Systematic design of split range controllers

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Outline

1. Introduction
2. Split range control
3. Selection of slopes
4. Proposed systematic procedure for split range controller design
5. Case study: room temperature control
6. Conclusions
1. Introduction

Objective

- simple control structures to implement optimal operation
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- simple control structures to implement optimal operation
- systematic design procedure
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- systematic design procedure

Advanced control structures

- cascade control
- feedforward control
- decoupling
- split range control (SRC)
- valve positioning control (VPC)
- selectors (min,max)
1. Introduction

**Objective**
- simple control structures to implement optimal operation
- systematic design procedure

**Advanced control structures**
- cascade control
- feedforward control
- decoupling
- **split range control (SRC)**
- valve positioning control (VPC)
- selectors (min,max)
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Application

- more than one MV\(^1\) available for one CV\(^2\)

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\(^1\)Manipulated Variable

\(^2\)Controlled Variable
1. Introduction

Application

- more than one MV\(^1\) available for *one* CV\(^2\)
- extend the steady-state operating range

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\(^1\)Manipulated Variable
\(^2\)Controlled Variable
1. Introduction

Application

- more than one MV\textsuperscript{1} available for one CV\textsuperscript{2}
- extend the steady-state operating range
- switch to another MV when the original MV saturates

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\textsuperscript{1}\text{Manipulated Variable}

\textsuperscript{2}\text{Controlled Variable}
1. Introduction

Application

- more than one MV\(^1\) available for \textit{one} CV\(^2\)
- extend the steady-state operating range
- switch to another MV when the original MV saturates

Motivation

- > 75 years (Eckman, 1945)
- commonly used in industry
- little studied from a theoretic perspective

\(^1\)Manipulated Variable
\(^2\)Controlled Variable
2. Split range control. Text books examples

2. Split range control. Textbook examples

2. Split range control (SRC)

\[ e = r - C \]

\[ v = v^* \text{ split value (degree of freedom)} \]

\[ u_i = \text{controller output (physical meaning)} \]

\[ \alpha_i = \text{gain from } v \text{ to } u_i \text{ (slope)} \]

\[ \sum C \]

\[ \text{SRC} \]

\[ u_1, u_2 \]

\[ y \]
2. Split range control (SRC)

\[ \sum C \rightarrow \text{SR} \rightarrow \text{P} \]

\[ r \rightarrow \Sigma e \rightarrow C \rightarrow v \rightarrow \text{SR} \rightarrow u_1 \rightarrow y \]

\[ u_{\text{max}}^2 \rightarrow u_{\text{min}}^2 \rightarrow u_2 \rightarrow u_{\text{max}}^1 \rightarrow u_{\text{min}}^1 \]

\[ v^* = 50\% \]

\[ \alpha_1 \alpha_2 \]

Manipulated variable \((u_i)\)

0 100%

Internal signal to split range block \((v)\)

internal signal to the split range block (limited physical meaning)

split value (degree of freedom)

controller output (physical meaning)

gain from \(v\) to \(u_i\) (slope)
2. Split range control (SRC)

\[ \sum \rightarrow e \rightarrow C \rightarrow v \rightarrow SR \rightarrow u_1 \rightarrow P \rightarrow y \]

\[ v \] internal signal to the split range block (limited physical meaning)

\[ v^* \] split value (degree of freedom)

\[ u_i \] controller output (physical meaning)

\[ \alpha_i \] gain from \( v \) to \( u_i \) (slope)
2. Split range control

\[ \Sigma \] CPI SR

\[ \text{SRC} \]

\[ T_{\text{amb}} \]

\[ T_{\text{ref}} \]

\[ e \]

\[ \Sigma \]

\[ C_{\text{PI}} \]

\[ \text{SR} \]

\[ u_{\text{AC}} \]

\[ u_{\text{CW}} \]

\[ u_{\text{HW}} \]

\[ u_{\text{EH}} \]

\[ \text{Room} \]

\[ T \]

\[ v \]

Internal signal to split range block \((v)\)

\[ \Delta v_{\text{AC}} \]

\[ \Delta v_{\text{CW}} \]

\[ \Delta v_{\text{HW}} \]

\[ \Delta v_{\text{EH}} \]

\[ v_{\text{min}} = 0 \]

\[ v_{\text{max}} = 1 \]

\[ \alpha_{\text{AC}} \]

\[ \alpha_{\text{CW}} \]

\[ \alpha_{\text{HW}} \]

\[ \alpha_{\text{EH}} \]

\[ u_{\text{max}} \]

