methods
- Gear-stiff

#### Collision solver
- Particle solver

#### Process models
- Task handling

#### Component libraries
- Tyres
- Power train
- Hydraulics
- Fluid resistance

### Interfaces
- Synchronous
- Asynchronous

---

**Multibody system dynamics (MBS) basic equation in numerically solvable matrix form**

\[
\begin{bmatrix}
\dot{q}
\end{bmatrix} = \begin{bmatrix}
M & C_q^T \\
C_q & 0
\end{bmatrix}^{-1} \begin{bmatrix}
Q_e + Q_v \\
Q_d
\end{bmatrix}
\]

**Method of Lagrange multipliers**

\[
M\ddot{q} + C_q^T \alpha (\ddot{C} + 2\Omega \dot{C} + \Omega^2 C) + C_q^T \lambda^* = Q_e + Q_v
\]

\[
\lambda_i = \lambda^* + \alpha (\ddot{C} + 2\Omega \dot{C} + \Omega^2 C)_{i+1}, \quad i = 0, 1, 2, \ldots
\]

**Augmented Lagrangian method**

**Recursive method**

\[
(R^TMR + \alpha C_q^T C_q) \ddot{z} = R^T(Q_e + Q_i) - R^TMS_i + \alpha C_q^T (Q_e - C_q S_c)
\]

\[
C_z = C_q R
\]

---

**External forces** $Q_e$ acting to a body
- Hydraulic actuator forces
- Tyre forces
- Rope forces
- Contact forces
- Wind resistance forces
- Etc.
Mevea Solver - Structural Flexibility

- Modelling of structural flexibility is done utilising the floating frame of reference approach.
- The approach is used in most off-line simulation applications.
- The method is based on local floating frame to which the modes describing flexibility are attached.
- The modes $\mathbf{y}$ are solved using FE-software (Ansys + mode solver).
- The description of flexible behaviour is solved by summing separate modes multiplied with their coefficient factor $q_f$. 

$$
\begin{bmatrix}
\int \rho \beta h w_t^2 \, dV & -\int \rho \beta h w_t v_t \, dV \\
-\int \rho \beta h w_t v_t \, dV & \int \rho \beta h v_t^2 \, dV \\
\end{bmatrix}
\begin{bmatrix}
w_t \\
v_t \\
\end{bmatrix}
= 
\begin{bmatrix}
\int \rho \beta h w_t \mathbf{F}^T \, dV \\
-\int \rho \beta h v_t \mathbf{F}^T \, dV \\
\end{bmatrix}
+ 
\begin{bmatrix}
\int \left( \rho \beta h w_t^2 + 2\rho \beta h \mathbf{w}^T \mathbf{v} \mathbf{v}^T \mathbf{v} \right) \, dV \\
\int \left( -\rho \beta h v_t^2 + 2\rho \beta h \mathbf{w}^T \mathbf{v} \mathbf{v}^T \mathbf{v} \right) \, dV \\
\end{bmatrix}
\begin{bmatrix}
w_t \\
v_t \\
\end{bmatrix}
- 
\begin{bmatrix}
0 \\
0 \\
\end{bmatrix}
= 
\begin{bmatrix}
Kq_t \\
0 \\
\end{bmatrix}
\end{align*}
Mevea Solver - Tyre Modelling

• Tyre modelling is based on either Pacejka’s Magic Formula or LuGre friction model

• Currently used Magic Formula version is 2002

• LuGre friction model based tyre model includes static friction

• In basic form Magic Formula does not provide any force with zero slip
Mevea Solver - Hydraulics Modelling

- Hydraulics modelling is based on the theory of evenly distributed pressures

\[ \dot{p}_i = \frac{B_{el}}{V_i} \left( \sum_{j=1}^{n_c} Q_{ij} \right) \]

- Hydraulic components produce flow rate into volumes

- Flow rates are modelled based on the equation of turbulent flow

\[ Q = C_v U \sqrt{|p_0 - p_1|} \]

- Hydraulic pumps effect on engine load
Mevea Solver - Hydraulics Editor

• Hydraulic circuits can also be modelled schema based editor

• Add components into schema and connect ports

• Visual presentation can be viewed during simulation run time

• Components are visualised in detailed level – even the positions of valve internal spools move

• Flow rates, pressure rates, etc. can be observed from shcema
<table>
<thead>
<tr>
<th>Model Characteristics</th>
<th>Value</th>
<th></th>
<th>Model Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excavator Simulation Model</strong></td>
<td></td>
<td></td>
<td><strong>Forest Harvester Simulation Model</strong></td>
<td></td>
</tr>
<tr>
<td>Mechanical bodies</td>
<td>13</td>
<td></td>
<td>Mechanical bodies</td>
<td>29</td>
</tr>
<tr>
<td>Dummy bodies</td>
<td>20</td>
<td></td>
<td>Dummy bodies</td>
<td>75</td>
</tr>
<tr>
<td>Valves</td>
<td>Pressure relief: 11 Counter balance: 3 Directional: 12 Safety: 15</td>
<td></td>
<td>Valves</td>
<td>Pressure relief: 9 Directional: 17 Safety: 8</td>
</tr>
<tr>
<td>Actuators</td>
<td>Cylinders: 8 Motors: 4 Pumps: 2</td>
<td></td>
<td>Actuators</td>
<td>Cylinders: 21 Motors: 7</td>
</tr>
<tr>
<td>Hydraulic volumes in simulation model</td>
<td>48</td>
<td></td>
<td>Others</td>
<td>Pumps: 2 Accumulators: 2</td>
</tr>
<tr>
<td>Simulation time step</td>
<td>1 ms</td>
<td></td>
<td>Hydraulic volumes in simulation model</td>
<td>48</td>
</tr>
<tr>
<td>Control signals</td>
<td>25</td>
<td></td>
<td>Simulation time step</td>
<td>1 ms</td>
</tr>
<tr>
<td>Machine control systems</td>
<td>none</td>
<td></td>
<td>Control signals</td>
<td>Input: 40, Output: 21</td>
</tr>
<tr>
<td>Machine control systems</td>
<td>Real for harvester head control and powertrain</td>
<td></td>
<td>Machine control systems</td>
<td>Real for harvester head control and powertrain</td>
</tr>
</tbody>
</table>
Contents

