On the Tuning of Predictive Controllers for Hybrid Fuel Cell Vehicle Applications

Syed Ahmed
Corning

Oluwasanmi Adeodu
and
Donald J. Chmielewski
Illinois Institute of Technology
Outline

• Hybrid Vehicle Model
• Controller Tuning Challenge
• Economic Linear Optimal Control
• Constrained ELOC
Hybrid Vehicle Operation
Servo-Loops with PI Controllers
Supervisory Control

High Level Controller

Vehicle Power System

$P_{mot}^{(sp)}$

$P_{fc}^{(sp)}$

$P_{bat}^{(sp)}$

$P_{scap}^{(sp)}$

$P_{mot}$

$P_{fc}$

$P_{bat}$

$P_{scap}$

$P_{bat}$

$P_{fc}$

$P_{scap}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$

$P_{mot}$

$P_{bat}$

$P_{fc}$
High Level Battery Model

\[ \dot{E}_{bat} = P_{bat} - P^{(loss)}_{bat} \]

\[ 0 \leq E_{bat} \leq E_{bat}^{\max} \]

\[ P_{bat}^{\min} \leq P_{bat} \leq P_{bat}^{\max} \]

\[ P^{(loss)}_{bat} = c_{l,bat} P_{bat}^2 \]
High Level Super Capacitor Model

\[
\dot{E}_{sc} = P_{sc} - P_{sc}^{(loss)}
\]

\[
0 \leq E_{sc} \leq E_{sc}^{\max}
\]

\[
P_{sc}^{\min} \leq P_{sc} \leq P_{sc}^{\max}
\]

\[
P_{sc}^{(loss)} = c_{l,sc} P_{sc}^{2}
\]
High Level Fuel Cell Model

\[ \dot{P}_{fc} = \Delta P_{fc} \]

\[ 0 \leq P_{fc} \leq P_{fc}^{max} \]

\[ \Delta P_{fc}^{min} \leq \Delta P_{fc} \leq \Delta P_{fc}^{max} \]
Driver Commands

Power Balance:

\[ P_{mot} = P_{bat} + P_{sc} + P_{fc} \]

\[ P_{sc} = P_{mot} - P_{bat} - P_{fc} \]

\[ \dot{E}_{sc} = P_{sc} - c_{l,sc} P_{sc}^2 \]
Outline

- Hybrid Vehicle Model
- **Controller Tuning Challenge**
- Economic Linear Optimal Control
- Constrained ELOC
Constraints Motivate the use of MPC

\begin{align*}
0 \leq E_{bat} & \leq E_{bat}^{\text{max}} \\
P_{bat}^{\text{min}} & \leq P_{bat} \leq P_{bat}^{\text{max}} \\
0 \leq E_{sc} & \leq E_{sc}^{\text{max}} \\
P_{sc}^{\text{min}} & \leq P_{sc} \leq P_{sc}^{\text{max}} \\
0 \leq P_{fc} & \leq P_{fc}^{\text{max}} \\
\Delta P_{fc}^{\text{min}} & \leq \Delta P_{fc} \leq \Delta P_{fc}^{\text{max}}
\end{align*}
Model Predictive Control

\[ P_{mot}^{(sp)} \rightarrow PI \rightarrow k_{fc} \rightarrow P_{fc} \]

\[ P_{scap}^{(sp)} \rightarrow PI \rightarrow k_{scap} \rightarrow P_{scap} \]

\[ P_{bat}^{(sp)} \rightarrow PI \rightarrow k_{bat} \rightarrow P_{bat} \]

Vehicle

Power System

MPC

\[ P_{mot}^{(sp)} \]

\[ P_{fc} \]

\[ P_{scap} \]

\[ P_{bat} \]
MPC Tuning

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q x_{k|i} + u_{k|i}^T R u_{k|i}) \right\} \quad \text{s.t.}
\]

\[
x_{k+1|i} = A x_{k|i} + B u_{k|i}
\]

\[
z_{k|i} = D_x x_{k|i} + D_u u_{k|i}
\]

\[
z_{\text{min}} \leq z_{k|i} \leq z_{\text{max}}
\]

\[
x_{i|i} = x_i
\]
Outline

• Hybrid Vehicle Model
• Controller Tuning Challenge
• Economic Linear Optimal Control
• Constrained ELOC
Economic Linear Optimal Control

\[ u_k = L_{ELOC} x_k \]
Where are the Economics?

