JENSEN HUGHES

Advancing the Science of Safety

HOW TO MODEL COMPLEX BEHAVIOR USING SIMPLE CONTROL FUNCTIONS

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A BRIEF HISTORY OF CONTROLS

PRIOR TO FDS 5

- Limited means of controlling the simulation
  - Add or remove VENT, OBST, HOLE at a point in time or based on a heat detector (Sprinkler, Vent & Draft Curtain work)
  - Unique keywords for each method on each Namelist group
- Separate input groups for each type of device (THCP, SPRK, HEAT, and SMOD)
- Requests were being made for more options – gas temperature, wall temperature, smoke detection.
- Adding more and more unique keywords was not a good option

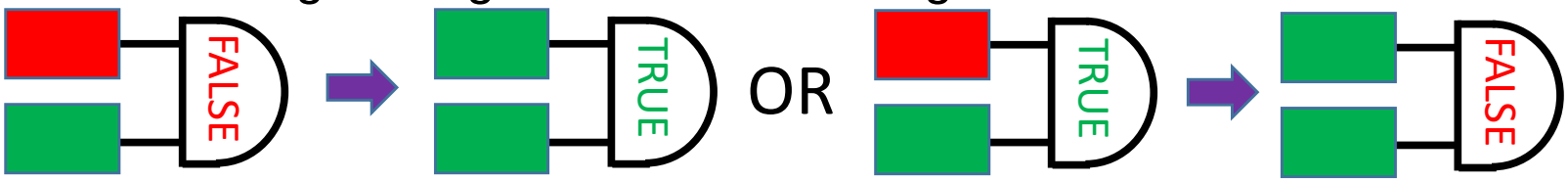
A BRIEF HISTORY OF CONTROLS

FDS 5

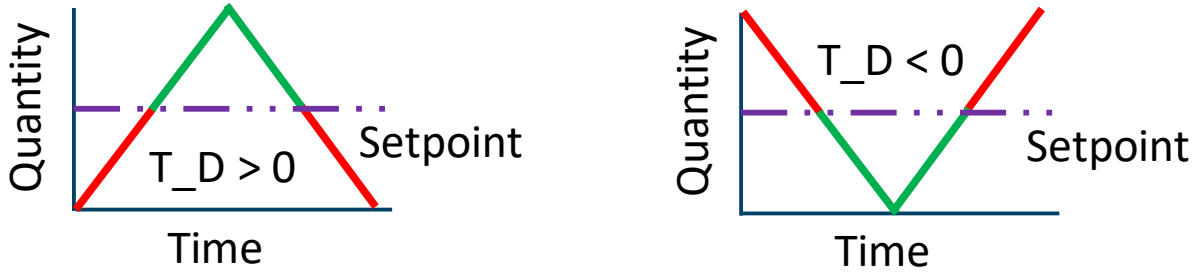
- Inputs were reorganized - THCP, SPRK, HEAT, and SMOD were combined into DEVC and PROP.
- Any DEVC could have a SETPOINT
- The new Namelist group CTRL was added with the ability to do logical and mathematic operations
- Items that could be added / removed, turned on / off, etc. were given the inputs DEVC_ID and CTRL_ID

BASIC CONTROL LOGIC

- DEVC and CTRL have a logical state
  - TRUE
  - FALSE
- You can assign the state at the start of the simulation. For DEVC or CTRL with a numerical value define a SETPOINT where the state changes. Logical functions change state when TRUE



- A state change (or trip) occurs by rising above or falling below the SETPOINT. Controlled by TRIP_DIRECTION



- Enable multiple changes by setting LATCH = FALSE

TYPES OF CTRL FUNCTIONS

FUNCTION_TYPE	Purpose
ANY	Changes state if any INPUTs are .TRUE.
ALL	Changes state if all INPUTs are .TRUE.
ONLY	Changes state if and only if N INPUTs are .TRUE.
AT_LEAST	Changes state if at least N INPUTs are .TRUE.
TIME_DELAY	Changes state DELAY s after INPUT becomes .TRUE.
CUSTOM	Changes state based on evaluating a RAMP of the function's input
DEADBAND	Behaves like a thermostat
KILL	Terminates code execution if INPUT is .TRUE.
RESTART	Dumps restart files if INPUT is .TRUE.
SUM	Sums the outputs of the INPUTs
SUBTRACT	Subtracts the second INPUT from the first
MULTIPLY	Multiplies the INPUTs
DIVIDE	Divides the first INPUT by the second
POWER	The first INPUT to the power of the second
EXP	The exponential of the INPUT
LOG	The natural logarithm of the INPUT
COS	The cosine of the INPUT
SIN	The sine of the INPUT
ACOS	The arccosine of the INPUT
ASIN	The arcsine of the INPUT
MAX	Maximum value of the INPUTs
MIN	Minimum value of the INPUTs
PID	A Proportional-Integral-Derivative control for the INPUT

LOGICAL*: Output TRUE or FALSE.