Manipulated variable \((u_i)\)

\[ 0 \]

\[ 100\% \]

\[ 0 \]

\[ 100\% \]

\[ u_1 \]

\[ u_2 \]

\[ u_3 \]

\[ u_4 \]

\[ \alpha_1 \]

\[ \alpha_2 \]

\[ \alpha_3 \]

\[ \alpha_4 \]

\[ u_{\text{max}} = 2 \]

\[ u_{\text{max}} = 1 \]

\[ u_{\text{max}} = 4 \]

\[ u_{\text{max}} = 3 \]
3. Selection of slopes

\[ u_i = u_{i,0} + \alpha_i \ v \quad \forall i \in \{1, \ldots, N\} \]
3. Selection of slopes

Liptak, Shinskey (1985): *control valve sequencing loops must be designed that will keep the loop gain constant while switching valves.*

Our goal, get the desired loop gain at the crossover frequency \((\omega_c = \frac{1}{\tau_c})\)

\[
\text{Loop gain } = |g_c|
\]

Desired loop gain: Obtained using SIMC PI-tunings for each MV
3. Selection of slopes

\[ C(s) = K_C \left(1 + \frac{1}{\tau_I s}\right) \implies \omega_c = \frac{1}{\tau_C} \implies C(j\omega_c) = K_C \left(1 - j\frac{\tau_c}{\tau_I}\right) \]

\[ K_I = \frac{K_C}{\tau_I} \]
3. Selection of slopes

\[ C(s) = K_C \left(1 + \frac{1}{\tau_I s}\right) \implies \omega_c = \frac{1}{\tau_C} \implies C(j\omega_c) = K_C \left(1 - j\frac{\tau_C}{\tau_I}\right) \]

\[ K_I = \frac{K_C}{\tau_I} \]

For fast process \((\tau \ll \theta)\)

\[ K_{I,i} = \alpha_i K_I \]

For slow process \((\tau \gg \theta)\)

\[ K_{C,i} = \alpha_i K_C \]
4. Proposed systematic procedure for split range controller design

Step 1  Define the range for the internal signal $\nu = [\nu_i^{\min} \nu_i^{\max}]$
4. Proposed systematic procedure for split range controller design

Step 1 Define the range for the internal signal \( v = [v_{i_{\text{min}}} v_{i_{\text{max}}}] \)

Step 2 Define the range for each MV \( u = [u_{i_{\text{min}}} u_{i_{\text{max}}}] \)
4. Proposed systematic procedure for split range controller design

Step 1 Define the range for the internal signal $v = [v_{i\text{min}} v_{i\text{max}}]$

Step 2 Define the range for each MV $u = [u_{i\text{min}} u_{i\text{max}}]$

Step 3 Tune controllers for each individual $MV_i$
4. Proposed systematic procedure for split range controller design

Step 1 Define the range for the internal signal $v = [v_i^\text{min} \ v_i^\text{max}]$

Step 2 Define the range for each MV $u = [u_i^\text{min} \ u_i^\text{max}]$

Step 3 Tune controllers for each individual MV $i$

$$K_{C,i} = \frac{\tau_i}{K_{p,i}(\tau_{C,i} + \theta_i)}$$

$$\tau_{I,i} = \min(\tau_i, 4(\tau_{C,i} + \theta))$$

Step 4 For PI control, choose the integral time ($\tau_I$)
4. Proposed systematic procedure for split range controller design

Step 1 Define the range for the internal signal $v = [v_i^{\text{min}}, v_i^{\text{max}}]$

Step 2 Define the range for each MV $u = [u_i^{\text{min}}, u_i^{\text{max}}]$

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Step 4 For PI control, choose the integral time ($\tau_I$)

a) Select $\tau_I$ of the most used MV or average $\tau_{I,i}$
4. Proposed systematic procedure for split range controller design

Step 1 Define the range for the internal signal $v = [v_{i \text{min}}^i \ v_{i \text{max}}^i]$

Step 2 Define the range for each MV $u = [u_{i \text{min}}^i \ u_{i \text{max}}^i]$

Step 3 Tune controllers for each individual MV $i$

$$K_{C,i} = \frac{\tau_i}{K_{p,i}(\tau_{C,i} + \theta_i)}$$

$$\tau_{I,i} = \min(\tau_i, 4(\tau_{C,i} + \theta))$$

Step 4 For PI control, choose the integral time ($\tau_I$)

a) Select $\tau_I$ of the most used MV or average $\tau_{I,i}$

b) For fast process ($\tau \ll \theta$)
Select small $\tau_I = \min(\tau_{I,i})$
4. Proposed systematic procedure for split range controller design

