On-Off Control

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- On-off control is the simplest form of control.
- It is very commonly employed in industry.
- It exhibits many of the fundamental trade-offs inherent in *all* control solutions.

High Gain Feedback Control

- Readers will recall the advantages of *high gain* feedback control (*see Chapter 2*).
- An on-off controller is a very simple way of implementing a *high gain* feedback controller.

We will illustrate the ideas by a simple problem, namely heating a room:

- $u(t)$: The input (*manipulated variable*) is the room heating device.
- $y(t)$: The output (*process variable*) is the measured room temperature.

Model for the room

We will model the relationship between input and output by a transfer function

$$G(s) = \frac{10}{5s^2 + 50s + 1}$$

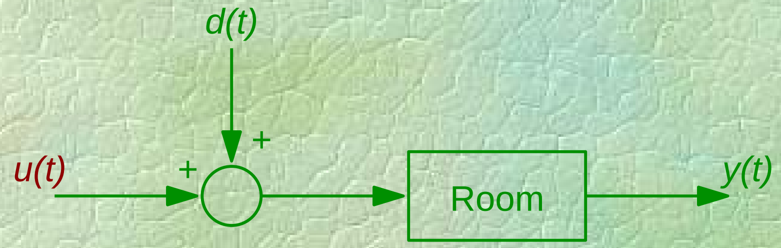
(*Note that it is not necessary to understand Laplace Transforms or Transfer Functions to understand the remainder of this module*)

The Open Loop model is illustrated on the next slide.

Open Loop Model

Disturbance (*door opening*)

Input (*heater*)



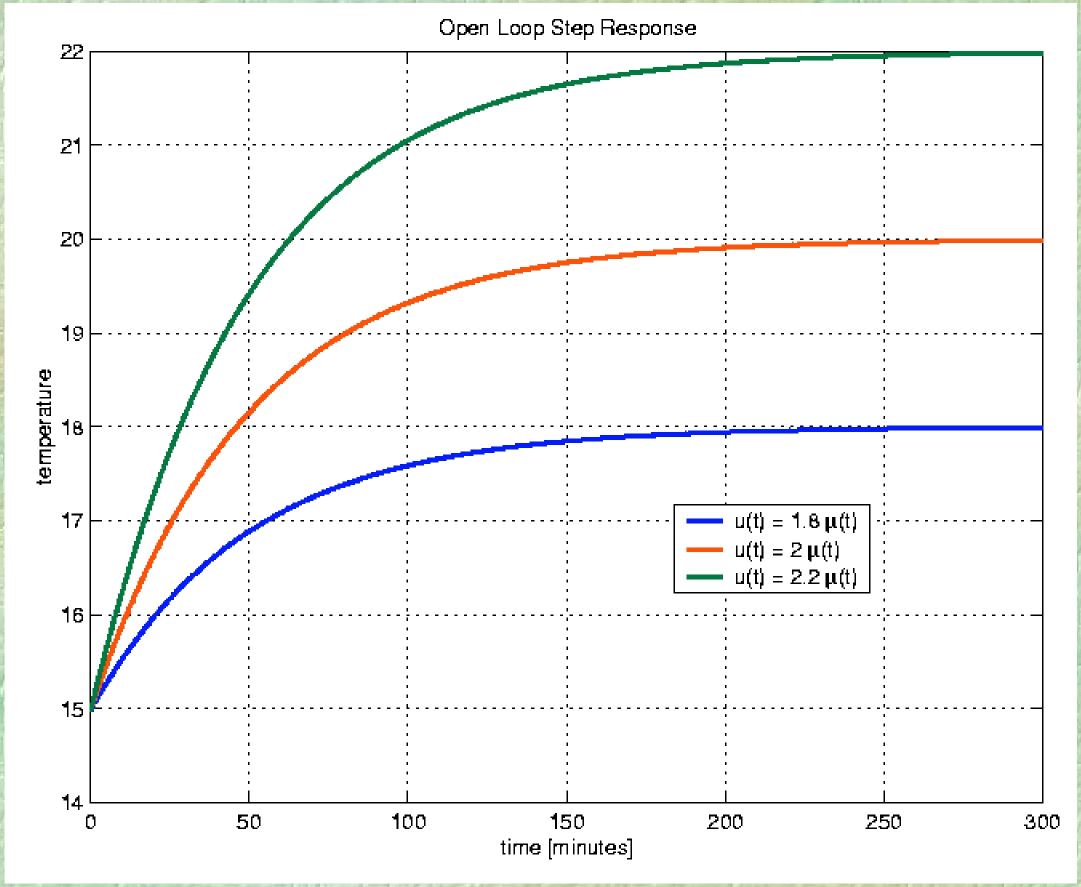
Output (*temperature*)

Open Loop Responses

We run the heater at different settings (1.8, 2.0, 2.2) and measure the output temperature response.

Note that the room starts out at 15ºC.

