Industrial Automation and Control
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Lecture – 17

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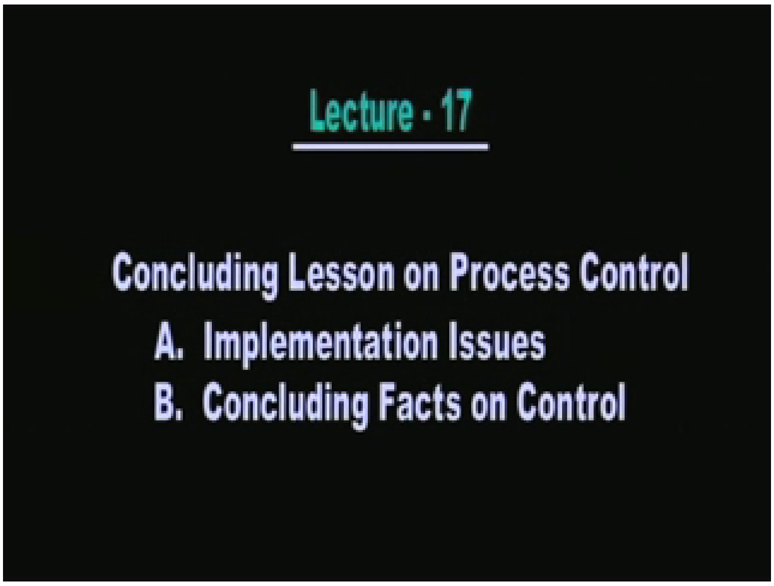

Lecture - 17

Concluding Lesson on Process Control

A. Implementation Issues

B. Concluding Facts on Control

Welcome to lecture number 17 th which is the concluding lesson on process control of this course on industrial automation. So, in this concluding lesson we shall look at two things, we have seen the PID algorithm we have seen several control structures. Today we are going to talk about the implementation issue, if you really want to make a control loop work for a process there are several things that you have to do. If you go to buy a PID controller in the market you find controllers with several features and you briefly need to understand them.

And, secondly, because since we are closing our important module on process control. So, we will take a bird's eye view of control again and mention certain facts which we have to remember because, while we study control in engineering. Typical electrical engineering we often focus on, we often focus very intently on one part of the control problem and tend to neglect the others. But they are very important parts of control, and I would like to draw your attention to them. So, that is the purpose of this lecture.

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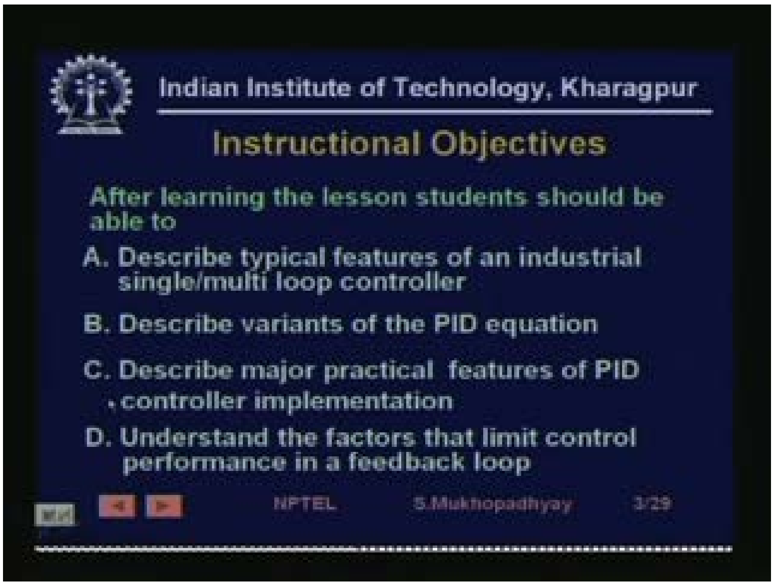

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Instructional Objectives

After learning the lesson students should be able to

A. Describe typical features of an industrial single/multi loop controller

B. Describe variants of the PID equation

C. Describe major practical features of PID controller implementation

D. Understand the factors that limit control performance in a feedback loop

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Instructional objectives are, firstly, describe typical features of an industrial controller what you might expect in a typical controller. There are lots of variations, but we will only have the opportunity to look at a particular case. There are various variance of the PID equation. If you read the PID equation, sometimes you feel that is the only variant and you might implicitly assume the same variant to be existing in your controller that is not the case. The several manufacturers implement PID controllers in various ways and you need to understand that before setting gains.

Describe major practical features of PID controller implementation, if you want to build a PID controller then there are certain facts that you need to pay attention to… So, those things. And understand the factors that limit control performance in the feedback loop. So, one is to understand what is possible, what is not possible what causes problems before being able to make control work for a work for a particular process.

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A. Implementation Issues

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So, let us begin with the implementary issues, implementation issues. So, let us first look at an industrial PID controller specification.

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Industrial PID Controller Specification

- PID with alarm and relay outputs
- Configuration in engineering units
- Serial communication : RS232 and RS485
- Provision for SCADA interface

Supervisory Control and data acquisition

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This is a very typical specification, this one is adapted from a Honeywell PID controller which is very, Honeywell is a very standard company, very well-known company in the field of process control.

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Industrial PID Controller Specification

- PID with alarm and relay outputs
- Configuration in engineering units
- Serial communication : RS232 and RS485
- Provision for SCADA interface
- Temperature / time profile set-point ramp
- Fuzzy and adaptive tuning of PI settings
- Alternative control algorithms
- Dual set-points where two sets of PID parameters may be required
- Remote set-point operation

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So, we first have, we have several features, first with that you have it says that you have PID with alarm and relay outputs. So, you could have you could depending on process conditions you could set certain alarm outputs may be it will it will lighten up some annunciation or it will ring and ring a buzzer.

