Modeling, Simulation and Optimal Control for Ground Moving Innovations

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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

\begin{align*}
\text{States:} & \quad \begin{cases}
\omega_{ice} & \text{Engine speed} \\
S & \text{Travelled distance} \\
V & \text{Vehicle speed} \\
H_{bucket} & \text{Lift height} \\
V_{bucket} & \text{Lift speed}
\end{cases} \\
\text{Controls:} & \quad \begin{cases}
U_{mf} & \text{Fuel} \\
U_{ab} & \text{Bucket acceleration} \\
U_b & \text{Braking torque}
\end{cases}
\end{align*}

\begin{align*}
\frac{d\omega_{ice}}{dt} &= \frac{1}{J_{ice}} \left( T_{ice}(U_{mf}, \omega_{ice}) - \frac{P_{load}(V_{buc}, V)}{\omega_{ice}} \right) \\
\frac{dS}{dt} &= V \\
\frac{dV}{dt} &= \text{sign}(\gamma) \left( F_{trac}(U_b, \omega_{ice}) - F_{roll} \right) \frac{1}{M_{tot}} \\
\frac{dH_{buc}}{dt} &= V_{buc} \\
\frac{dV_{buc}}{dt} &= U_{ab}
\end{align*}
Diesel engine model

\[ T_{ice} = T_{ig} - T_{fric} \]

\[ \eta_{ig} = \eta_{ig, ch} \left( 1 - \frac{1}{r_{c}^{\gamma_{cyl}} - 1} \right) \]

\[ T_{ig} = \frac{\eta_{ig} q_{hv} n_{cyl} U_{mf} 10^{-6}}{2 \pi n_{r}} \]

\[ T_{fric} = \frac{V_{d} 10^{5}}{4 \pi} \left( c_{fr1} \omega_{ice}^2 + c_{fr2} \omega_{ice} + c_{fr3} \right) \]

\[ \dot{m}_{f} = \frac{10^{-6}}{4 \pi} U_{mf} \omega_{ice} n_{cyl} \]

\[ P_{load} = P_{trac} + P_{lift} \]

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

\[ F_{trac} = \frac{T_w - \text{sign}(V) T_b}{r_w} \]

\[ F_{roll} = c_r (M_{veh} + M_{buc}) g \]

\[ T_w = T_{gb} \eta_{gb} \gamma \]

\[ T_b = U_b \]

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

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

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

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

\[
\begin{align*}
\min_{s(t), u(t), \gamma(t)} & \quad T \quad \text{or} \quad M_f \\
\text{s.t.} & \quad \dot{s}(t) = f(s(t), u(t), \gamma(t)) \\
& \quad u_{\min} \leq u(t) \leq u_{\max} \\
& \quad s_{\min} \leq s(t) \leq s_{\max} \\
& \quad R \leq R_{\max} \\
& \quad T_{\text{ice}}(s(t), u(t)) \leq T_{\text{ice, max}} \\
& \quad p_{\text{cyl}}(s(t), u(t)) \leq p_{\text{cyl, max}} \\
& \quad s(0) = (120, 0, 0, 0, 1.1 \times 10^3, 0, 0, 0, \frac{\pi}{2}, 0, 0, 0) \\
& \quad t \in [0, t_1] : \quad \gamma(t) = 0, \quad h_{\text{lift}}(t_1) = 0.2, \\
& \quad t \in [t_1, t_2] : \quad \gamma(t) = -60, \\
& \quad t \in [t_2, t_3] : \quad \gamma(t) = 0, \quad v(t_3) = 0, \quad \dot{v}_{\min} \leq |\dot{v}(t)|, \\
& \quad t \in [t_3, t_4] : \quad \gamma(t) = 60, \quad h_{\text{lift}}(t_4) = h_{\text{end}}, \\
& \quad t \in [t_4, t_5] : \quad \gamma(t) = 0, \quad u_{\text{dstr}}(t) = u_{\text{ab}}(t) = \delta(t) = v(t_5) = 0, \\
& \quad \int_{t_4}^{t_5} v \, dt = L_p, \quad (x, y)(t_5) = [x_e, y_e], \quad \dot{v}_{\min} \leq |\dot{v}(t)|, \\
& \quad t \in [t_5, t_6] : \quad \gamma(t) = v(t) = 0, \quad h(t_6) = h_{\text{end}} - 0.2, \\
& \quad t \in [t_6, t_7] : \quad \gamma(t) = -60, \quad u_{\text{ab}}(t) = u_{\text{dstr}}(t) = \delta(t) = 0, \\
& \quad \int_{t_6}^{t_7} v \, dt = -L_p, \\
& \quad t \in [t_7, t_8] : \quad \gamma(t) = -60, \quad h_{\text{lift}}(t_8) = 0.2, \\
& \quad t \in [t_8, t_9] : \quad \gamma(t) = 0, \quad u_{\text{ab}}(t) = v(t_9) = 0, \quad \dot{v}_{\min} \leq |\dot{v}(t)|, \\
& \quad t \in [t_9, t_{10}] : \quad \gamma(t) = 60, \quad u_{\text{ab}}(t) = 0, \\
& \quad t \in [t_{10}, T] : \quad \gamma(t) = 0, \quad u_{\text{ab}}(T) = u_{\text{dstr}}(T) = u_{\text{b}}(T) = 0, \\
& \quad s(T) = (-0.0, 0.0, -\frac{\pi}{2}, 0.0, 0.0), \quad \dot{v}_{\min} \leq |\dot{v}(t)|,
\end{align*}
\]
PROPT tool and model implementation
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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

Optimal Control Points out Optimal Solution
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
- Its a free lunch.
- In production = Innovation
Intelligent Braking
Torque Converter vs Service Brakes

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

New idéa:
• Switch to reverse
• Control service brakes
• At rest switch to forward

- How much is saved?
Intelligent braking is
- More efficient
- Faster
- In production = Innovation
Free Load Receiver Placement

Increased freedom

- Position
- Orientation
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

  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!