MATH: Output a value and are TRUE or FALSE based on a SETPOINT

*Note CUSTOM outputs both a logical state and a value

CTRL INPUTS AND OUTPUTS

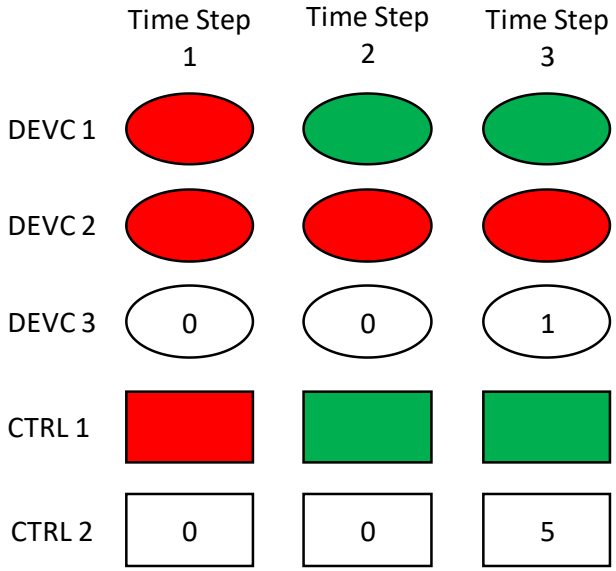
- CTRL Inputs
  - Logical state of a DEVC or CTRL
  - Numerical value of a CTRL
  - Smoothed value of a DEVC (SMOOTHING_FACTOR)
- CTRL Outputs
  - CHID_ctrl.csv file: -1 if FALSE, and +1 if TRUE.
  - DEVC
    - CONTROL VALUE: For math control functions or the CUSTOM function (RAMP output)
    - CONTROL: For any control function. 0 if FALSE, and 1 if TRUE
    - Values in CHID_devc.csv are the average value over DT_DEVC.

Time (s)	Original DEVC	DEVC Squared Output
1	1	1
2	3	9
3	9	81
3 s Average	4.33	30.3

Example: A CTRL that squares the value of a DEVC and the value is written to CHID_devc.csv

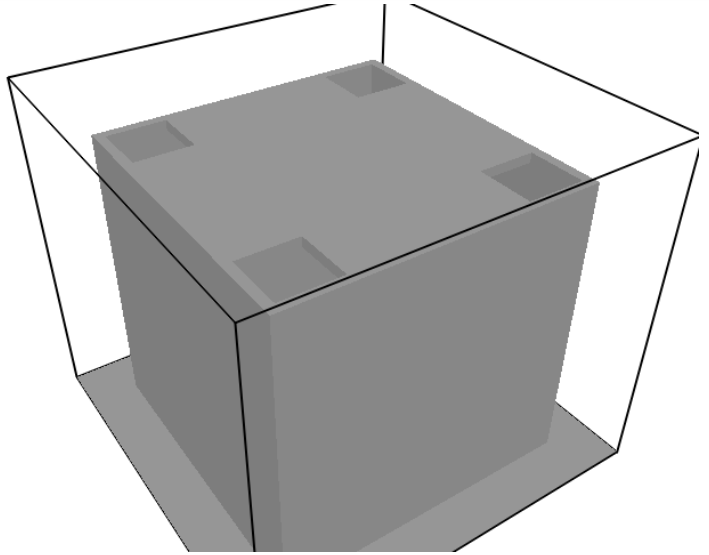
EVALUATION OF CTRL AND DEVC

- CTRL are evaluated recursively. Order in the input file does not matter
- DEVC are evaluated in the order specified in the input file
- DEVC are evaluated once prior to CTRL
  - Example: Two DEVC with SETPOINTs are inputs to an OR function
  - The OR function is converted to a 0/1 using a third DEVC
  - A third CTRL multiplies the third DEVC by 5

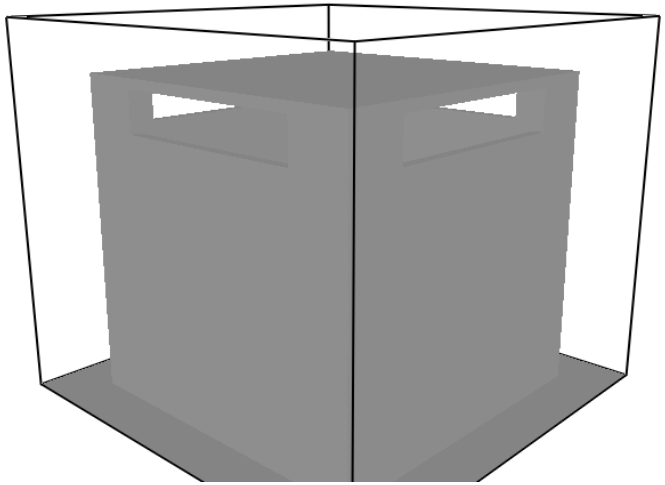


EXAMPLE 1: FINDING TOTAL OUTFLOW

Holes are in the same plane, we could assign a single DEVC with QUANTITY='MASS FLOW' that encompasses all four openings.



Each hole has a different orientation. Must use four DEVC, one per hole.



EXAMPLE 1: FINDING TOTAL OUTFLOW

- We can use a SUM CTRL function to add the four DEVC together and output the result with a CONTROL VALUE DEVC.

```
&HOLE XB= 0.45,0.65,1.1,3.1,2.6,3.0/ Vent 1
&HOLE XB= 3.55,3.75,1.1,3.1,2.6,3.0/ Vent 2
&HOLE XB= 1.1,3.1,0.45,0.65,2.6,3.0/ Vent 3
&HOLE XB= 1.1,3.1,3.55,3.75,2.6,3.0/ Vent 4
&DEVC XB= 0.55,0.55,1.1,3.1,2.6,3.0, QUANTITY='MASS FLOW', IOR=1, ID='MF Vent 1'/
&DEVC XB= 3.65,3.65,1.1,3.1,2.6,3.0, QUANTITY='MASS FLOW', IOR=1, ID='MF Vent 2'/
&DEVC XB= 1.1,3.1,0.55,0.55,2.6,3.0, QUANTITY='MASS FLOW', IOR=2, ID='MF Vent 3'/
&DEVC XB= 1.1,3.1,3.65,3.65,2.6,3.0, QUANTITY='MASS FLOW', IOR=2, ID='MF Vent 4'/
&DEVC QUANTITY='CONTROL VALUE', CTRL_ID='SUM MF', ID='Total Mass Flow', UNITS='kg/s'/
&CTRL ID='SUM MF', FUNCTION_TYPE='SUM',
    INPUT_ID='MF Vent 1', 'MF Vent 2', 'MF Vent 3', 'MF Vent 4'/
```

- If you wish to suppress output for the individual DEVC, put OUTPUT=FALSE on each line.

