Accomplishing Ground Moving Innovations through Modeling, Simulation, and Optimal Control

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The Application

Big Toys for Big Boys
The Application
Short Loading Cycle

- Pick up gravel
- Reverse and lift
- Stop
- Drive and lift
- Empty bucket
- Reverse and lower
- Stop
- Drive
- Fill Bucket

-How to drive optimally?
Outline

• Wheel loader application
  • How to operate the wheel loader optimally
  • Modeling for control and optimal control
• Formulating and solving the optimal control problem
  • Numerical optimal control
• Design problems and trade-offs
  • Solving fuel and time optimal driving
  • Design case – Stiff converter
  • Design case – Intelligent braking
  • Design case – Where to park load receiver?
• Conclusions
Wheel loader model

Sub systems:

1- Driveline

Controls: Fuel injection, Brake torque signal.

States: Engine speed, Intake manifold pressure, Vehicle speed.

2- Lifting system

Controls: Bucket lift acceleration.

States: Bucket height, Bucket lift speed.

3- Steering system

Controls: Derivative of steering angle.

States: Vehicle position X & Y, Heading angle, Steering angle.
Wheel loader model

\[
\frac{d\omega_{\text{ice}}}{dt} = \frac{1}{J_{\text{ice}}} \left( T_{\text{ice}}(U_{mf}, \omega_{\text{ice}}) - \frac{P_{\text{load}}(V_{\text{buc}}, V)}{\omega_{\text{ice}}} \right)
\]

(1)

\[
\frac{dS}{dt} = V
\]

(2)

\[
\frac{dV}{dt} = \text{sign}(\gamma) \left( F_{\text{trac}}(U_b, \omega_{\text{ice}}) - F_{\text{roll}} \right)
\]

(3)

\[
\frac{dH_{\text{buc}}}{dt} = V_{\text{buc}}
\]

(4)

\[
\frac{dV_{\text{buc}}}{dt} = U_{ab}
\]

(5)
Diesel engine model

\[ T_{ic} = T_{ig} - T_{fric} \]
\[ \eta_{ig} = \eta_{ig,ch} \left( 1 - \frac{1}{r_c \gamma_{cyl}-1} \right) \]
\[ T_{ig} = \frac{\eta_{ig} q_{hv} n_{cyl} U_{mf} 10^{-6}}{2 \pi n_r} \]
\[ T_{fric} = \frac{V_d 10^5}{4\pi} \left( c_{fr1} \omega_{ic}^2 + c_{fr2} \omega_{ic} + c_{fr3} \right) \]
\[ \dot{m}_f = \frac{10^{-6}}{4 \pi} U_{mf} \omega_{ic} n_{cyl} \]
\[ P_{load} = P_{trac} + P_{lift} \]

\[ \frac{d\omega_{ic}}{dt} = \frac{1}{J_{ic}} \left( T_{ic} (U_{mf}, \omega_{ic}) - \frac{P_{load}(V_{buc}, V)}{\omega_{ic}} \right) \quad (1) \]
Lift system and constraints

\[
F_{\text{load}} = M_{\text{buc}} (g + U_{ab})
\]

\[
P_{\text{lift,net}} = F_{\text{load}} V_{\text{buc}}
\]

\[
P_{\text{lift}} = \frac{(1 + C_{\text{loss}}) P_{\text{lift,net}}}{\eta_{\text{lift}}}
\]

\[
\frac{dH_{\text{buc}}}{dt} = V_{\text{buc}} \quad (4)
\]

\[
\frac{dV_{\text{buc}}}{dt} = U_{ab} \quad (5)
\]

\[
V_{\text{lift, max}} = k(\theta_2) V_{\text{pist, max}}
\]
Torque converter

- 2 T.C. studied (one delivers 15% more torque)
- Remove the discontinuities (efficient numerical optimization)
  - Differentiable model
Vehicle speed and position