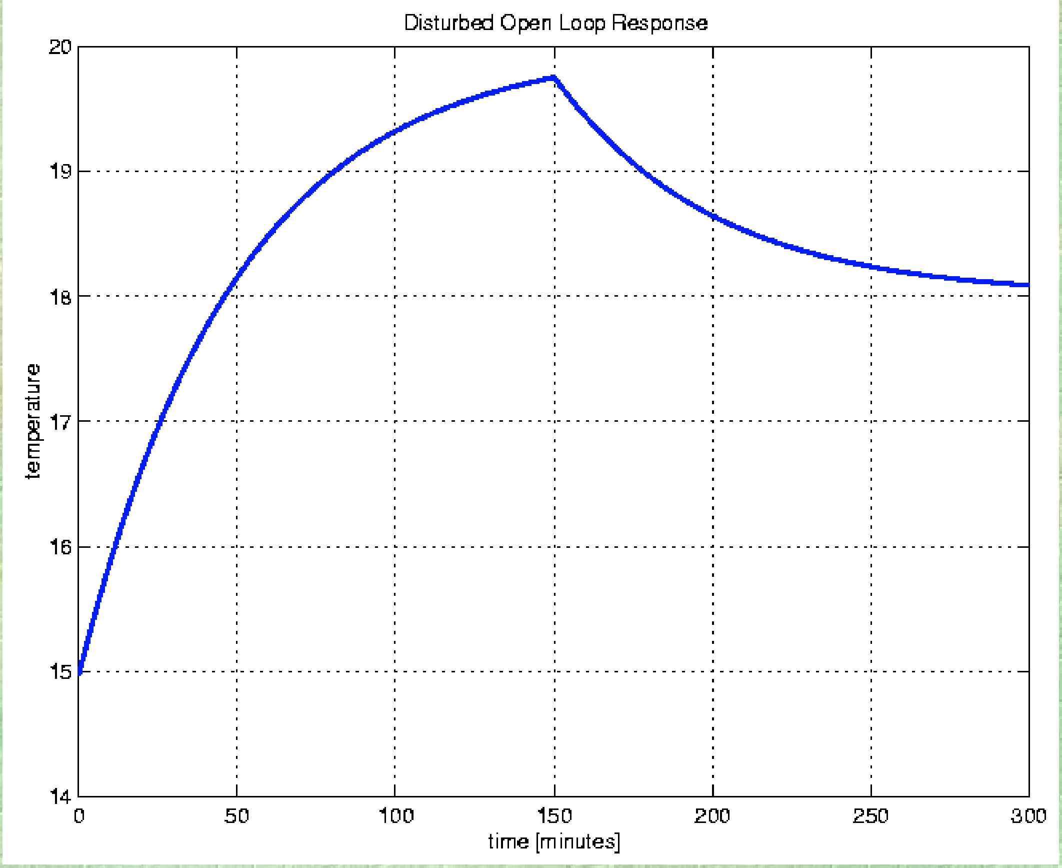
The responses are shown on the next slide.


Open Loop Step Response
22
21
20
19
18
17
16
15
14
temperature
0
50
100
150
200
250
300
time [minutes]
u(t) = 1.8 μ(t)
u(t) = 2 μ(t)
u(t) = 2.2 μ(t)

- We see from the previous slide that it takes about 250 minutes for the room to reach a new equilibrium temperature.
- We also see that to achieve a final temperature of 20ºC, we need to run the heater at setting 2.0.

Effects of Disturbances

- We set the heater at setting 2.0. However, we now assume that after some time (*actually 150 minutes*) the door to the room is opened. The next plot shows that this causes the room temperature to drop even though the heater is set to 2.0.
- As expected, the open loop controller is very sensitive to disturbances.

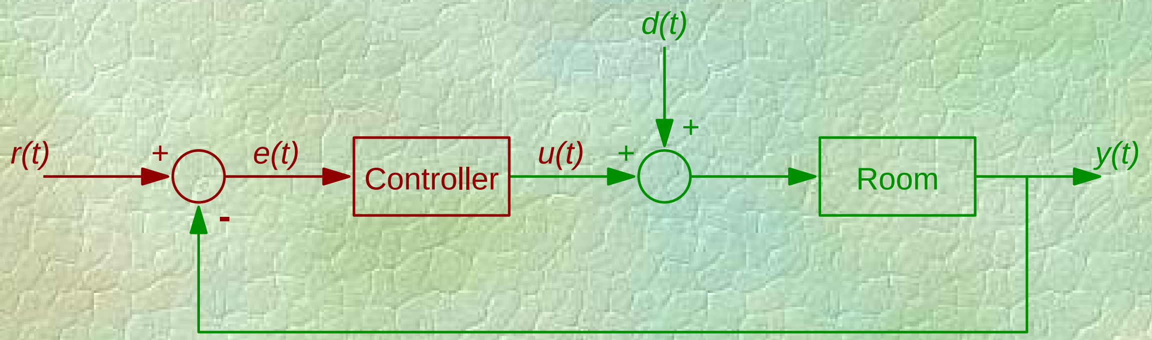

Disturbed Open Loop Response
temperature
time [minutes]
20
19
18
17
16
15
14
0
50
100
150
200
250
300

Control with a finite number of levels

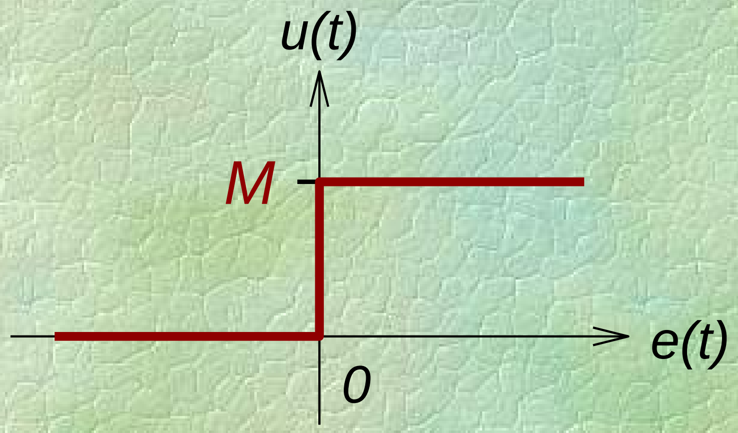
In the above discussion, we have assumed that the heater could have any desired setting. Now we assume, perhaps more realistically, that the heater actually has only 2 settings, namely, *off* and *level M*.