EXAMPLE 2: INTEGRATION

- Now we wish to determine the total mass through the openings between 100 and 110 s.
- For this we can use the PID (Proportional-Integral-Derivative) control function. Given an error between a desired state and the current state, a PID function outputs a correction signal.

$$u(t) = K_\mathrm{p} e(t) + K_\mathrm{i} \int_0^t e(t)\,\mathrm{d}t + K_\mathrm{d} \frac{\mathrm{d}e(t)}{\mathrm{d}t}$$

- K_p = 0, K_i=1, K_d=0 and $e(t)$ = mass flow rate. The PID function will output the integral of the mass flow.
- We need to limit that to the time period of 100 to 110 . This can be done by making the mass flow rate zero outside of that interval.
- A CUSTOM CTRL can be used to output specific values over specific intervals.

EXAMPLE 2: INTEGRATION

```
&DEVC QUANTITY='TIME', ID='Time'/
&DEVC QUANTITY='CONTROL VALUE', CTRL_ID='INTEGRAL MF',
    ID='Integrated Total Mass Flow', UNITS='kg'/
&CTRL ID='MULTIPLY CONSTANT', FUNCTION_TYPE='CUSTOM', INPUT_ID='Time',
    RAMP_ID='Time Ramp'/
&RAMP ID='Time Ramp', T=99.997 F=0/
&RAMP ID='Time Ramp', T=100.00, F=1/
&RAMP ID='Time Ramp', T=110.00, F=1/
&RAMP ID='Time Ramp', T=110.003, F=0/
&CTRL ID='INTEGRAND', FUNCTION_TYPE='MULTIPLY',
    INPUT_ID='MULTIPLY CONSTANT','SUM MF'/
&CTRL ID='INTEGRAL MF', FUNCTION_TYPE='PID', INPUT_ID='INTEGRAND',
    PROPORTIONAL_GAIN=0, DIFFERENTIAL_GAIN = 0, INTEGRAL_GAIN=1/
```

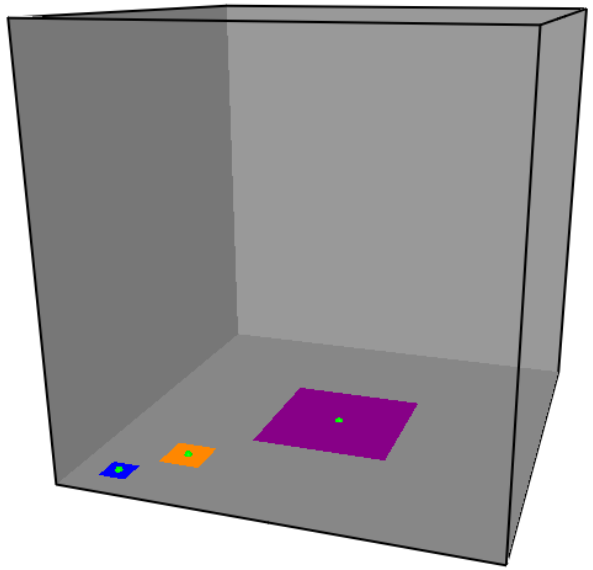
- RAMPs in FDS are converted into a look up table with 5000 equally spaced points between the lower and upper limits.
  - Example if the limits of T are 0 to 1, the ramp will be tabulated in steps of 0.0002.
  - There may be slight errors if the time step does not align perfectly with the RAMP; however, these errors would likely exist if the CHID_devc.csv file was used in post-processing.

EXAMPLE 3: CONTROLLING VENT FLOW

Three flow inlets:0.4 m^2, 0.9 m^2, and 1 m^2.

Total mass flow of 1 kg/m^2

Flow at each VENT proportional to the total radiant flux over the VENT.



EXAMPLE 3: CONTROLLING VENT FLOW

- Assign each VENT a linear RAMP and a MASS_FLUX that give a mass flow if 1 kg/s.
- Each RAMP uses the output of a control function that will pick the correct mass flow.

```
&VENT XB=0.2,0.4,0.2,0.4,0.0,0.0,SURF_ID='FLOW1'/
&SURF ID='FLOW1',SPEC_ID(1)='AIR',MASS_FLUX(1)=2.5,RAMP_MF(1)='RAMP1'/
&RAMP ID='RAMP1',T=0,F=1,CTRL_ID='FRACTION1'/
&RAMP ID='RAMP1',T=1,F=1/

&VENT XB=0.5,0.8,0.5,0.8,0.0,0.0,SURF_ID='FLOW2'/
&SURF ID='FLOW2',SPEC_ID(1)='AIR',MASS_FLUX(1)=1.111111,RAMP_MF(1)='RAMP2'/
&RAMP ID='RAMP2',T=0,F=1,CTRL_ID='FRACTION2'/
&RAMP ID='RAMP2',T=1,F=1/

&VENT XB=1.0,2.0,1.0,2.0,0.0,0.0,SURF_ID='FLOW3'/
&SURF ID='FLOW3',SPEC_ID(1)='AIR',MASS_FLUX(1)=1.,RAMP_MF(1)='RAMP3'/
&RAMP ID='RAMP3',T=0,F=1,CTRL_ID='FRACTION3'/
&RAMP ID='RAMP3',T=1,F=1/
```