\[
\begin{align*}
F_{trac} &= \frac{T_w - \text{sign}(V) T_b}{r_w} \\
F_{roll} &= c_r (M_{veh} + M_{buc}) g \\
T_w &= T_{gb} \eta_{gb} \gamma \\
T_b &= U_b
\end{align*}
\]

\[
\frac{dS}{dt} = V
\]

\[
\frac{dV}{dt} = \frac{\text{sign}(\gamma) \left( F_{trac}(U_b, \omega_{ice}) - F_{roll} \right)}{M_{tot}}
\]
Steering system and vehicle position

\[ P_{\text{steer}} \propto \text{Derivative of steering angle} \ U_{\text{str}}^2 \]

\[
\frac{d\delta}{dt} = U_{\text{str}} \\
\frac{d\theta}{dt} = \frac{V}{R} \\
\frac{dX}{dt} = V \cos(\theta) \\
\frac{dY}{dt} = V \sin(\theta)
\]

Constraints during steering

**Continuous steering angle**

\[ U_{\text{str,min}} \leq U_{\text{str}} \leq U_{\text{str,max}} \]

**Minimum turning radius**

\[ R_{\text{min}} \leq \frac{L}{2 \tan(\frac{\delta}{2})} = R \]
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Lift transport section (and complete cycle)

- Minimum Time
- Minimum Fuel
Optimal Control Problem
Complete cycle – Fork lift application

\[
\min_{s(t), u(t), \gamma(t)} \quad T \text{ or } M_f
\]

s.t.

\[
\dot{s}(t) = f(s(t), u(t), \gamma(t))
\]

\[
u_{min} \leq u(t) \leq u_{max}
\]

\[
s_{min} \leq s(t) \leq s_{max}
\]

\[
R \leq R_{max}
\]

\[
T_{ice}(s(t), u(t)) \leq T_{ice,max}
\]

\[
p_{cyl}(s(t), u(t)) \leq p_{cyl,max}
\]

\[
s(0) = (120, 0, 0, 0, 1.1 \times 10^{13} 00, \frac{\pi}{2}, 0, 0, 0)
\]

\[
t \in [0, t_1] : \gamma(t) = 0, h_{lift}(t_1) = 0.2,
\]

\[
t \in [t_1, t_2] : \gamma(t) = -60,
\]

\[
t \in [t_2, t_3] : \gamma(t) = 0, \dot{v}(t_3) = 0, \dot{v}_{min} \leq |\dot{v}(t)|,
\]

\[
t \in [t_3, t_4] : \gamma(t) = 60, h_{lift}(t_4) = h_{end},
\]

\[
t \in [t_4, t_5] : \gamma(t) = 0, u_{dstr}(t) = u_{ab}(t) = \delta(t) = v(t_5) = 0,
\]

\[
\int_{t_4}^{t_5} v \, dt = L_p, (x, y)(t_5) = [x_c, y_c], \dot{v}_{min} \leq |\dot{v}(t)|,
\]

\[
t \in [t_5, t_6] : \gamma(t) = v(t) = 0, h(t_6) = h_{end} - 0.2,
\]

\[
t \in [t_6, t_7] : \gamma(t) = -60, u_{ab}(t) = u_{dstr}(t) = \delta(t) = 0,
\]

\[
\int_{t_6}^{t_7} v \, dt = -L_p,
\]

\[
t \in [t_7, t_8] : \gamma(t) = -60, h_{lift}(t_8) = 0.2,
\]

\[
t \in [t_8, t_9] : \gamma(t) = 0, u_{ab}(t) = v(t_9) = 0, \dot{v}_{min} \leq |\dot{v}(t)|,
\]

\[
t \in [t_9, t_{10}] : \gamma(t) = 60, u_{ab}(t) = 0,
\]

\[
t \in [t_{10}, T] : \gamma(t) = 0, u_{ab}(T) = u_{dstr}(T) = u_b(T) = 0,
\]

\[
s(T) = (-, 0, 0, 0, -\frac{\pi}{2}, 0, 0, 0), \dot{v}_{min} \leq |\dot{v}(t)|,
\]
PROPT tool and model implementation
Path to Efficient Solution