\[ P_{bat}^{(loss)} = c_{l,bat} P_{bat}^2 \]

\[ E[P_{bat}] = P_{bat} \]
\[ = c_{l,bat} \left( P_{bat}^2 + \sigma_{bat}^2 \right) \]

\[ \dot{E}_{bat} = P_{bat} - P_{bat}^{(loss)} \]
\[ 0 = P_{bat} - P_{bat}^{(loss)} \]

\[ P_{bat}^{(loss)} = P_{bat} \]
\[ 0 = P_{bat} - c_{l,bat} \left( P_{bat}^2 + \sigma_{bat}^2 \right) \]
ELOC for Hybrid Vehicle

\[
\min \left\{ \overline{P}_{bat}^{(loss)} + \overline{P}_{sc}^{(loss)} \right\}
\]

\[
\overline{P}_{bat}^{(loss)} = \overline{P}_{bat} \quad 0 = \overline{P}_{bat} - c_{l,bat} \left( \overline{P}_{bat}^2 + \sigma_{bat}^2 \right)
\]

\[
\overline{P}_{sc}^{(loss)} = \overline{P}_{sc} \quad 0 = \overline{P}_{sc} - c_{l,sc} \left( \overline{P}_{sc}^2 + \sigma_{sc}^2 \right)
\]

Plus constraints on dynamics

\[
\Rightarrow \quad u_k = L_{ELOC} \chi_k
\]
Controller Constraints

\[ E_{\text{cap}} \text{ (kJ)} \]

\[ P_{\text{cap}} \text{ (KW)} \]

\[ E_{\text{bat}} \text{ (kJ)} \]

\[ P_{\text{bat}} \text{ (KW)} \]

\[ P_{\text{fc}} \text{ (KW)} \]

\[ \Delta P_{\text{fc}} \text{ (mW/s)} \]
Average Power Loss

\[
\overline{P}_{sc} = \overline{P}_{sc}^{(loss)}
\]

\[
\overline{P}_{bat} = \overline{P}_{bat}^{(loss)}
\]
ELOC Scatter Plots

1. Scatter plot showing the relationship between $E_{cap}$ (kJ) and $P_{cap}$ (KW).
2. Scatter plot showing the relationship between $E_{bat}$ (kJ) and $P_{bat}$ (KW).
3. Scatter plot showing the relationship between $P_{fc}$ (KW) and $\Delta P_{fc}$ (mW/s).

Illinois Institute of Technology
Department of Chemical and Biological Engineering
Outline

• Hybrid Vehicle Model
• Controller Tuning Challenge
• Economic Linear Optimal Control
• Constrained ELOC
Inverse Optimality

Linear Quadratic Regulator

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x^T_{k|i}Qx_{k|i} + u^T_{k|i}Ru_{k|i}) + x^T_{i+N|i}Px_{i+N|i} \right\} \quad \text{s.t.} \quad \begin{align*}
    x_{k+1|i} &= Ax_{k|i} + Bu_{k|i} \\
x_{i|i} &= x_i
\end{align*}
\]

\[
u_i = L_{LQR} x_i
\]

Predictive Form of ELOC

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x^T_{k|i}Q_{ELOC}x_{k|i} + u^T_{k|i}R_{ELOC}u_{k|i}) + x^T_{i+N|i}P_{ELOC}x_{i+N|i} \right\} \quad \text{s.t.} \quad \begin{align*}
    x_{k+1|i} &= Ax_{k|i} + Bu_{k|i} \\
x_{i|i} &= x_i
\end{align*}
\]

\[
u_i = L_{ELOC} x_i
\]

* see Chmielewski & Manthanwar (2004) for details
Constrained ELOC

\[
\min_{x_{k|i}, u_{k|i}} \left\{ \sum_{k=i}^{i+N-1} (x_{k|i}^T Q_{ELOC} x_{k|i} + u_{k|i}^T R_{ELOC} u_{k|i}) + x_{i+N|i}^T P_{ELOC} x_{i+N|i} \right\} \]

s.t.

\[
x_{k+1|i} = A x_{k|i} + B u_{k|i}
\]

\[
x_{i|i} = x_i
\]

\[
z_{k|i} = D_x x_{k|i} + D_u u_{k|i}
\]

\[
z_{\text{min}} \leq z_{k|i} \leq z_{\text{max}}
\]
Constrained ELOC Scatter Plots

- Constrained ELOC Scatter Plots for $E_{\text{cap}}$ and $P_{\text{cap}}$
- Constrained ELOC Scatter Plots for $E_{\text{bat}}$ and $P_{\text{bat}}$
- Constrained ELOC Scatter Plots for $P_{fc}$ and $\Delta P_{fc}$
Constrained ELOC

![Graph showing ELOC and Constrained ELOC over time with corresponding E and P values.](image-url)
Constrained ELOC
Constrained ELOC

![Graph showing constrained ELOC and ELOC over time.](image)
Conclusions

- Hybrid vehicle constraints suggest the use of MPC
- Selection of MPC tuning parameters unclear
- ELOC used to minimize power loss
- ELOC and inverse optimality used to tune MPC
Acknowledgements

• **Current Students and Former Students:**
  - Ben Omell
  - David Mendoza-Serrano
  - Dr. Ming-Wei Yang (Taiwan Electric)
  - Dr. Jui-Kun Peng (ANL)
  - Amit Manthanwar

• **Funding:**
  - National Science Foundation (CBET – 0967906)
  - Starr Research Fellowship
  - Graduate and Armour Colleges, IIT