And it also provides some relay output. So, that if you need you can switch of things or transfer it from automatic to manual you can do various things. Configuration in engineering units is very important because generally the process control engineers they are not electronics people neither they always experienced control engineers they are generally plant engineers. So, they understand they understand things in the in the domain of the process.

So, it is important to be able to understand gains times outputs and inputs in terms of the engineering units of the process. So, if you are taking a flow feedback, then you then somebody might be interested in knowing that what is the what is what is the flow in. Let us say meter cubic per minute rather than actually the feedback is coming as a possibly as a voltage or a current 0 to 5 volts or 4 to 20 mill amperes.

But learning the, but if you it will be a lot easier for the process engineer if the if everything is expressed in terms of engineering unit. These are this may seem trivial when you are studying an engineering course, but they are very important in the field. There is most PID controllers will support communication. Communicate standard communication using standard communication protocols like RS232 and RS485.

So, these are used for a variety of purposes for example, provision for SCADA interface. SCADA stands for SCADA stands for this one, we choose a white pen, supervisory control and data acquisition and data acquisition. It means that the controller can be in the field close to a machine or in a separate place while the controller can be monitored from a different place may be a central control room.

So, if you want to do that then you need to have a supervisory control and data acquisition interface by which sitting in the control room you can monitor the controller and see the performance of the control loop. So, this is usually provided this can be done using the using these communication standards and interfacing it with a PC and then using a visualization standard visualization software, there are very good visualization software available on the PC’s. So, you could use them.

Then there are facilities for temperature time, this particular controller was mainly built for a temperature controller application, you will you will very many times you will find that controllers are marked as temperature controllers, flow controllers, special controllers. So, they are they may be all PID controllers, but they are marked as such because of certain reasons for example, first of all you will find that they will be able to take inputs of that particular kind right?

So, for a temperature controller probably there will be a direct facility to interface thermocouples or RTD’s similarly, for a flow controller there will be a there will be a directly direct interface to a flow sensor that is possible. Second thing is that realize that temperature, flow, pressure these control applications typically work at different bandwidths.

So, while a temperature controller may be it may be adequate to have a temperature controller which is within say 10 hertz, for flow control you make require a bandwidth of something like 100 hertz. And for pressure control you may you may require even higher bandwidth you know something like may be 500 hertz.

So, the devices themselves that is the electronics inside everything is to be made according to that. So, you might have an if you know you might have an anti-aliasing filter in the controller, and the anti-aliasing filter bandwidth will have to will have to be decided by the sampling time as we all know, and this may be decided based on what kind of control it is. So, the anti-aliasing filter for a temperature controller is likely to be quite different from that used for a pressure control right?

So, this is a temperature controller that we are seeing here. So, there is a facility to provide a temperature time profile set point ramp, you know there are there could be certain processes where you do not need to keep the temperature constant. On the other hand you need to may be keep it constant at T 1 for sometime may be 10 minutes, and then ramp it up to T 2 within 2 minutes and then keep it at T 2 for 20 minutes and then ramp it down to 0. So, such temperature profiles need to be set up for various chemical processes because, they are often very temperature sensitive.

So, here they have provided a facility by which you can actually set up this you know, this set point ramps and their temperature time profiles that would that would be very useful in this case. Similarly, processes keep changing because of you know because of their characteristics you know furnaces, fire lining of bricks, degenerate heat transfer coefficients change, depositions, typically heat exchangers heat transfer coefficients tend to change because of deposition.

For example in let us say there are there is a plant where you say in the say in the Middle East people make drinking water by using sea water. So, that is called a desalination process, and it turns out that there is huge amount of it is a very energy intensive process and the heat transfer coefficient is very important. So, that incidentally the heat transfer coefficient tends to change because there are in the pipes you get depositions from sea water.

So, in such cases you for efficient response as well as for things like energy efficiency you need to tune PID controllers from time to time. And that is so they have provided algorithms for doing that using you know this fuzzy means there is a special technique called using called fuzzy set theory which is used to design controllers so you so you can have fuzzy and adaptive tuning. Adaptive tuning means that the controller continuously keeps adapting as the plant changes.

So, you could choose one of these to get the PID settings. You could use some special purpose alternative control algorithms, which the manufacturers are providing in a bundle fashion. So, they are actually they have some experience they have designed some algorithms which are which work well in certain applications. So, they are providing you some alternate control algorithms may be some variance of PID. So, you are free to use them if you want.

Then, sometimes you may require two different sets of PID parameters, and you need to have, so you need to give dual set points. So, or the same process you could use two different PID parameters may be depending on two different modes. For example, there could be you know for example, suppose, there are heat cool PID controllers. So, sometimes the same the same device has to heat let us say building, let us take a heating ventilation air conditioning HVSC application.

So, down in the basement you have the heater which will probably operate a operate basically controller a steam boiler or you could have a chiller which will operate the centralized air conditioning using cold water. So, you could use so both of these may be controlled from the same controller box, but since these are controlling two different equipment. So, it is obvious that two different sets of PID controllers will be required, and for them you might need two different set points. So, such facilities have been provided here.

And finally, you could have remote set point operation where basically this remote set point is actually a subset of SCADA. So, if you have supervisory controller from a remote place then you could you could given give set points may be may be the operator sitting in the controller room can give set points. So, this is a this is what a typical PID controller looks like and if you look at its input outputs for all controllers input outputs are very important.