On-Off Control

We next form the system into a closed loop using an on-off controller as shown on the next two slides.


d(t)
+
r(t)
+
e(t)
Controller
u(t)
+
Room
y(t)
-

Realization of Controller as an on-off Controller

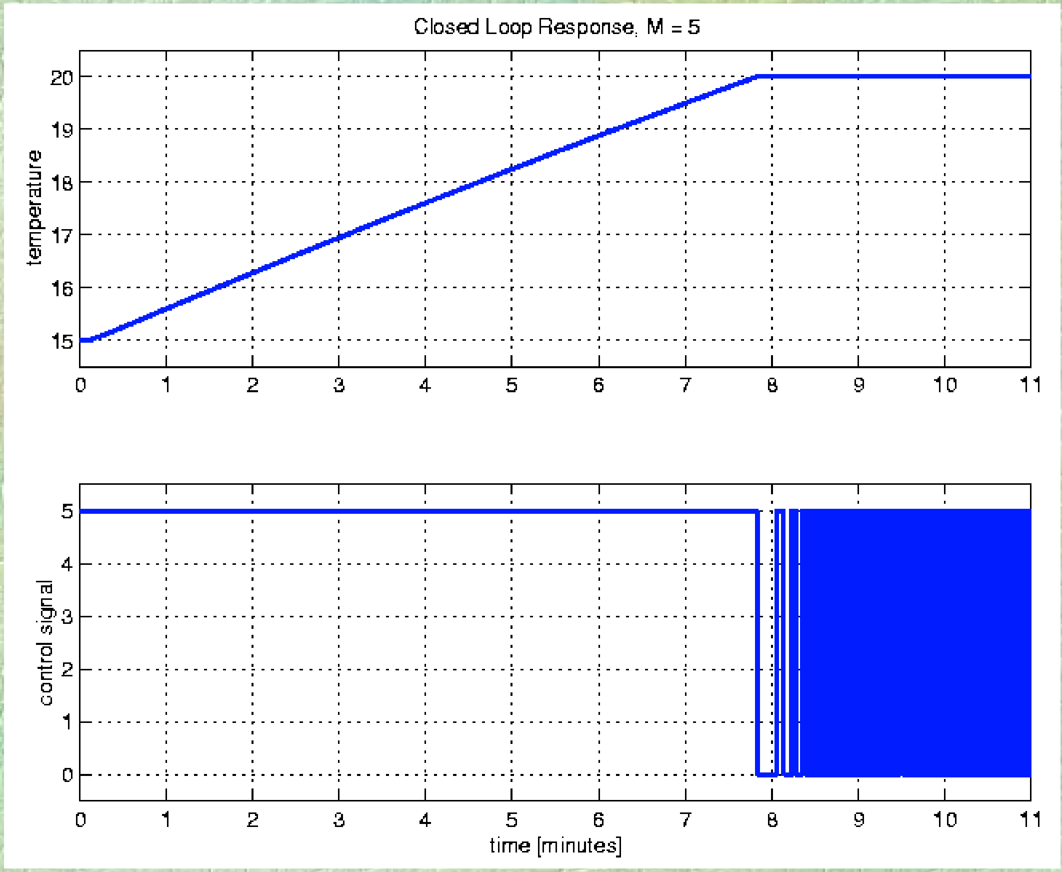


Closed Loop Responses

We next simulate the system. The results are shown on the next slide when

$$M = 5$$

Note that the disturbance is applied after 10 minutes.