Step 1 Define the range for the internal signal \( v = [v_{i\min} \, v_{i\max}] \)

Step 2 Define the range for each MV \( u = [u_{i\min} \, u_{i\max}] \)

Step 3 Tune controllers for each individual MV \( i \)

\[
K_{C,i} = \frac{\tau_i}{K_{P,i}(\tau_{C,i} + \theta_i)}
\]

\[
\tau_{I,i} = \min(\tau_i, 4(\tau_{C,i} + \theta))
\]

Step 4 For PI control, choose the integral time (\( \tau_I \))

a) Select \( \tau_I \) of the most used MV or average \( \tau_{I,i} \)

b) For fast process (\( \tau \ll \theta \))

Select small \( \tau_I = \min(\tau_{I,i}) \)

For slow process (\( \tau \gg \theta \))

Select large \( \tau_I = \max(\tau_{I,i}) \)
4. Proposed systematic procedure for split range controller design

Step 5  Order the use of MVs $\Rightarrow$ split range block:

- Define the desired operating point for each MV $i$ (open or closed)
- Group MVs:
  - Moving away from desired operating point $\Rightarrow CV$ increase
  - Moving away from desired operating point $\Rightarrow CV$ decreases
- Consider economics:
  - MV most expensive
  - Least expensive
  - Least used
  - Most used
  - Closer to the nominal operating point
4. Proposed systematic procedure for split range controller design

Step 5 Order the use of MVs → split range block:

Step 5.1 Define the desired operating point for each MV_i (open or closed)
4. Proposed systematic procedure for split range controller design

Step 5 Order the use of MVs $\Rightarrow$ split range block:

Step 5.1 Define the desired operating point for each $\text{MV}_i$ (open or closed)

Step 5.2 Group MVs:
   a) moving away from desired operating point $\Rightarrow$ CV *increase*
   b) moving away from desired operating point $\Rightarrow$ CV *decreases*
4. Proposed systematic procedure for split range controller design

Step 5  Order the use of MVs $\implies$ split range block:

Step 5.1 Define the desired operating point for each $MV_i$ (open or closed)

Step 5.2 Group MVs:
   a) moving away from desired operating point $\implies$ CV *increase*
   b) moving away from desired operating point $\implies$ CV *decreases*

Step 5.3 Consider economics

most expensive

least expensive

most used

most used

closer to the nominal operating point

least used
4. Proposed systematic procedure for split range controller design

Step 6 Find the slopes $\alpha_i$ and the common controller gain $K_C$ by combining the following equations:

$$v^{\text{max}} - v^{\text{min}} = \sum_{i=1}^{N} \frac{u_i^{\text{max}} - u_i^{\text{min}}}{|\alpha_i|}$$

For fast process ($\tau \ll \theta$)

$$K_{I,i} = \alpha_i K_I$$

For slow process ($\tau \gg \theta$)

$$K_{C,i} = \alpha_i K_C$$
5. Case study: room temperature control

\[ T_{\text{amb}} = \Sigma CPI SR \]

\[ \text{MV1 air conditioning (AC)} \]
\[ \text{MV2 cooling water (CW)} \]
\[ \text{MV3 hot water (HW)} \]
\[ \text{MV4 electric heating (EH)} \]

\[ T_{\text{ref}} = T_{\text{amb}} \]

\[ v_{\text{min}} = 0 \]
\[ v_{\text{max}} = 1 \]

\[ \Delta v_{\text{AC}} \]
\[ \Delta v_{\text{CW}} \]
\[ \Delta v_{\text{HW}} \]
\[ \Delta v_{\text{EH}} \]

Internal signal to split range block (v)
5. Case study: room temperature control

CV room temperature ($T$)

\[ T_{\text{amb}} = \Sigma \text{CPI SR} \]

\[ u_{\text{AC}} - u_{\text{CW}} - u_{\text{HW}} - u_{\text{EH}} \]

\[ T_{\text{ref}} - v \]

\[ \text{MVs degrees of freedom:} \]
- MV1 air conditioning (AC)
- MV2 cooling water (CW)
- MV3 hot water (HW)
- MV4 electric heating (EH)

\[ v_{\text{min}} = 0 \quad v_{\text{max}} = 1 \]

\[ \alpha_{\text{AC}} - \alpha_{\text{CW}} - \alpha_{\text{HW}} - \alpha_{\text{EH}} \]