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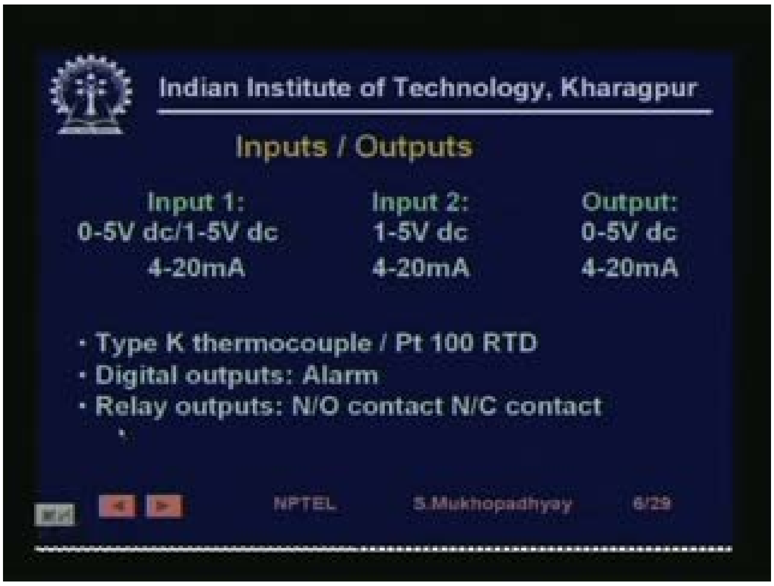

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Inputs / Outputs

Input 1:	Input 2:	Output:
0-5V dc/1-5V dc	1-5V dc	0-5V dc
4-20mA	4-20mA	4-20mA

- Type K thermocouple / Pt 100 RTD
- Digital outputs: Alarm
- Relay outputs: N/O contact N/C contact

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So, it provides 0 to 5 volt dc or 1 to 5 volt dc, 1 to 5 volt dc sometimes provided to you know detect wire breaks or shorts to ground. Or you could have 4 to 20 mill amperes or so you have two inputs on one of them it can take 0 to 5 volt or 1 to 5 volt dc and 4 to 20 mill amperes. And in the other input it can take 1 to 5 volt dc and 4 to 20 mill amperes and as output it can provide 0 to 5 volt dc and 4 to 20 mill amperes.

And similarly it can directly take type K thermocouple or Pt 100 RTD's it can take it can give digital alarm outputs or it can also give relay outputs in the form of N/O and N/C contacts. And all these that you have are actually configurable you can actually view the configuration, you can change the configuration, and set the controller. So, this a typical industrial PID controller.

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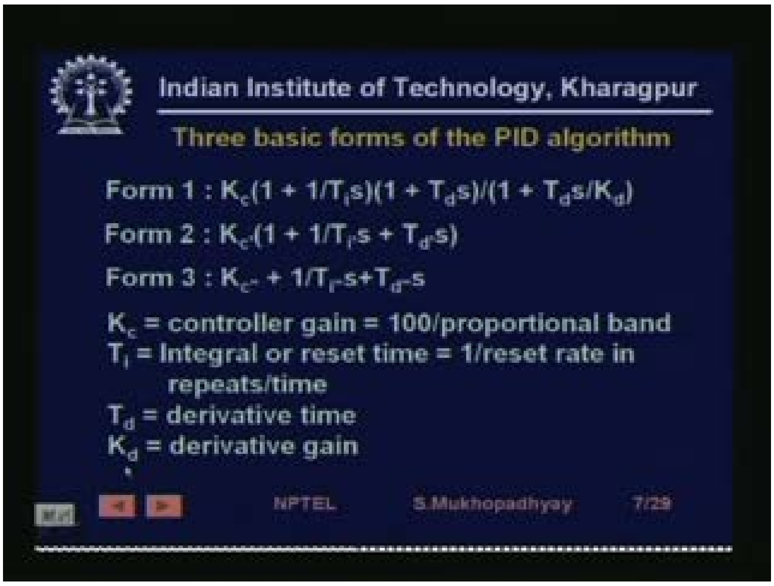

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Three basic forms of the PID algorithm

Form 1 : $K_c(1 + 1/T_i s)(1 + T_d s)/(1 + T_d s/K_d)$

Form 2 : $K_c \cdot (1 + 1/T_i \cdot s + T_d \cdot s)$

Form 3 : $K_c \cdot + 1/T_i \cdot s + T_d \cdot s$

K_c = controller gain = 100/proportional band
T_i = Integral or reset time = 1/reset rate in repeats/time
T_d = derivative time
K_d = derivative gain

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So, we first have, we have several features, let us come to this point that what is the PID controller and what are interpretations of its gains. It turns out that there are several PID controllers, which are several forms of the PID equation, which are in use in the industry today.

So, for example you have this form which is called which is which I call form one, you have the other form which is form two which is probably the most popular in text books. And form three which is a rather you know an which is an abstract control systems kind of form, typically if you ask an if you ask any an electrical engineers he would like to see it in this form. So, while chemical process engineers will probably use this form and these two forms.

So, as we know that in this, in these K c, K c dash, K c double dash all sets for controller gain. T i is integral or reset time or 1 by reset rate. And T d is derivative time. And K d is derivative gain, right? So, sometimes you know here we a K d. So, this K d is this K d is used for a certain purpose we will discuss it right now.