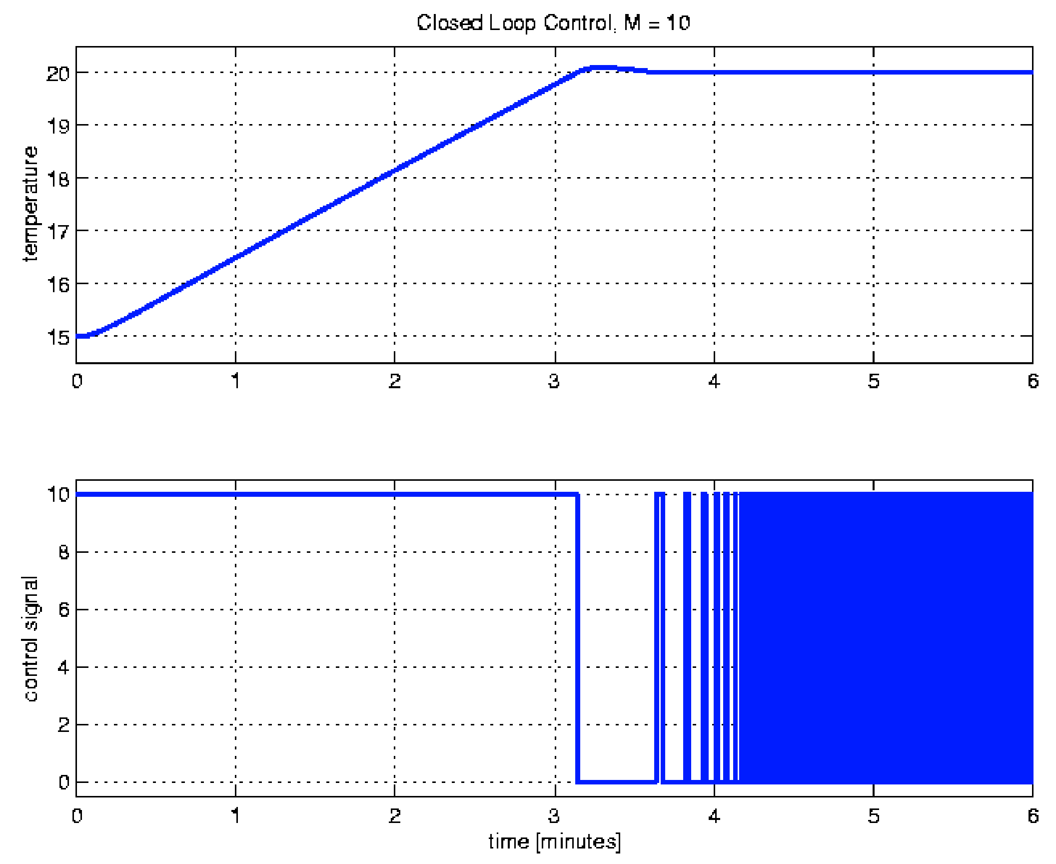

Closed Loop Response, M = 5
temperature
20
19
18
17
16
15
0 1 2 3 4 5 6 7 8 9 10 11
control signal
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time [minutes]

Observations

- The response settles to the desired temperature much faster than when we used open loop control.
- The disturbance now has little effect on the response
- Once the desired temperature has been reached - the controller continues to switch on and off rapidly.
- The *average* value of the rapidly switched on-off control is 2.0 (*as expected*).

Effect of Larger Control Effort

The next slide shows the closed loop response when *M* is changed from *M*=5 (*previous result*) to *M*=10. Notice that the system now reaches the new steady state of 20ºC in about $^1/_2$ the time that it took previously.


Closed Loop Control, M = 10
temperature
20
19
18
17
16
15
0
1
2
3
4
5
6
control signal
10
8
6
4
2
0
time [minutes]

Trade-Offs

We have achieved a rather good result (*as far as the output temperature is concerned*).

However, the price we have paid is a rapidly switching input - this would probably not be useful in practice as it would soon wear out the heater.

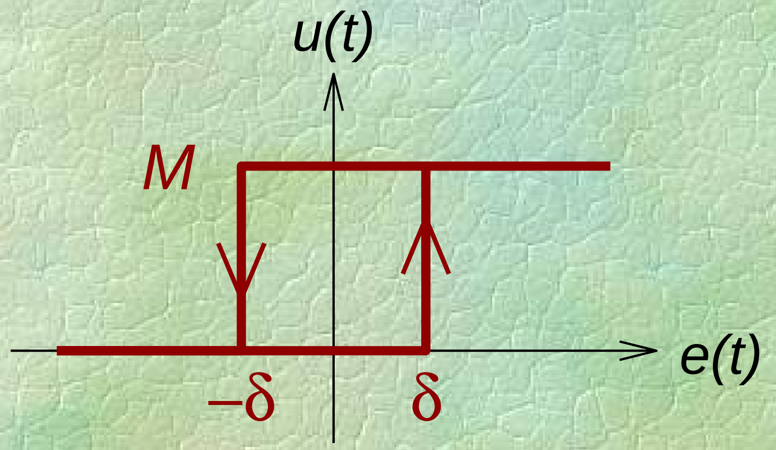
An extra degree of freedom in the design

The problem with our design so far is that it is too simplistic - we need to add more sophistication to the controller.

Readers familiar with household refrigerators will know that, although they utilize an on-off controller, the switch on temperature is set differently to the switch off temperature. This is called Hysteresis.