Internal signal to split range block ($v$)
5. Case study: room temperature control

CV room temperature (T)

4 MVs degrees of freedom:

MV1 air conditioning (AC)
MV2 cooling water (CW)
MV3 hot water (HW)
MV4 electric heating (EH)
5. Case study: room temperature control

CV room temperature ($T$)

4 MVs degrees of freedom:

MV1 air conditioning (AC)
MV2 cooling water (CW)
MV3 hot water (HW)
MV4 electric heating (EH)

DV outdoor temperature ($T_{amb}$)
5 Case study: room temperature control

Procedure

**Step 1** Define the range for the internal signal

\[ v = [0, 1] \]
5 Case study: room temperature control

Procedure

**Step 1** Define the range for the internal signal

\[ \nu = [0, 1] \]

**Step 2** Find range for every MV (min and max values)

\[ \mu = [0, 1] \]

<table>
<thead>
<tr>
<th>MV</th>
<th>( u_{AC} )</th>
<th>( u_{CW} )</th>
<th>( u_{EC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.4000</td>
<td>-0.2143</td>
<td>0.1389</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
5 Case study: room temperature control

Procedure

Step 1 Define the range for the internal signal
\[ \nu = [0, 1] \]

Step 2 Find range for every MV (min and max values)
\[ u = [0, 1] \]

Step 3 Tune for each MV

<table>
<thead>
<tr>
<th>( u_i )</th>
<th>( \tau_{C,i}[min] )</th>
<th>( K_{C,i} )</th>
<th>( \tau_{I,i}[min] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{AC} )</td>
<td>2</td>
<td>-0.4000</td>
<td>8</td>
</tr>
<tr>
<td>( u_{CW} )</td>
<td>4</td>
<td>-0.2143</td>
<td>15</td>
</tr>
<tr>
<td>( u_{HW} )</td>
<td>3</td>
<td>0.1389</td>
<td>10</td>
</tr>
<tr>
<td>( u_{EH} )</td>
<td>3</td>
<td>0.1563</td>
<td>5</td>
</tr>
</tbody>
</table>

Step 4 Choose common integral time
\[ \tau_I = 9.5 \text{ min} \]
5. Case study: room temperature control

Step 5  Order the use of MVs
5. Case study: room temperature control

Step 5 Order the use of MVs

Step 5.1 Desired operating point: \( u = 0 \implies T_{\text{amb}} = T \)

Step 5.2 Group MVs:

a) heating (HW and EH)
5. Case study: room temperature control

Step 5 Order the use of MVs

Step 5.1 Desired operating point: $u = 0 \implies T_{\text{amb}} = T$

Step 5.2 Group MVs:
   a) heating (HW and EH)
   b) cooling (AC and CW)

Step 5.3 Consider economics
5. Case study: room temperature control

Step 5  Order the use of MVs

Step 5.1 Desired operating point: \( u = 0 \implies T_{\text{amb}} = T \)

Step 5.2 Group MVs:
   a) heating (HW and EH)
   b) cooling (AC and CW)

Step 5.3 Consider economics

- AC: expensive, use last
- CW: use first
- HW: expensive, use last
- EH: expensive, use last
5. Case study: room temperature control

Step 6 Find the slopes $\alpha_i$ and the common controller gain $K_C$

$$K_C = 0.0482$$

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>CW</th>
<th>HW</th>
<th>EH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_i$</td>
<td>-8.3067</td>
<td>-4.4500</td>
<td>2.8843</td>
<td>3.2448</td>
</tr>
</tbody>
</table>

Internal signal to split range block $(v)$

$\Delta v_{AC}$ $\Delta v_{CW}$ $\Delta v_{HW}$ $\Delta v_{EH}$

$v_{min}=0$ $v_{max}=1$
5. Case study: room temperature control. Changes in $T^{\text{amb}}$
5. Case study: room temperature control. Changes in $T^{\text{ref}}$
6. Conclusions

Split range control

- one CV and any number of MVs
- extend the steady-state operability range
- handles operation for changing of active constraints

Split range control systematic design

- need to consider the different MVs dynamics
- decide the bandwidth to control the process
- consider economics to order the use of MVs
6. Conclusions

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- one CV and any number of MVs
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Split range control systematic design

- need to consider the different MVs dynamics
- decide the bandwidth to control the process
- consider economics to order the use of MVs

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