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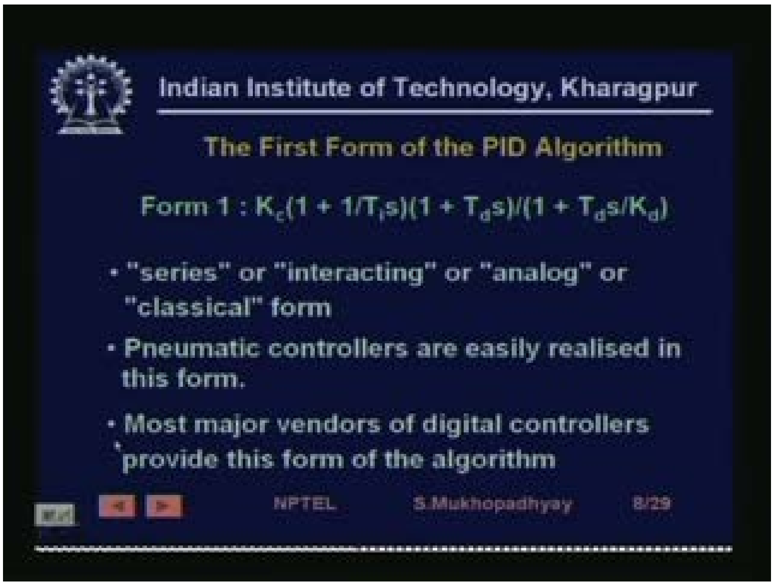

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The First Form of the PID Algorithm

Form 1 : $K_c(1 + 1/T_i s)(1 + T_d s)/(1 + T_d s/K_d)$

- "series" or "interacting" or "analog" or "classical" form
- Pneumatic controllers are easily realised in this form.
- Most major vendors of digital controllers provide this form of the algorithm

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So, you see that we have three different forms why is it? So, let us look at the first form in slightly more detail. You need to understand and you need to find which of these forms your PID controller is using because if you mentally assume that it is using one of the forms with which perhaps you are familiar. And if the controller is actually using another form then the gain settings that you are going to compute are not going to be right for that form.

So, let us look at form 1. Actually turns out that form one is sometimes called the series or interacting or classical form, the reasons for these names is that, firstly, series that you can understand that this is in series. So, this is one term, and this is the other term and this is the other term. So, there are three terms which are getting multiplied. So, therefore, they are in series. Why is it interacting?

It is interacting because for example, if you change if you change with respect to the with the respect to the second form which is probably the probably the most popular, if you change any one of the let us say if you change K c, then integral time. And basically the integral and the derivative gains will change if you change T i also they will change if you change T d also they will change and then all of them will change.

So, you see that they interact that is you cannot independently unless you do it very carefully by actually solving equations if you just change T i then it is not just that the integral time is going to change, the derivative time will also change and the proportional gain will also change.

So, therefore, the changes are interacting with one another that is why it is called an interacting control this is called analog because this controller has it is origin in the old days pneumatic controls. Actually, it turns out that it was easier to generate the PID equation in this form using pneumatic elements you know things like things like orifices, and then bellows, flapper nozzles.

So, with such thing it is easy to build it in this form and not in the parallel form right? So, therefore, it is called analog and classical. So, similarly, so basically this form came originated from the pneumatic controllers and still persists. Most major vendors of digital controllers provide this form of the algorithm because again you know legacy is going on. So, if you look at the second form, this is the most common.

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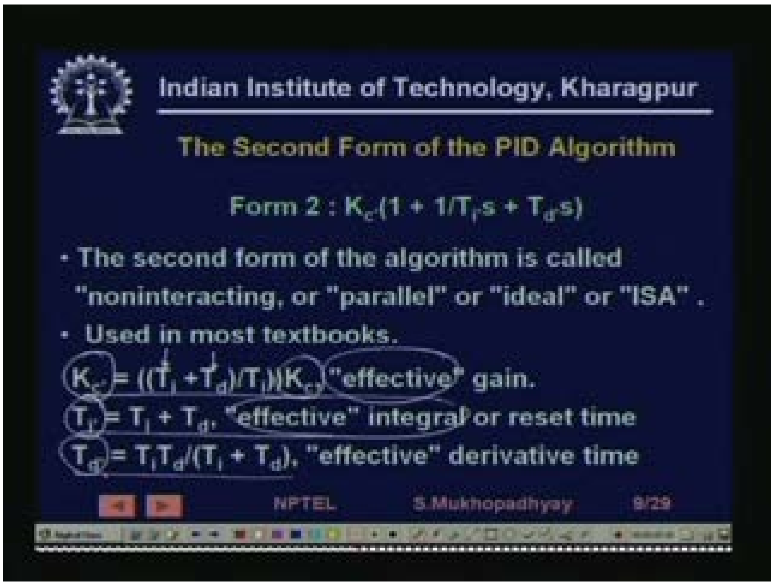

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The Second Form of the PID Algorithm

Form 2 : $K_{c'}(1 + 1/T_{i'}s + T_{d'}s)$

- The second form of the algorithm is called "noninteracting, or "parallel" or "ideal" or "ISA" .
- Used in most textbooks.

$K_{c'} = ((T_i + T_d)/T_i)K_c$, "effective" gain.