• Introduction

• Virtual machine model

• Machine interaction with environment and realistic environment behavior

• Interaction with real machine control system

• Conclusion
Machine interaction with environment and realistic environment behaviour

• Machine environment interaction modelling in real time simulation is called process modelling. Examples of the process models are:
  • Earth moving, e.g. soil and rocks
  • Container fields in harbours
  • Forest
  • Line systems like cables, hydraulic hoses and tracks
  • Solid rock walls, e.g. scaling

• Accurate environment model is critical element in real time construction equipment simulation – environment should not only look nice, but it should also behave in realistic manner including:
  • Sinking in the ground
  • Soil compaction
  • Embedding particles back to the soil with volume update, i.e. accumulation of material on the ground
  • Visually and physically correct behaviour under operations like excavating, e.g. weight of the soil and soil resistance
Collision Modelling

- Triangularized collision model
- Key advantages in comparison to traditional contact models
  - Objects do not slide over time. For example if left to steep slopes for extended periods. This is due to the use of a dynamic friction model. Models with static friction suffer from several problems for example creep. A dynamic friction model requires temporal data which has not been available in any previous triangle based method.
  - Collision model functions consistently regardless of the colliding object shape.
  - The possibility to realize complicated processes involving collisions
Line Systems

- Elongation under tension
- Bending forces
- Internal friction in reels and pulleys
- Layering on the reel
- Varying spool position
- Simulation when several pulleys are connected in series
  - Pulleys can be modeled separately or they can be combined to behave as a rigid assembly
  - Rope is defined from constraint to constraint starting from the reel

Machine interaction with environment and realistic environment behaviour
Tracks

- Driving pulleys are connected to power transmission system of the vehicle
- Can be modeled utilizing line systems by coupling the chains in transverse direction
- Each track piece is considered as dynamic object
- Reaction forces from the track contact to vehicle is adjusted by contact and friction properties
Earthmoving

- Progression from deformable geometry approach to heightfields
- As a shape of contact geometry is a sphere the reaction forces from the track contact to vehicle must be tuned using friction properties
- In both solutions realistic environment interaction
Earth moving - Heightfield

- Heightfield based algorithm
- Sinking in the ground
- Soil compaction
- Visual and physically correct grooves after drawing
- Filling of the bucket using physically correct mass particles
- Embedding particles back to the heightfield with volume update
Machine interaction with environment and realistic environment behaviour

Examples of Environments for Virtual Testing
Contents

• Introduction

• Virtual machine model

• Machine interaction with environment and realistic environment behavior

• Interaction with real machine control system

• Conclusion
Integration with real machine control system

Model Creation
- Mevea Modeller
- Mevea I/O Mapping Tool
- Mevea I/O Signal Tool

Simulation Model
- Machine Model
- Environment Model
- Mevea I/O Map

Real Time Simulation
- Mevea Solver
- Motion Platform Controller
- I/O Pool

User Experience
- Motion Platform
- Adapter (joystick, pedal)
- Adapter
- Adapter
- ECU (Electronic Control Unit)
- Other Hardware (HIL simulation)
- I/O

- I/O Pool = Universal I/O storage (controls, sensors, motion platform, etc.)
- Mevea I/O Client = Middleware for connecting IO Pool to case specific I/O
- I/O = Case specific software and/or hardware
- Mevea I/O Signal Tool = Software for defining signal properties of I/O
- Mevea I/O Mapping Tool = Software for defining signal pairs
- Mevea I/O Map = Signal pair definition file between I/O and simulation model
Interaction with real machine control system

**Simulator Example**

**REAL PRODUCT (OR IDEA)**

- PC - machine model
- - environment model
- - I/O map
- - virtual control modules

**SIMULATOR**

- Display
- Motion controller
- Motion actuator

**CANbus**

- I/O
- CAN master
- Controls

**Real life view (Virtual environment)**

- Real operator environment
- Motion feedback

- Computers (Virtual machine)
Contents

• Introduction

• Virtual machine model

• Machine interaction with environment and realistic environment behavior

• Interaction with real machine control system

• Conclusion
Conclusion

Final words

• Mevea aims to be state of the art in simulation and simulation solutions by focusing real time simulation of dynamics based on extensive research
  • Mechanics
  • Hydraulics
  • Power transmission
  • Operating environment

• In order to get realistic testing scenarios for test operators accurate environment model must be considered as one of the critical elements in real time off-road vehicle simulation