EXAMPLE 3: CONTROLLING VENT FLOW

- Measure the total INCIDENT HEAT FLUX over each VENT
- Compute the fraction that each VENT sees using SUM and DIVIDE CTRL functions.

```
&DEVC XB=0.2,0.4,0.2,0.4,0.0,0.0, QUANTITY='INCIDENT HEAT FLUX',
  STATISTICS='SURFACE INTEGRAL',ID='HF1'/
&DEVC XB=0.5,0.8,0.5,0.8,0.0,0.0, QUANTITY='INCIDENT HEAT FLUX',
  STATISTICS='SURFACE INTEGRAL',ID='HF2'/
&DEVC XB=1.0,2.0,1.0,2.0,0.0,0.0, QUANTITY='INCIDENT HEAT FLUX',
  STATISTICS='SURFACE INTEGRAL',ID='HF3'/
&CTRL ID='SUM HF',FUNCTION_TYPE='SUM',INPUT_ID='HF1','HF2','HF3'/
&CTRL ID='FRACTION1',FUNCTION_TYPE='DIVIDE',INPUT_ID='HF1','SUM HF'/
&CTRL ID='FRACTION2',FUNCTION_TYPE='DIVIDE',INPUT_ID='HF2','SUM HF'/
&CTRL ID='FRACTION3',FUNCTION_TYPE='DIVIDE',INPUT_ID='HF3','SUM HF'/
```

EXAMPLE 3: CONTROLLING VENT FLOW

- Assign each VENT a linear RAMP and a MASS_FLUX that give a mass flow if 1 kg/s.
- Each RAMP uses the output of a control function that will pick the correct mass flow.

```
&VENT XB=0.2,0.4,0.2,0.4,0.0,0.0,SURF_ID='FLOW1'/
&SURF ID='FLOW1',SPEC_ID(1)='AIR',MASS_FLUX(1)=2.5,RAMP_MF(1)='RAMP1'/
&RAMP ID='RAMP1',T=0,F=1,CTRL_ID='FRACTION1'/
&RAMP ID='RAMP1',T=1,F=1/

&VENT XB=0.5,0.8,0.5,0.8,0.0,0.0,SURF_ID='FLOW2'/
&SURF ID='FLOW2',SPEC_ID(1)='AIR',MASS_FLUX(1)=1.111111,RAMP_MF(1)='RAMP2'/
&RAMP ID='RAMP2',T=0,F=1,CTRL_ID='FRACTION2'/
&RAMP ID='RAMP2',T=1,F=1/

&VENT XB=1.0,2.0,1.0,2.0,0.0,0.0,SURF_ID='FLOW3'/
&SURF ID='FLOW3',SPEC_ID(1)='AIR',MASS_FLUX(1)=1.,RAMP_MF(1)='RAMP3'/
&RAMP ID='RAMP3',T=0,F=1,CTRL_ID='FRACTION3'/
&RAMP ID='RAMP3',T=1,F=1/
```

COMPLEX BEHAVIORS

HOW TO DEVELOP CONTROL FUNCTIONS

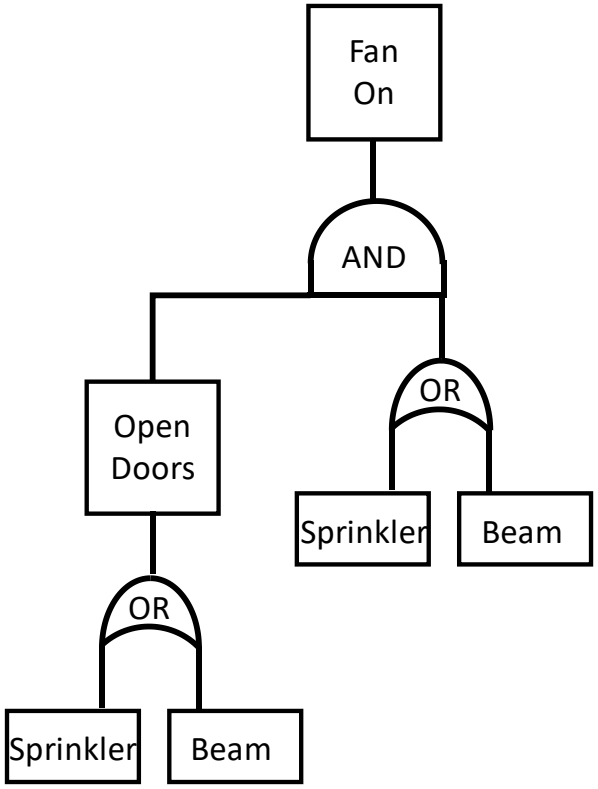
- List all the states of the system that need to be represented
- Define the events required for each state to occur (drawing a logic diagram may help)
- Determine what inputs are needed to generate the required events
- Develop FDS inputs
- Test inputs

EXAMPLE 4: SMOKE CONTROL SYSTEM

- System states:
  - Smoke barriers deployed
  - Makeup air vents open
  - Smoke exhaust fan on
- Events:
  - Deploying smoke barriers and makeup air vents require the event of detecting a fire.
  - Turning on the exhaust fan requires the events of detecting a fire and having makeup air.
- Inputs needed for Events:
  - Fire detection
  - Time for smoke barriers to deploy and makeup air vents to open

EXAMPLE 4: SMOKE CONTROL SYSTEM

- For this example the system requires either sprinkler operation or beam detection.