$T_{i'} = T_i + T_d$, "effective" integral or reset time

$T_{d'} = T_iT_d/(T_i + T_d)$, "effective" derivative time

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It is called non interacting although it is actually partially non interacting in the sense that if you can change T i without effecting T d and you can change T d without effecting T i. However if you change K c both T i and T d are changed. So, to that extent it is partially non interacting. It is called parallel because rather than having multiplication of three terms, here you have sum of three terms. So, you have sum of three terms. So, that is why it is called parallel although there is a multiplication. So, it is again partially parallel. Sometimes ideal or ISA means instrument society of America I do not whether how far these ideal or ISA are so valid. It is used in most of the text books.

And if you now, you know you could you try to covert right. So, what is the relationship between form one and form two for example. It turns out if you solve by equating coefficients of s in the numerator and in the denominator. Then you would find very easily that K c dash if you there is there is a catch, that catch is that if K d is high that is at 1 plus that is this factor. Let me just go back, that is this factor this particular factor if you ignore then it turns out that you can match the gains right? And how do you match the gains?

So, you match the gains second form. So, if you so it turns out that you get such formulae that K c dash turns out to be equal to this, the T i dash turns out to be equal to this and T d dash turns to be equal to this. So, as you see that, if you set, if you set gains T i and T d in the first form you are actually setting. If you set T i T d and K c in the first form then the actual gain which sometimes is called the effective gain and the effective integral time are will be actually obtained according to your understanding.

Suppose, you have read this equation and you are going to a controller which implements in the first form, and if you set some values then these the actual value which will be realized are will not be equal. So, that needs to remembered.

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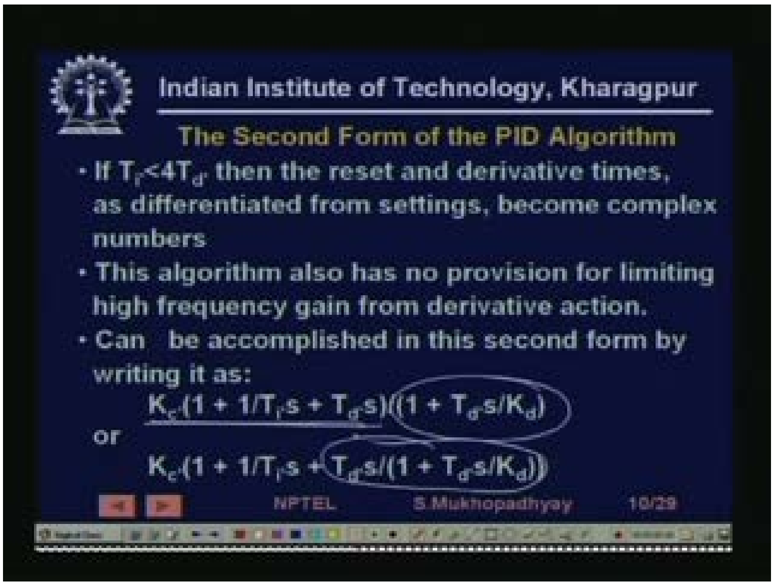

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The Second Form of the PID Algorithm

- If $T_i < 4T_d$, then the reset and derivative times, as differentiated from settings, become complex numbers
- This algorithm also has no provision for limiting high frequency gain from derivative action.
- Can be accomplished in this second form by writing it as:

$$\underline{K_c(1 + 1/T_i s + T_d s)}/\boxed{(1 + T_d s/K_d)}$$

or

$$K_c(1 + 1/T_i s + \boxed{T_d s/(1 + T_d s/K_d)})$$

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So, in fact, interestingly it turns out that sometimes you get you absurd readings. For example, if you set some value in the second form where T i dash is less than equal to 4 T d dash if you want to set you actually cannot set it in the first form. Because, it turns out that if T i dash is less than 4 T d dash then T i T d values are complex, they are not they are not you would not get real numbers T i and T d which will be able to realize this. So, you see the first form is somewhat constrained.

On the other hand, the second form in the second form there is no the second form does not have that 1 plus that denominator with the derivative term. So, there is that denominator can be is actually used for limiting the derivative gains as we have as we have pointed out earlier that the derivative gain needs to be checked, because of the fact that the sensor signal may contain noise. And then the derivative will give you very noisy signals if you try differentiate noisy signals we get very noisy signal.

So, there is a need to restrict the high frequency gain of the derivative. So, that noise is not amplified while the process signal gets differentiated. So, that is possible in the first form while in the second form it is as such not possible, but you could add such factors. For example, you could add that factor by adding such a term. So, by adding such a term with the overall equation or by adding that term only with the derivative part one of these two things you can do.

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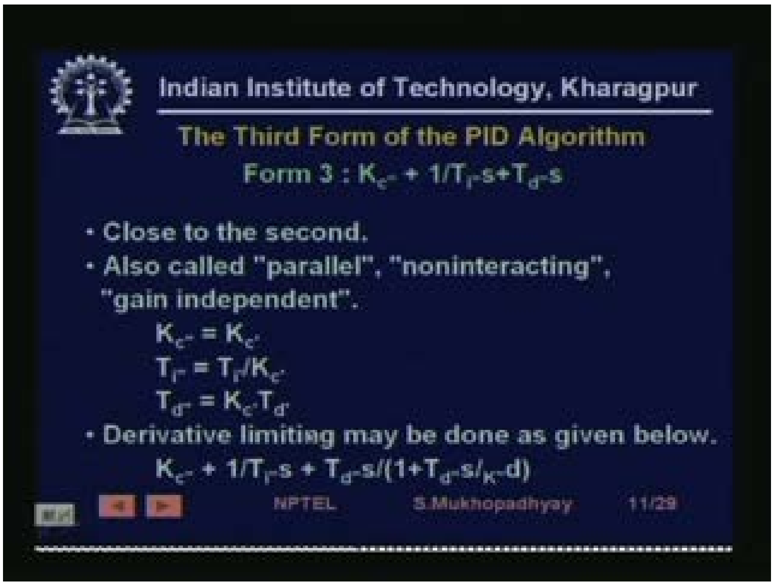

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The Third Form of the PID Algorithm

Form 3 : $K_{c''} + 1/T_{i''}s + T_{d''}s$

- Close to the second.
- Also called "parallel", "noninteracting", "gain independent".