Inclusion of Hysteresis

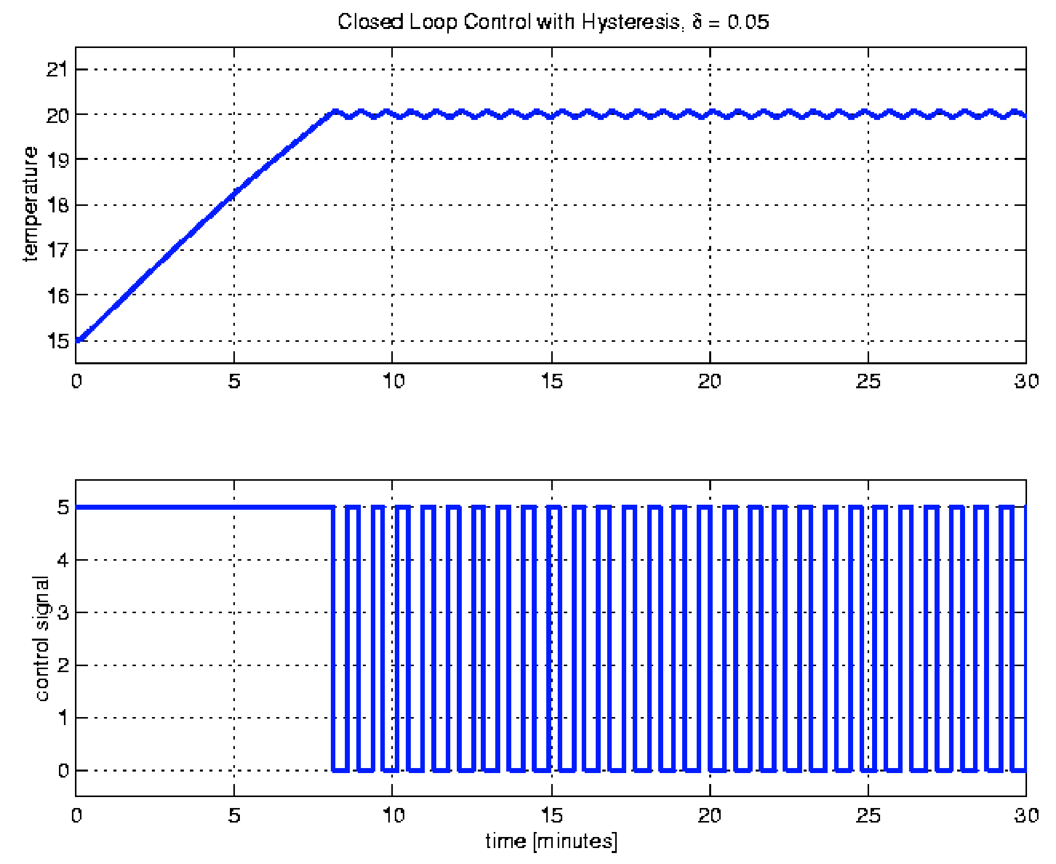
The next figure shows an on-off controller incorporating hysteresis. Note that the switching delay δ gives us an extra degree of freedom in the design.


u(t)
M
e(t)
−δ
δ

Closed Loop Responses

The next plot shows the closed loop response when

$$M = 5$$
$$\delta = 0.05$$


Closed Loop Control with Hysteresis, δ = 0.05
temperature
21
20
19
18
17
16
15
0
5
10
15
20
25
30
control signal
5
4
3
2
1
0
time [minutes]

Observations

Note that:

1. The input now does not switch so rapidly,

   but

2. The price we pay is an oscillation (*or limit cycle*) in the output temperature

Another design trade-off

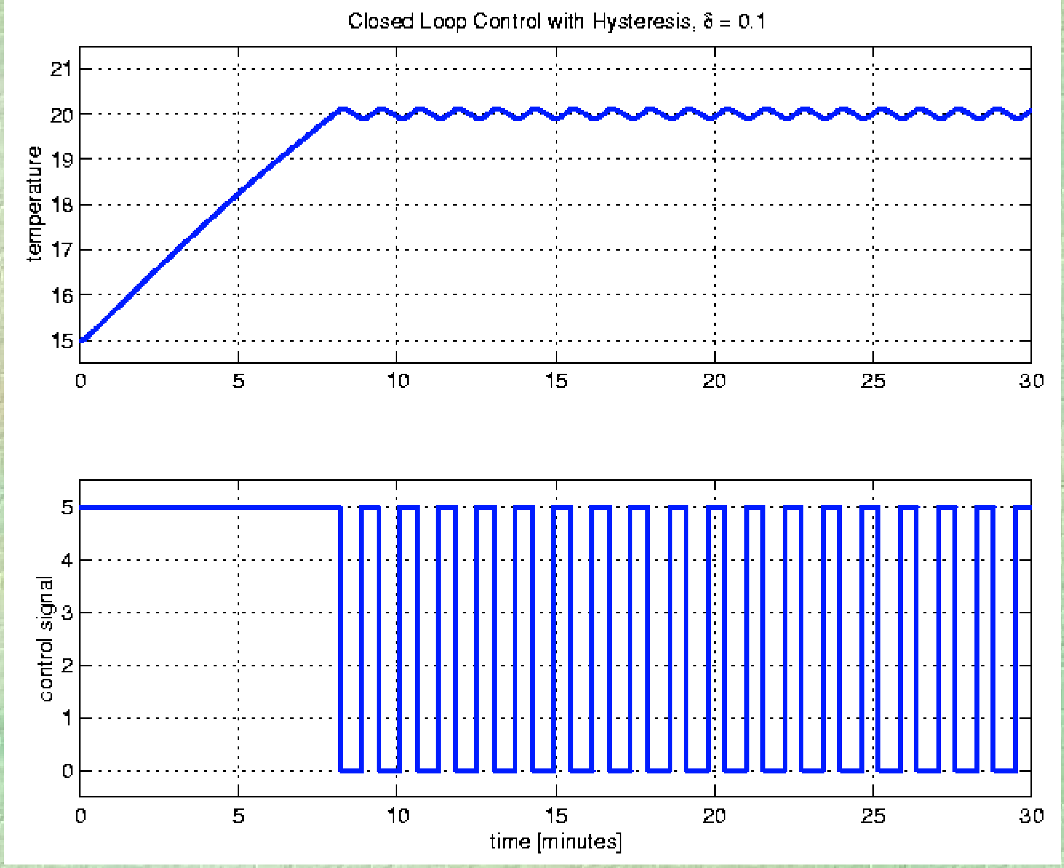
Alternative Design Parameters

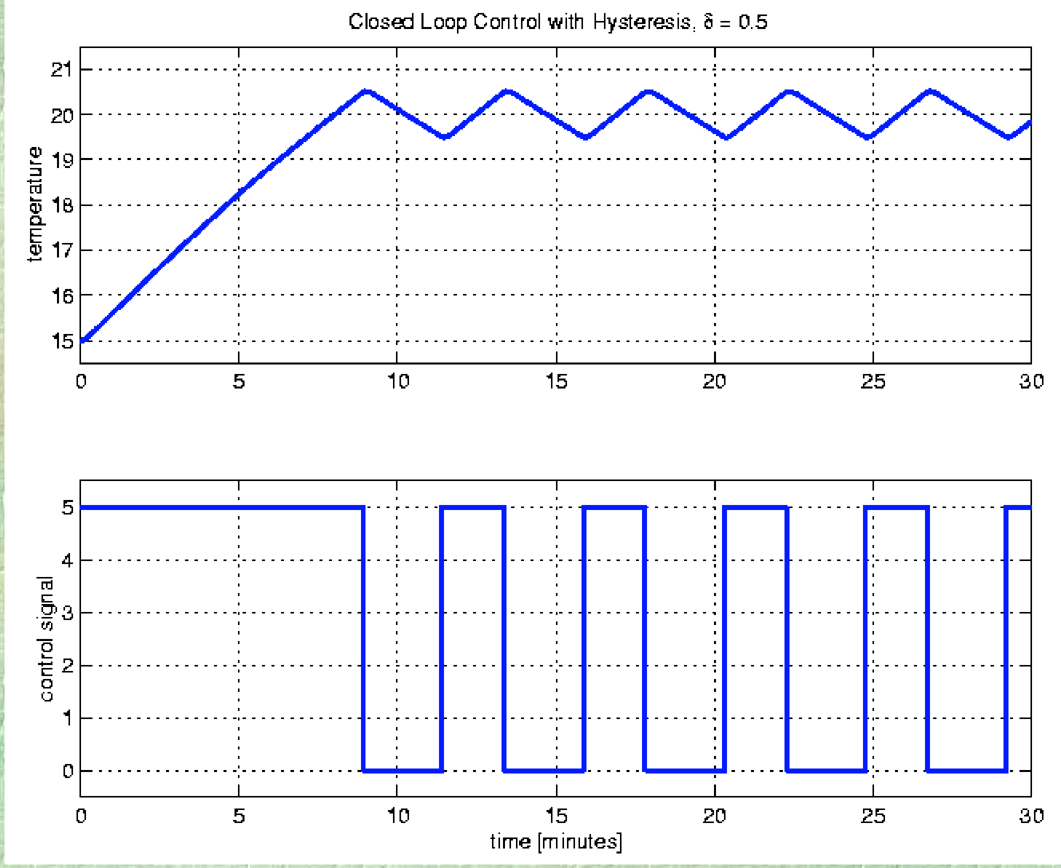
We next try

$$M = 5 \quad (\textit{as before})$$
$$\delta = 0.1 \ (\textit{2 times larger than before})$$

and

$$M = 5$$
$$\delta = 0.5$$


Closed Loop Control with Hysteresis, δ = 0.1
temperature
21
20
19
18
17
16
15
0
5
10
15
20
25
30
control signal
5
4
3
2
1
0
time [minutes]


Closed Loop Control with Hysteresis, δ = 0.5
temperature
21
20
19
18
17
16
15
0
5
10
15
20
25
30
control signal
5
4
3
2
1
0
time [minutes]

Observations

We see that as the hysteresis level *increases*, so the switching frequency *decreases* **but** the size of the output oscillation *increases*.

Clearly there is a design trade-off in choosing the hysteresis level.

Discussion of Trade-Offs

We have seen in the above design that there is a trade-off between the tightness of the temperature regulation and the price we pay in terms of the input switching.

This kind of trade-off actually occurs in all control system design.

Nothing comes at zero price !

A More Sophisticated Model?