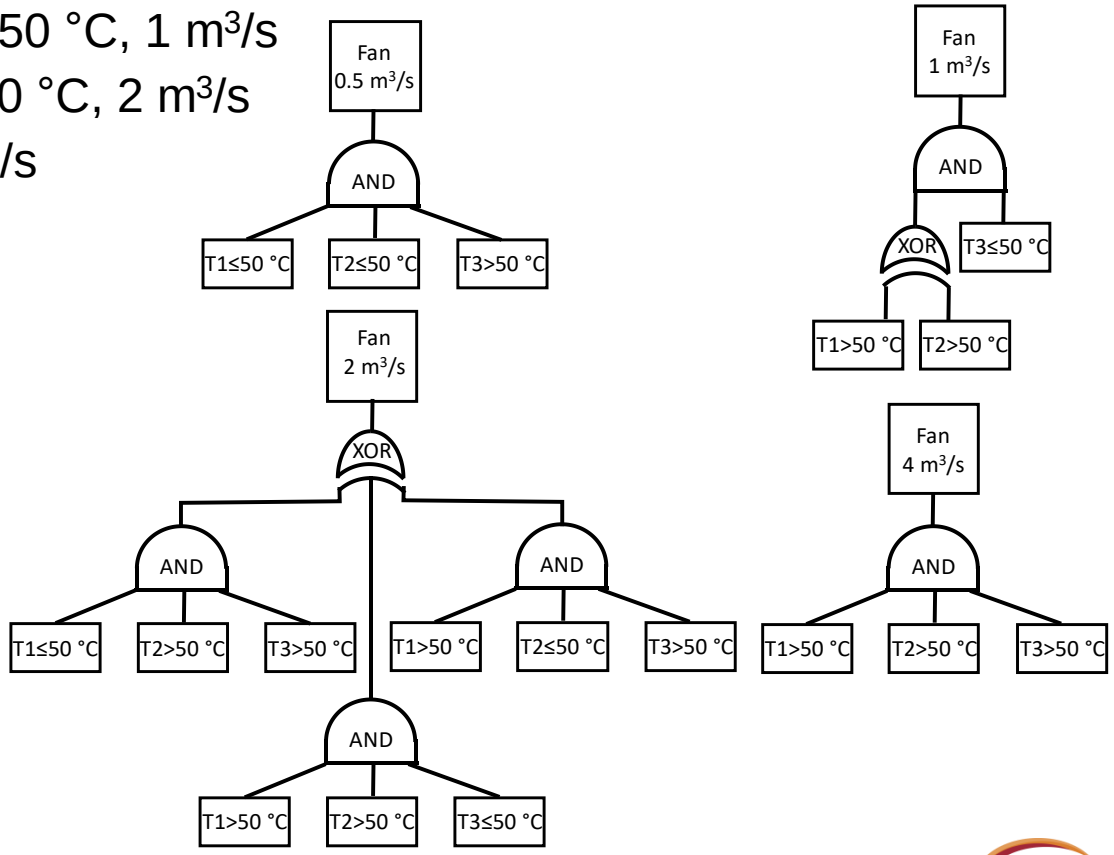
EXAMPLE 4: SMOKE CONTROL SYSTEM

- For this example it takes one minute for doors to open for makeup air and a half a minute for the fans to reach full flow once they are turned on.

```
&VENT XB=…, SURF_ID='EXHAUST', CTRL_ID='DOORS OPEN'/
&SURF ID='EXHAUST', VOLUME_FLOW=…, RAMP_V='FAN RAMP'/
&RAMP ID='FAN RAMP', T= 0, F=0/
&RAMP ID='FAN RAMP', T=30, F=1/


&HOLE XB= …, CTRL_ID='DOORS OPEN'/ Door 1
&HOLE XB= …, CTRL_ID='DOORS OPEN'/ Door 2


&DEVC ID='BEAM', XB=…, QUANTITY='PATH OBSCURATION', SETPOINT = …/
&DEVC ID='SPRK 1', XYZ=…, PROP_ID='MY SPRK'/
&DEVC ID='SPRK 2', XYZ=…, PROP_ID='MY SPRK'/
…
&DEVC ID='SPRK N', XYZ=…, PROP_ID='MY SPRK'/


&CTRL ID='SPRK ACTIVATE', FUNCTION_TYPE='ANY', INPUT_ID='SPRK 1','SPRK 2',…,'SPRK N'/
&CTRL ID='START OPEN DOORS', FUNCTION_TYPE='ANY', INPUT_ID='SPRK ACTIVATE','BEAM'/
&CTRL ID='DOORS OPEN', FUNCTION_TYPE='TIME_DELAY', INPUT_ID='START OPEN DOORS',
DELAY=60/
```

EXAMPLE 5: TEMPERATURE CONTROL OF EXHAUST FLOW

- A room has three temperature measurements (T1, T2, and T3).
- Exhaust flow is a function of the temperature
  - Only T3 > 50 °C, 0.5 m^3/s.
  - Only T1 or T2 > 50 °C, 1 m^3/s
  - Two of three < 50 °C, 2 m^3/s
  - All > 50 °C, 4 m^3/s



EXAMPLE 5: TEMPERATURE CONTROL OF EXHAUST FLOW

- There are five cases to consider. No exhaust plus the four temperature states.
- Consider if we assign T3> 50 °C a value of 0.5 and T1 and T2 a value of 1.