$K_{c''} = K_{c'}$

$T_{i''} = T_{i'}/K_{c'}$

$T_{d''} = K_{c'}T_{d'}$

- Derivative limiting may be done as given below.

$K_{c''} + 1/T_{i''}s + T_{d''}s/(1+T_{d''}s/_{K}d)$

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So, if you look at the third form, that is the most you know quote and quote theoretically from its close to the second, but it is, but it is completely parallel, in the sense that the three coefficient K c T i and T d are totally decoupled you can change any one of them without changing the other. So, in that sense it is completely parallel and completely interacting. And to stress the fact that even by even K c is not interacting it is sometimes called gain independent.

And these are the standard equations which you get by. So, this is the relationship between the third form and the second form, you already have a relationship between the second and the first. So, you can substitute and get the other one. And you can similarly do a derivative limiting by having another you know lag term with the derivative term. So, this is so this it needs to be understood that PID equations come in different in different formats.

So, now let us quickly run through some of the, you know just putting the PID equation is not going to be enough. So, we first look at the hardware of the PID controller, we have looked at the PID equation, and now we are going to look at some of the software features of the PID controller. So, that we have a some idea about the whole PID controller implementation.

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Implementation Considerations

1. The option to have the derivative function act only on the process variable, not on set point changes.
2. Provision for reset windup protection.
3. Provision for setpoint and process variable tracking, to permit bumpless automatic/manual transfers.
4. Special purpose filtering such a notch filtering to avoid resonance

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So, you have, I just list them, there in there are no particular order and some of them you have already seen. So, this you have you have already seen that the option to have the derivative function act only on the process variable and not set point changes because, set point changes can be step like. So, that would give sudden suddenly a, induce a very high input to the plant. So, the input will rise like a like almost like an impulse and will come down if you make step change because of the derivative term.

So, you never apply the such set point changes on the derivative term, but you take the derivative term through the through the only from the process variable. So, you need to provide provision for reset windup protection this we have discussed in detail. You need to provide bump less auto manual transfer this. Also we have discussed. Sometimes apart from you know there are there are in a controller there are different kinds of filters, which are used.

So, one filter is to limit derivatives, you could use special purpose filters not to excite certain modes of a process which are very oscillated. For example, if you are imagine that if you are trying to trying if you are if you are having a container which contains molten steel, liquid steel and if you try to move that control container and what will happen is that the steel surface will try to move and it might spill over molten steel.

So, you need to construct so for such operation which are typically used in you know steel melting steel melting what is called a basic oxygen furnaces which are to be tilted where the molten steel has to be slowly moved. So, for such controllers standard PID controller is all right, but apart from that just before the actuator you put certain filters like that those oscillatory modes this liquid surface spilling can be linked to a can link to a resonant behavior very highly un-damped oscillate I mean very lowly lamped oscillatory behavior at a certain frequency. So, you do not want to excite that. So, you so you do not want to give input at that frequency.

So, for such purposes you sometimes use notch filter which have which will give you which will pass all signals, but only in a very so they have you know they have gain characteristics over frequency I am sorry. Somewhat like this you know. So, in this range they will pass control signals in this range also they will pass control signals, but in this narrow range they will stop the signal.

So, if you have your resonant frequency in this range, this is omega this is say u omega j omega. So, in this range this notch filter rather this is actually gain of the notch filter. So, it is G j omega. So, in this range the notch filter will not allow any inputs to come. So, such things need to be done.

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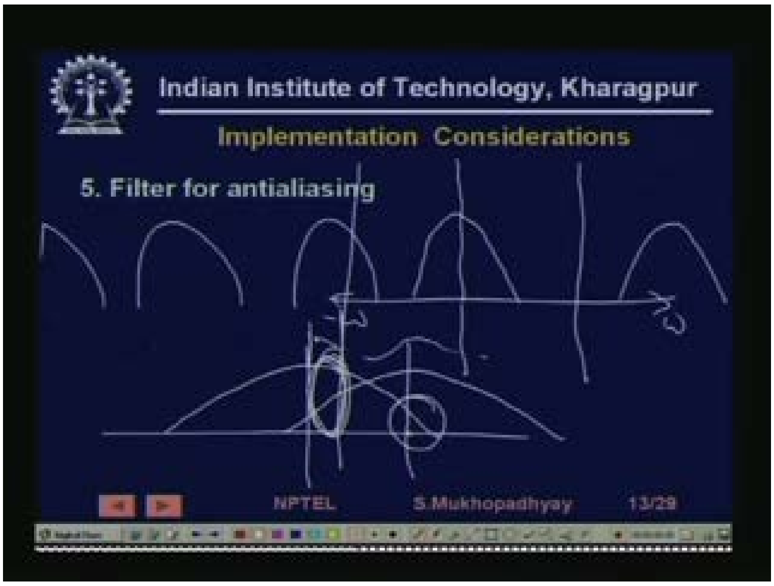

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Implementation Considerations

5. Filter for antialiasing

You need filter for anti-aliasing, you are probably aware of this that the after all this PID controllers are actually digital devices now, today they all contain microprocessors and they will do all kinds of computation using digital signal processing methods. So, it is well know that if a signal is sampled then it is analog spectrum gets repeated. So, you can you can this these are very standard signal processing phenomenon. So, if you if you take a signal which is which is low pass. So, it is spectrum this is omega minus omega complex spectrum we are talking about.