- Discretize state and controls in time
  Very large but sparse optimization problems

- Efficient solvers available
  IPOPT, SNOPT, KNITRO

- Efficient by using gradients and hessians.
  Use Algorithmic Differentiation

- Packages enable us to formulate problem and enter models that are differentiable.
  DIRCOL, ACADO, PROPT, CasADi, OpenModelica…

- Can now solve large non-linear problems efficiently
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Lift & transport section

- Minimum Time
- Minimum Fuel
Time and fuel optimal solutions, trajectories

Min $T$:
- acceleration » lifting » acceleration » lifting

Min Fuel:
- Avoiding high engine speeds.
- Simultaneous acceleration and lifting
Trade-off between fuel and time optimal

- Pareto front informative
  - Fuel optimal cycle 50 % shorter -> only 5 % fuel cost
  - Time optimal cycle 5 % longer -> 30 % fuel savings
- Total Cost Optimization
  - Site optimization
Torque converter selection

- 2 T.C. studied (one delivers 15% more torque)
- No efficiency difference.
Trade-off between fuel and time optimal

- Stiff torque converter is proven better – New knowledge
- It's a free lunch.
- In production = Innovation
Intelligent Braking
Torque Converter vs Service Brakes

- How much is saved?

Easy driving
- Switch to reverse
- Use engine and torque converter to brake

New idéa:
- Switch to reverse
- Control service brakes
Intelligent Braking
Torque Converter vs Service Brakes

Intelligent braking is
- More efficient
- Faster
- In production = Innovation
Free Load Receiver Placement

Increased freedom

- Position
- Orientation
Full Wheel Loader Model

Sub systems:

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Trajectory from loading point to load receiver
(Half short loading cycle)

Same trajectory for Min $M_f$ and Min $T$ cycles
Innovation – Changed Driver Instructions
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Publications for further reading

• **1 - Parallel Multiple-Shooting and Collocation Optimization with OpenModelica.** Bernhard Bachmann, Lennart Ochel, Vitalij Ruge, Mahder Gebremedhin, Peter Fritzson, Vaheed Nezhadali, Lars Eriksson, and Martin Sivertsson (2012).
  In: Modelica 2012 -- 9th International Modelica Conference. Munich, Germany.

• **2 - Modeling and Optimal Control of a Wheel Loader in the Lift-Transport Section of the Short Loading Cycle.**
  Vaheed Nezhadali, and Lars Eriksson.
  In: 7th IFAC Symposium on Advances in Automotive Control. Tokyo, Japan.

• **3 - Optimal Control of Wheel Loader Operation in the Short Loading Cycle Using Two Braking Alternatives.**
  Vaheed Nezhadali, and Lars Eriksson.

• **4 - Optimal lifting and Path Profiles for a Wheel Loader Considering Engine and Turbo Limitations.**
  Vaheed Nezhadali, and Lars Eriksson.

• **5 - Turbocharger Dynamics Influence on Optimal Control of Diesel Engine Powered Systems.**
  Vaheed Nezhadali, Martin Sivertsson and Lars Eriksson.
  In: SAE World Congress 2014, Detroit, USA.

• **6 - Wheel loader optimal transients in the short loading cycle.**
  Vaheed Nezhadali, Lars Eriksson.
  The 19th IFAC World Congress 2014, South Africa.
Outline - Conclusions

• Numerical Optimal Control
  • Tools are now mature
  • Solve industrially relevant problems
    • Large size of the state vector
    • Significant nonlinearities
  • Impact on product development beside control
  • Point out counter-intuitive but optimal solutions
• Relevant models, tools, and problems accelerate innovation.
Thank You for Your Attention!