Temperature			Sum of Control Value	Fan Flow (m^3/s)
T1 > 50 °C	T2 > 50 °C	T3 > 50 °C		
TRUE	TRUE	TRUE	2.5	4
TRUE	TRUE	FALSE	2	2
TRUE	FALSE	TRUE	1.5	2
TRUE	FALSE	FALSE	1	1
FALSE	TRUE	TRUE	1.5	2
FALSE	TRUE	FALSE	1	1
FALSE	FALSE	TRUE	0.5	0.5
FALSE	FALSE	FALSE	0	0

EXAMPLE 5: TEMPERATURE CONTROL OF EXHAUST FLOW

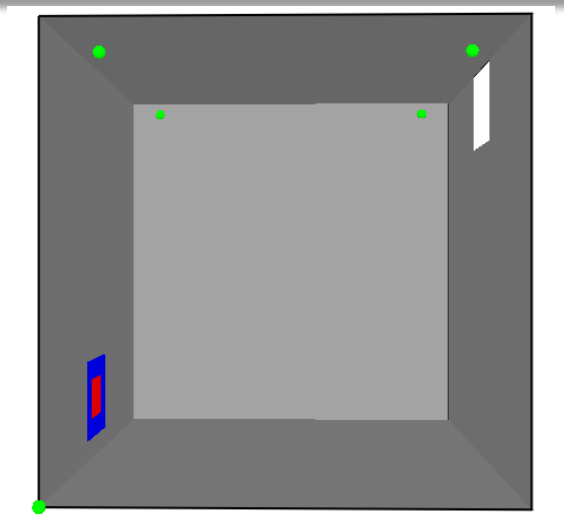
```
&VENT XB=…, SURF_ID='EXHAUST'/
&SURF ID='EXHAUST', VOLUME_FLOW=-1, RAMP_V='Exhaust Ramp'/
&RAMP ID='Exhaust Ramp', T=0.0, F=0.0, CTRL_ID='T Sum'/
&RAMP ID='Exhaust Ramp', T=0.5, F=0.5/
&RAMP ID='Exhaust Ramp', T=1.0, F=1.0/
&RAMP ID='Exhaust Ramp', T=1.5, F=2.0/
&RAMP ID='Exhaust Ramp', T=2.0, F=2.0/
&RAMP ID='Exhaust Ramp', T=2.5, F=4.0/

&DEVC XYZ=…, QUANTITY='TEMPERATURE', SETPOINT=50., LATCH=.FALSE., SMOOTHING_FACTOR=0.5,
ID='T1'/
&DEVC XYZ=…, QUANTITY='TEMPERATURE', SETPOINT=50., LATCH=.FALSE., SMOOTHING_FACTOR=0.5,
ID='T2'/
&DEVC XYZ=…, QUANTITY='TEMPERATURE', SETPOINT=50., LATCH=.FALSE., SMOOTHING_FACTOR=0.5,
ID='T3'/

&CTRL ID='T1 Status', FUNCTION_TYPE='ANY', INPUT_ID='T1'/
&CTRL ID='T2 Status', FUNCTION_TYPE='ANY', INPUT_ID='T2'/
&CTRL ID='T3 Status', FUNCTION_TYPE='ANY', INPUT_ID='T3'/
&DEVC QUANTITY='CONTROL', CTRL_ID='T1 Status', ID='T1 Value'/
&DEVC QUANTITY='CONTROL', CTRL_ID='T2 Status', ID='T2 Value'/
&DEVC QUANTITY='CONTROL', CTRL_ID='T3 Status', ID='T3 Value'/
&CTRL ID='T3 Mult', FUNCTION_TYPE='MULTIPLY', INPUT_ID='CONSTANT','T3 Value', CONSTANT=0.5/
&CTRL ID='T Sum', FUNCTION_TYPE='SUM', INPUT_ID='T1 Value','T2 Value','T3 Mult'/
```

EXAMPLE 6: CONTROLLING A FURNACE

- For a fire test furnace we want to achieve a specific time vs. temperature curve.
- We could by trial and error, define a time dependent burner flow rate that achieves that correct temperature.
  - This will likely take a large number of iterations to achieve
  - Modifying the geometry in any way (e.g. for “testing” different samples) will invalidate the flow to some extent
- Instead a PID controller can be used, but how to set the various gains?
- Manual tuning process (there are other approaches as well, consult texts on control systems):
  - Set K_i and K_d to 0 and adjust K_p to avoid oscillations of the controller output
  - Increase K_i to reduce error until oscillations begin to appear.
  - Increase K_d in small amounts to see if error improves.

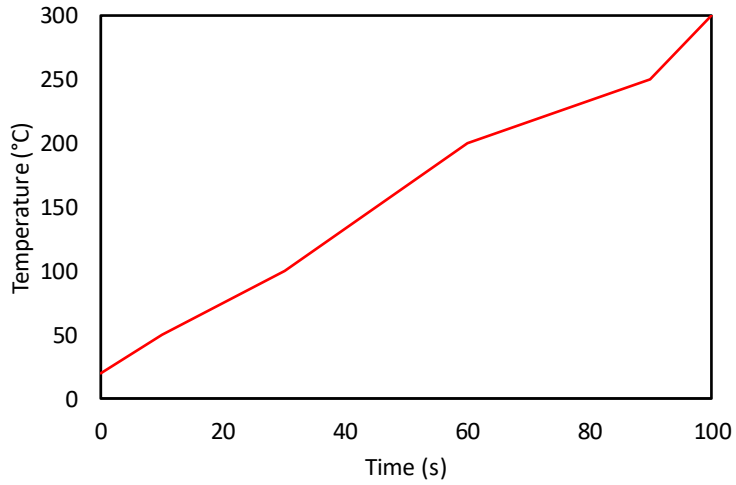
EXAMPLE 6: CONTROLLING A FURNACE

1 m^3 box with a fuel (red) and air (blue) inlet low on a wall and an OPEN VENT high on the opposite wall.