So, if a spectrum is like this then and if you are sampling it at this rate then it gets repeated actually, the spectrum of the sampled signal is going to be repeated. So, you it will it will be repeated repeating in indefinitely. So, now imagine that if you want to if you make this if you make the sampling frequency low, then it turns out that, suppose you, apart from suppose now I am just exaggerating the other way.

Suppose, the filter is signal is signal has this bandwidth and then you are filtering it at this frequency. Then, this loops will now come and start overlapping. So, this will be one of the loops and probably this will be the other loop. So, what will happen is that effectively once these two loops, if you take summation then you are going to get a frequency spectrum of the digital signal will look something like this.

So, you see that, but this is a very important part of signal, this generally for control low pass low frequency part is very important. So, you see that the high frequency part of the signal which was not. So, important for control has got kind of folded back and it has come on the low frequency part and is not effecting the low frequency part which is important, I am telling in where in very briefly.

So, for this purpose you need to ensure that it does not happen. So, you need to ensure that you only you first cut off the analog signal such that the high frequency part cannot fold back to the low frequency part. So, for that purpose you need filters and such filters are called anti-aliasing filters. So, you need such filters we must remember that.

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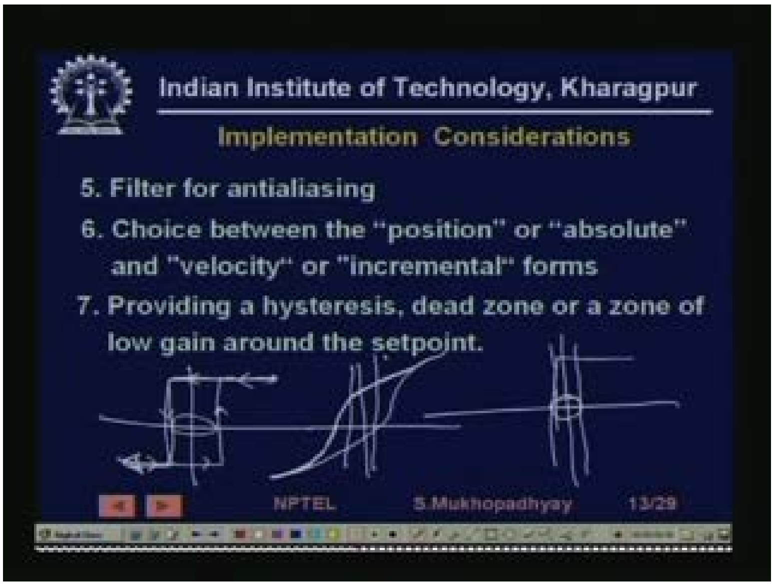

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Implementation Considerations

5. Filter for antialiasing
6. Choice between the "position" or "absolute" and "velocity" or "incremental" forms
7. Providing a hysteresis, dead zone or a zone of low gain around the setpoint.

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Similarly, this also we have seen that we need to decide whether we are going to realize the PID algorithm in the position or in the, or absolute or in other words or in the velocity form or incremental form. There are certain advantages with respect to auto manual transfer, there are certain actuators which will take incremental outputs. So, that needs to be decided.

Sometimes you know typically as we have learnt electronics also we have seen that suppose comparators. So, comparators if you have ideal comparators then the output will keep on switching right? So, therefore, we put we put a either a hysteresis or a small dead zone around the zero point. So, we say that if the error is little bit here within this zone then I am not going to I am going to keep my control output as before. So, you put a hysteresis you know let me draw it clearly.

So, you have an input output characteristic and you have a hysteresis curve. So, you have so you say that if the error is in this zone then I am going to maintain basically maintain. So, if I am, I was here I will maintain unless the error goes out of this zone and then I will. This is a hysteresis switch right now, you can have a smooth hysteresis comparator you can have something like this also. So, you say that I am going to keep the gain and then slowly change the gain. So, in this zone the gain is the output is not switched.

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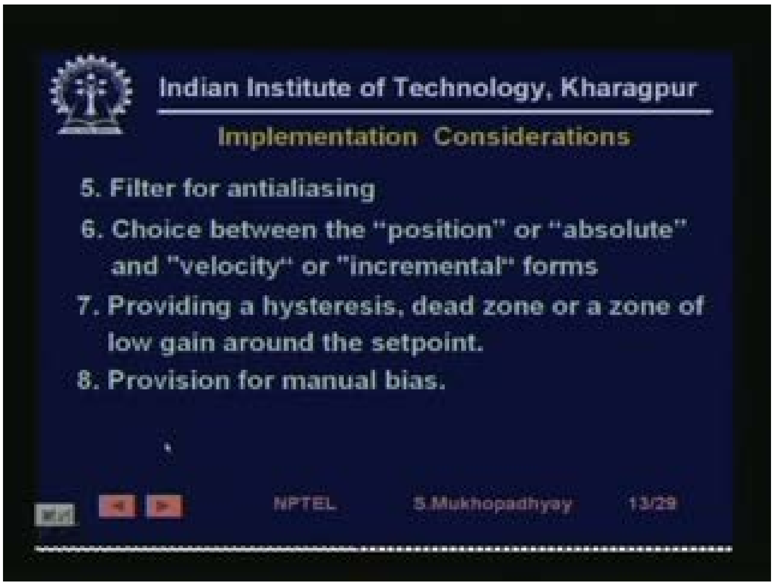

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Implementation Considerations

5. Filter for antialiasing
6. Choice between the "position" or "absolute" and "velocity" or "incremental" forms
7. Providing a hysteresis, dead zone or a zone of low gain around the setpoint.
8. Provision for manual bias.

