« INVERSION–BASED CONTROL »

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Objective: example of HEV control

Parallel HEV

Energy management (supervision/strategy)

Fast subsystem controls

Slow system supervision

Driver request
Parallel HEV

Objective: example of HEV control

How to define control scheme of complex systems?
(algorithm? sensors?)

Energy management
(supervision/strategy)

driver request

fast subsystem controls

slow system supervision
1. Principle of model-based control
   • Open-loop and closed-loop controls
   • Inversion-based control

2. Inversion of EMR elements
   • Inversion of accumulation and conversion elements
   • Inversion of coupling elements

3. Inversion-based control structures
   • Inversion-based methodology
   • Maximum and practical control schemes

4. Conclusion: towards energy management
1. « Principle of model-based control »
Controlling a system for output tracking can be interpreted as inverting the system control.

\[ \text{System}^{-1}(.), \quad \text{System} \]

\[ y_{\text{ref}}(t) \rightarrow \text{System}^{-1}(.) \rightarrow u(t) \rightarrow \text{System} \rightarrow y(t) \]

desired output \quad \text{input} \quad \text{output}

… if we can implement a good approximation of the system’s inverse.
Closed-loop control is required when:

• the model is not invertible,
• the model is ill known or too complex,
• and for robustness purpose.

Controller objectives:

• tracking of reference changes
• rejection of disturbances and uncertainties
EMR = system decomposition in basic energetic subsystems (SSs)

Inversion-based control: systematic inversion of each subsystems using open-loop or closed-loop control

… divide and conquer …
The control scheme is developed as a mirror of the model.

[Hautier 96] [Bouscayrol 03]
2. « Inversion of EMR elements »
There are 3 basic inversion categories:

1. Single-input time independent relationships (incl. conversion elements)
2. Multiple-input time independent relationships (incl. coupled conversion elements)
3. Single-input causal relationships (accumulation elements)

Other inversion schemes can be deduced from these basic inversions.

[Barre 06]
output depends on a single input without delay

Example:

\[ y(t) = K \, u(t) \]

\[ i(t) = \frac{1}{R} \, v(t) \]

1. no measurement
2. no controller (open-loop control)

Assumption: \( K \) well-know and constant
Objective: to control $y_2$

$y_2 = f(u_1)$

Manipulate $u_1$

$\Omega_{1_{\text{ref}}} = \frac{V_{\text{trans\_ref}}}{r_{\text{pull}}}$

Ex: pulley or roller

\[
\left\{
\begin{align*}
V_{\text{trans}} &= \frac{1}{r_{\text{pull}}} \Omega_1 \\
T_{\text{trans}} &= \frac{1}{r_{\text{pull}}} F_{\text{load}}
\end{align*}
\right.
\]
Output depends on several inputs without delay

Example:

\[ y(t) = u_1(t) + u_2(t) \]

- \( u_1 \) is chosen to act on the output \( y \)
- \( u_2 \) becomes a disturbance input

**Assumption:** \( u_2 \) well-known and can be measured

1. measurement of the disturbance input
2. no controller (open-loop control)
Objective: to control $y_2$

$y_2 = f(u_1, u_{21})$

Manipulate $u_{21}$ → $u_1$ is a disturbance

**Basic rule**: as a first step, compensate all disturbances assuming measurement is available.

Example: H-bridge chopper

\[
\begin{aligned}
    u_{Hb} &= m_{Hb} V_{DC} \\
    i_{Hb} &= m_{Hb} i_{dcm}
\end{aligned}
\]

\[m_{Hb} = \frac{u_{Hb_{ref}}}{V_{DC\_meas}}\]

$V_{DC\_meas}$ $m_{Hb}$
Objective: to control $y_2$

$y_2 = f(u_1, u_{21})$

Ex: speed transmission

\[
\begin{align*}
\Omega_{\text{trans}} &= k_{\text{trans}} \Omega_1 \\
T_{\text{trans}} &= k_{\text{trans}} T_{\text{load}}
\end{align*}
\]

$\Omega_{1_{\text{ref}}} = \frac{\Omega_{\text{trans_ref}}}{k_{\text{trans_meas}}}$

Manipulate $u_1$ $\Rightarrow$ $u_{21}$ is a disturbance

$\Omega_{1_{\text{ref}}} \div k_{\text{trans_meas}} \rightarrow \Omega_{\text{trans_ref}}$
**Inversion–Based Control**

- Inversion of neutral coupling elements

Example: Park's transformation

Use of the inverse matrix

- no measurement
- no controller / direct inversion
Inversion-based Control

- Inversion of upstream coupling elements

Implement a compromise or prioritize outputs.

Example: current node

no measurement
no controller

\[ p \] weighting variables

\[ u_1 = k_{W1} y_{21-ref} + ... + k_{Wp} y_{2p-ref} \]

\[ V_{DC} = \left[ k_W v_{1-ref} + (1 - k_W) v_{2-ref} \right] \]

\[ 0 \leq k_W \leq 1 \]
Inversion principle
Distribute the reference signal

Examples:
- Equal torque criteria;
- Equal power criteria;
- Field weakening strategy.

There are extra degrees of freedom!!!

... an opportunity for energy management, efficiency optimization, load sharing ...
Case 1: all inputs are used

\[
\begin{align*}
    u_{11} &= k_{D1} y_{2-ref} \\
    u_{1m} &= k_{Dm} y_{2-ref} \\
    y_{11} &= \text{no measurement} \\
    y_{1m} &= \text{no controller} \\
    m &= \text{distribution variables}
\end{align*}
\]

Example: chassis of a train
« Inversion–Based Control »

- Inversion 3: single-input causal relationship -

output depends on a single input and time (delay) ➔ causality principle

Example:

\[ y(t) = \int u(t) dt \]

1. measurement of output
2. a controller is required (closed-loop control)

\[ u(t) = C(t) [y_{ref}(t) - y_{meas}(t)] \]

direct inversion

not possible in real-time

indirect inversion

closed loop controller
output depends on a single input and time (delay) → causality principle

\[ L \frac{di}{dt} = u_1 - u_2 \]
Inversion–Based Control

Inversion of EMR elements

direct inversion + disturbance rejection

Legend

Control = light blue parallelogram with dark blue contour

Direct inversion

Indirect inversion

Sensor

Mandatory link

Optional link

Conversion element

Accumulation element

Coupling element

Controller + disturbance rejection

Distribution criteria
3. « Inversion-based control structures »
Paper processing using 2 induction machines

Technical requirements:
- paper tension control for high quality of paper roll
- winding velocity control for high quality of processing

[Djani 06]
Step 1: Develop the EMR of the system

Step 2a: identify all control variables (outputs) and control inputs

Step 2b: identify tuning paths from inputs to outputs, avoiding crossing the paths
Step 3: invert each element of the control paths by applying inversion rules
- assume that all the signals are measurable;
- compensate for all disturbances.
Step 4: Simplify the MCS: group operations, do not reject disturbances explicitly.
— Impact will be on cost, on processing time and on performance
Step 5: Estimate non-measured variables, e.g. disturbances that cannot be neglected, and estimate unknown or time-varying parameters.
Step 6: choose and tune all controllers (dynamic decoupling), and estimators
3b: Exploit degrees of freedom to implement advanced strategies
Inversion based control = inversion of EMR 
based on the cognitive systemic 
and the causality principle (energy)

Inversion rules for control scheme
closed-loop control to invert accumulation elements,
direct inversion for conversion elements,
degrees of freedom to invert coupling elements

Different steps in defining the control scheme
From Maximum Control Scheme…. 
… to Practical Control Scheme…. 
… to the strategy level