Insulating material set as the default SURF

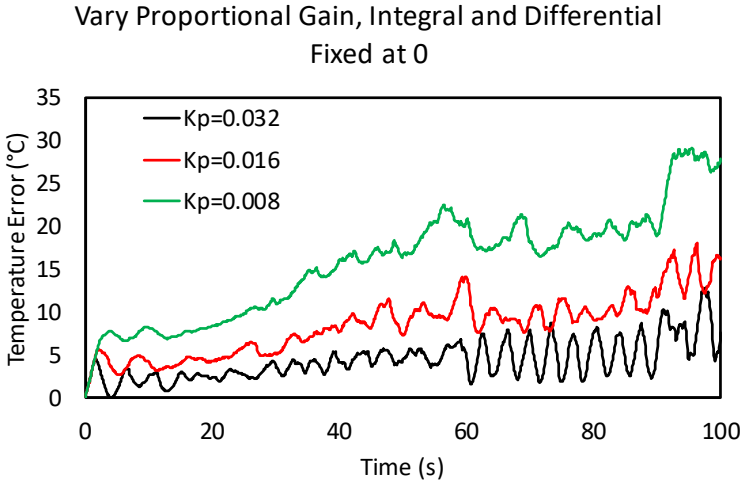
Control by the average of four thermocouples.

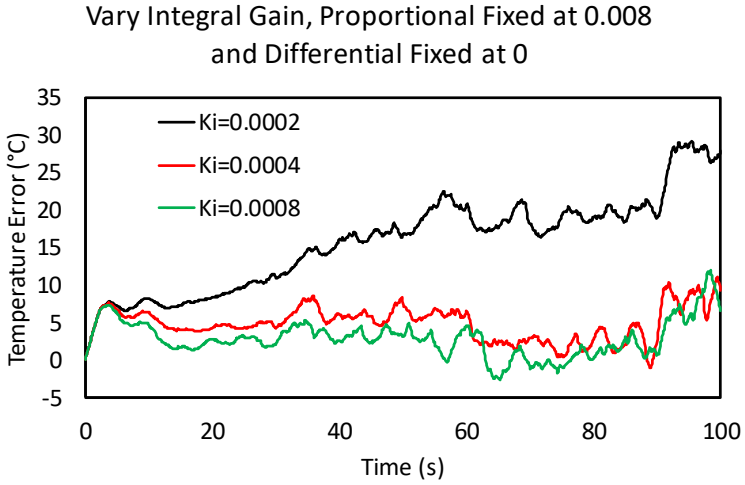


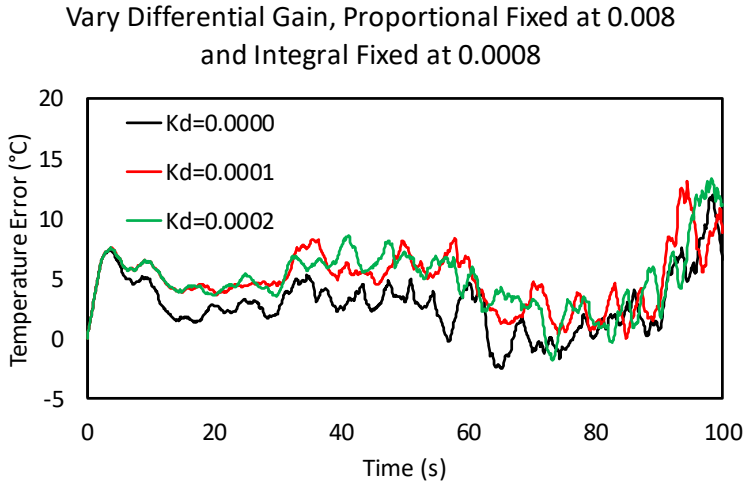
EXAMPLE 6: CONTROLLING A FURNACE

```
&SURF ID='FUEL',SPEC_ID(1)='PROPANE',MASS_FLUX(1)=0.1,RAMP_MF(1)='FLOW',COLOR='RED'/
&SURF ID='AIR',SPEC_ID(1)='AIR',MASS_FLUX(1)=0.5,RAMP_MF(1)='FLOW',COLOR='BLUE'/
&RAMP ID='FLOW', CTRL_ID='PID Out', T=0, F=0/
&RAMP ID='FLOW', CTRL_ID='PID Out', T=1, F=1/

&DEVC XYZ=0.1,0.1,0.95, QUANTITY='THERMOCOUPLE', ID='T1'/
&DEVC XYZ=0.1,0.9,0.95, QUANTITY='THERMOCOUPLE', ID='T2'/
&DEVC XYZ=0.9,0.1,0.95, QUANTITY='THERMOCOUPLE', ID='T3'/
&DEVC XYZ=0.9,0.9,0.95, QUANTITY='THERMOCOUPLE', ID='T4'/
&DEVC XYZ=0,0,0, QUANTITY='TIME', ID='Timer'/

&RAMP ID='TEMPERATURE', T=  0, F= 20/
…
&RAMP ID='TEMPERATURE', T=100, F=300/

&CTRL ID='TSUM', FUNCTION_TYPE='SUM', INPUT_ID='T1','T2','T3','T4'/
&CTRL ID='TAVG', FUNCTION_TYPE='DIVIDE', INPUT_ID='TSUM','CONSTANT', CONSTANT=4/
&CTRL ID='FTEMP', FUNCTION_TYPE='CUSTOM', INPUT_ID='Timer', RAMP_ID='TEMPERATURE'/
&CTRL ID='ERROR', FUNCTION_TYPE='SUBTRACT', INPUT_ID='FTEMP','TAVG'/
&CTRL ID='PID Out', FUNCTION_TYPE='PID', INPUT_ID='ERROR', PROPORTIONAL_GAIN=x,
INTEGRAL_GAIN=y, DIFFERENTIAL_GAIN=z/
&DEVC XYZ=0,0,0, QUANTITY='CONTROL VALUE', ID='TAVG V', CTRL_ID='TAVG'/
&DEVC XYZ=0,0,0, QUANTITY='CONTROL VALUE', ID='FTEMP V', CTRL_ID='FTEMP'/
&DEVC XYZ=0,0,0, QUANTITY='CONTROL VALUE', ID='ERROR V', CTRL_ID='ERROR'/
&DEVC XYZ=0,0,0, QUANTITY='CONTROL VALUE', ID='PID Out V', CTRL_ID='PID Out'/
```