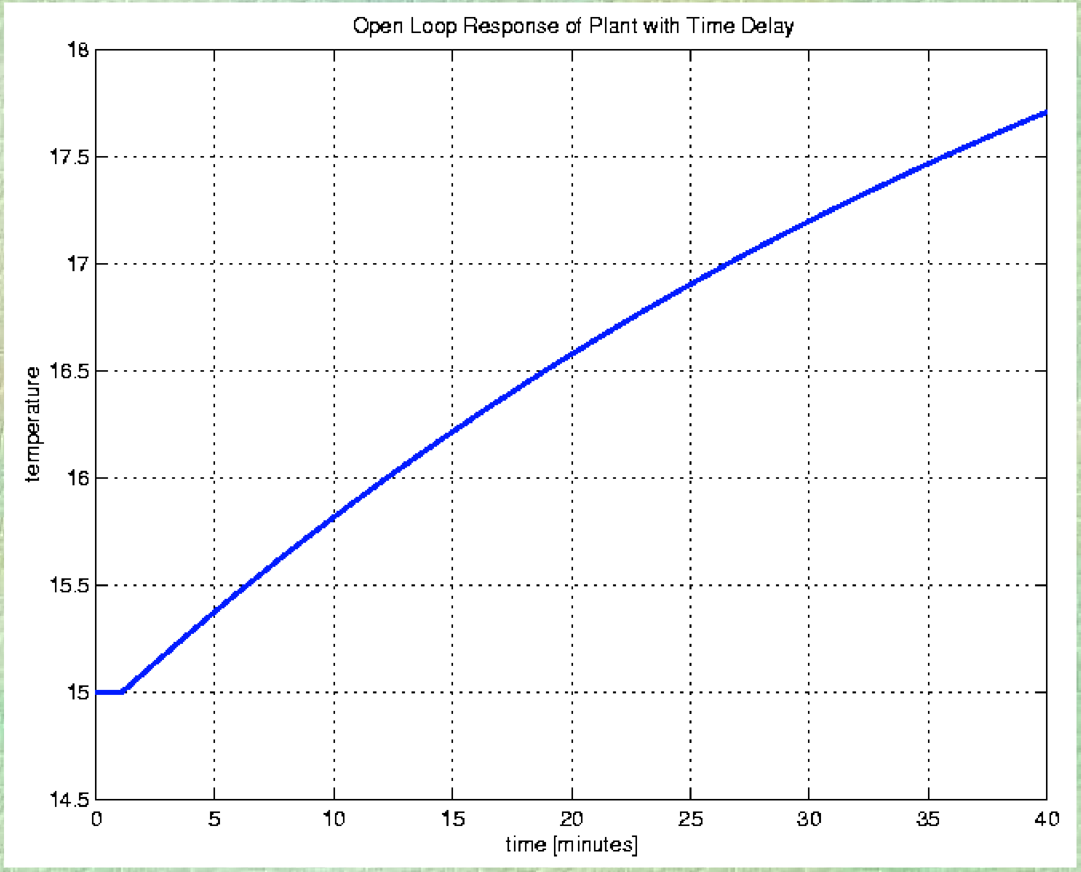
The model we have used above essentially described the room temperature so that it (*began to*) respond instantly that the heater was turned on or off. However, some extra thought indicates that this may not be realistic.

Inclusion of a Pure Delay

- A better model would have the same transfer function as before but would also incorporate a pure delay.

- Indeed, pure time delays are very common in industrial control.

The next plot shows the open loop step response of the room - with pure delay.


Open Loop Response of Plant with Time Delay
18
17.5
17
16.5
16
15.5
15
14.5
temperature
0
5
10
15
20
25
30
35
40
time [minutes]

Observations

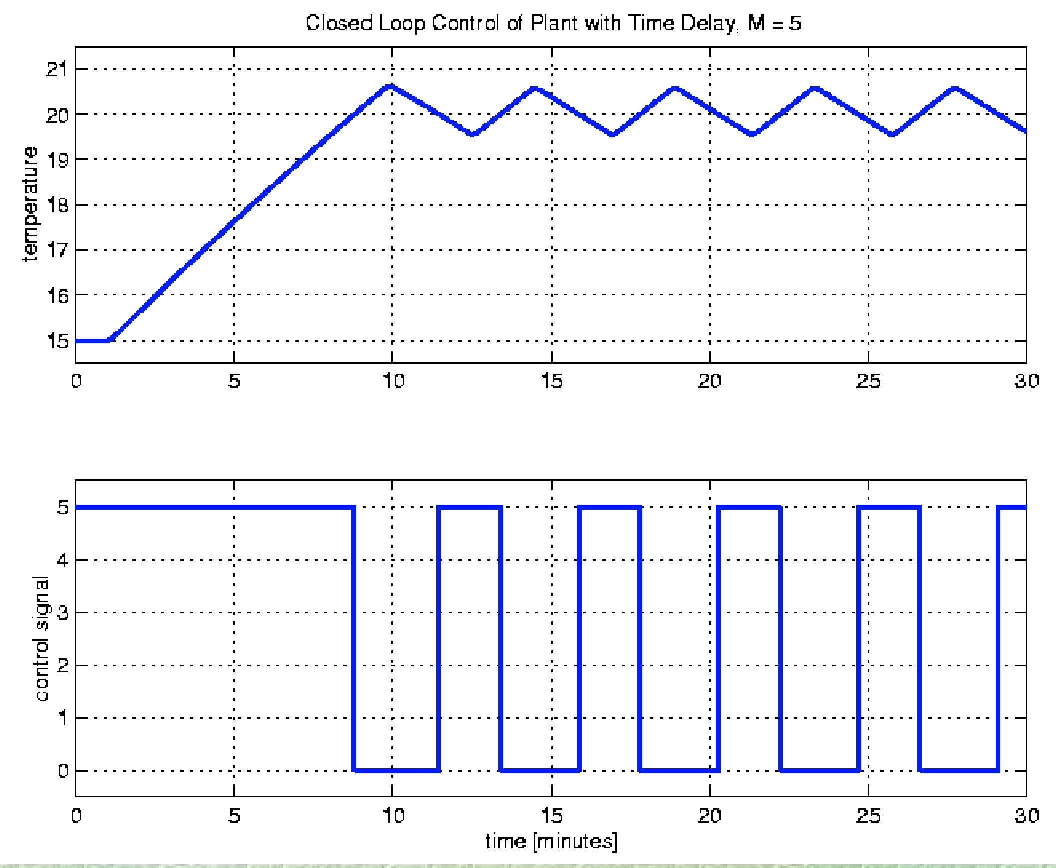
Note that the heater now has no effect for a period (*the pure delay*). Then the temperature responds as before!