EXAMPLE 6: CONTROLLING A FURNACE

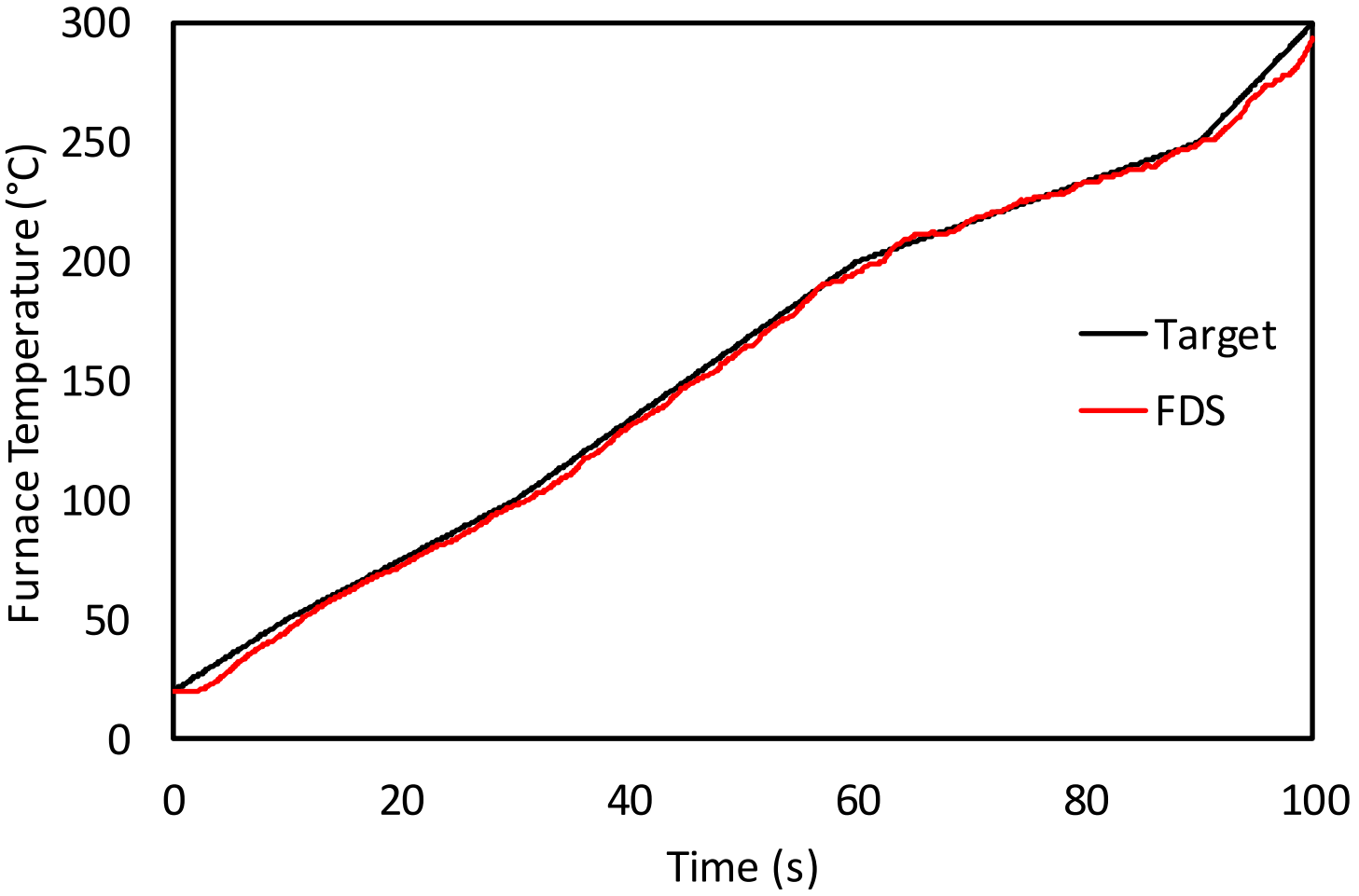






PROPORTIONAL_GAIN=0.008, INTEGRAL_GAIN=0.0008, DIFFERENTIAL_GAIN=0

EXAMPLE 6: CONTROLLING A FURNACE



TIPS

TIPS FOR CTRL AND DEVC INPUTS

- Test your inputs with simplified input files.
- Add DEVC and/or SLCF to help with testing
- Break the control system into parts and test each part
- Sketch logic diagrams
- Experiment with different approaches

QUESTIONS?

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