On-Off Closed Loop Control

Next we *remove* the hysteresis for the controller and simulate the system again.

$$M = 5$$

$$\delta = 0$$

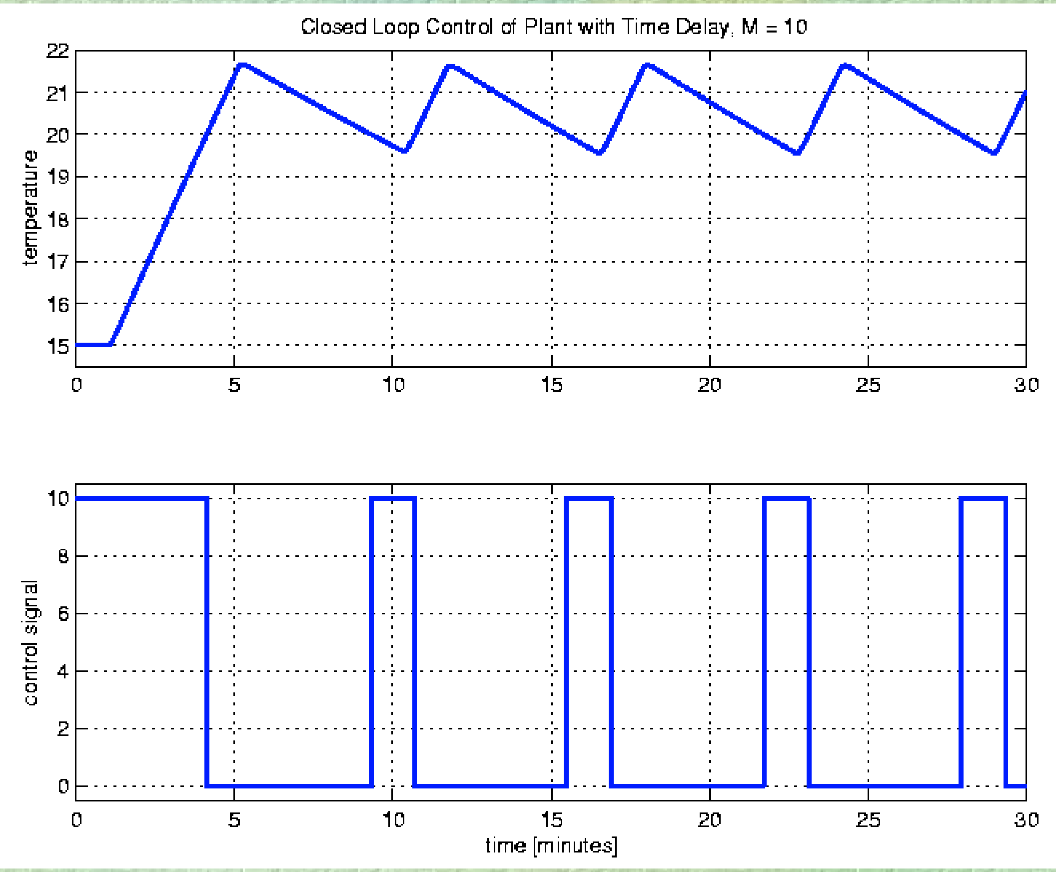

Closed Loop Control of Plant with Time Delay, M = 5
temperature
21
20
19
18
17
16
15
0
5
10
15
20
25
30
control signal
5
4
3
2
1
0
time [minutes]

Observations

- We see that the closed loop response gives a limit cycle.
- We next try

$$M = 10$$

$$\delta = 0$$


Closed Loop Control of Plant with Time Delay, M = 10
temperature
22
21
20
19
18
17
16
15
0
5
10
15
20
25
30
control signal
10
8
6
4
2
0
time [minutes]

Observations

We see that the limit cycle is even larger now.

We thus see that a pure time delay degrades the response.

Also, the more aggressive the controller (*larger M*) the more the performance degrades.

Another design trade-off

- We saw above that the presence of a pure-time delay makes control more difficult.
- Moreover, we need to have a less aggressive controller to deal with a delay.

Again these are general issues in control

More Sophisticated Controllers

- Of course *on-off* control is rather simple.
- Thus it exhibits a limited range of behaviour and trade-offs.
- Nonetheless many of the things we have seen here apply to *all* control laws.
- More sophisticated controllers do give better answers - but their design will depend on extra information, e.g. knowledge of the dynamics of the room.

Conclusions

1. Feedback controllers are preferable to open loop controllers.

2. Simple on-off controllers are a very basic solution (*to the control problem*) with inherent limitations.

3. There exist *trade-offs* between performance as measured at the output, and the nature of the control effort.

4. We need to be careful not to use too aggressive control when time delays are present.