So, these things can be done to avoid noise of course, because, they because you may be you can actually tolerate that much of error and it otherwise it will unnecessarily be all the time moving the actuator because of noise. So, the actuators for some actuators this may not be good.

Then, you need to provide provision for manual bias, you know manual inputs is are very important and you may like that the operator will sometimes provide manual bias that is if he if the operators are very experienced, and they themselves can act sometimes as very non-linear and sophisticated controllers. So, if he does not like the PID output you might like to give him a opportunity to change it.

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B. Concluding Facts on Control

Having said this let us so these are you know typical implementation features, and now we will come to some facts on control.

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The Early Tasks in Control

- Selection of manipulated variables
- Selection of controlled variables
- Selection of extra measurements
- Selection of control configuration that interconnects the controlled, manipulated and measured variables
- Selection of controller type (PID, decoupler, MPC etc.).

I wanted to start with the early task in control because these are the parts that we generally in an undergraduate control course we never pay attention to neither have I paid attention to them here, but at least let me mention that these are very important tasks. So, first of all selection of manipulated variables, which variables are to be manipulated? Selection of controlled variables, which variables are to be controlled? Selection of extra measurements sometimes required for you know choice is required for achieving good control performance like disturbance rejection as we have seen in the case of cascade loops. So, how are you going to do the cascade which are the variable you want to sense and feed it as an inner loop feedback you need to understand that.

Selection of control configuration that is you how whether, how you are going to connect the controllers and the sensors are you going to connect it in cascade with feed forward or you have seen some special features like you know Smith predictor. So, these needs to be need to be done. And selection of controller types whether you are going to use a set of single loop controllers or whether we are going to use multivariable controllers or you are going to use a set of single variable controllers with a decoupler.

So, all these things these choices need to made. And only after that will come the question of once you have selected these then will come the question of setting I mean the control loop design which we pay so much attention to. So, that comes at a much later stage this is something I wanted to mention.

However, it turns out that many of these questions are generally for given class of plants; these questions are generally settled. That is, if you are trying to control a reactor which of the variables are to be sensed is generally well know right, so but typically when you have a large plant this may not be so clear these options.

Next you have to find out so once you have done that roughly you need to set the control objectives, that is you need to know where you want to which are the variables you want to control in what way. And where do you want to set the values such that you have you have good performance from the plant and generally performance is measured in terms of money right?

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The Control Objectives

- What are the operational objectives?
- Quantify: Minimize scalar cost J (Rs./h)
- Identify constraints on flows, equipment constraints, product specifications, etc.
- Cost J depends normally on steady-state values of variables (such as flows)
- Cost optimisation depends on degrees of freedom

So, you have to you have to once you have you broadly understand the operational objectives you need to quantify them. So, you need to actually set values which will minimize some scalar cost right, scalar means a single overall cost of operation in perhaps expressed as rupees of rupees per hour.

So, you need to also understand that the various constraints on flow if you want to do that you want to you need to identify the constraints on flows the various equipment constraints actuator input constraints. And you also need to understand the product specifications, that is what are the let us say product composition bounds or whether the product dimension bounds.

So, these are very important to be identified before the control objectives can be specified, only after that you can aim you can you can even start doing a controller design. And it turns out that cost J that is the cost that you want to minimize depends generally depends much more on steady state values of variables especially, in process control such as flows. Because process controls are not processes are typically not always not all the time oscillating right, they will, they will oscillate once in a while. But most of the time they are going to stay you know in their steady states and therefore, it is the steady state values which are which mainly decide the cost.

So, this also needs to be identified and this is to be understood for people like us who pay a lot of attention to dynamics, but sometimes ignore the steady state operation. I want to emphasize that it is the steady state operation that generally decides cost of operation in a process control plant. Now, this cost optimization to what extent it is possible that depends on the degrees of freedom, now what is the degrees of freedom?

Degrees of freedom basically means basically, it tries to answer this question that suppose you say that ok I have these as this is the plant, these are the governing equations these are the things which are, which can be controlled or manipulated. Those are things which cannot be manipulated, they are given to us they are you know disturbances some feed coming from at some flow rate or some temperature no control on that.

Then, given this situation is it possible to independently set values for let us say some temperature and some level. So, such questions you know what is possible, that is you know degrees of freedom that is what is possible to achieve how what kind of control objectives are possible to achieve given the situation with control. So, that is very important to understand before setting the control objectives.

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Degree of Freedom

Does a control problem for a given plant and a given set of specification always have a solution ?

Let,
n : Number of process equations
f : Number of variables
n_d : Number of external/constrained variables
n^* : Number of control objectives/specifications

For the control to solved :

$$n^* \leq f - n - n_d$$

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For example if n is a number of process equations typically equated to the number of states. And f is the number of variables, and n d is the number of externally constrained variables, external or constrained you know sometimes they may be constrained in the sense that you cannot move them because, of certain specifications sometimes they are externally coming just like I said that to some flow of some feed.

And if n star is the number of control objectives or specifications typically, we are talking of steady state objectives. So, something should be maintained at this at this value constant, this is one control objective. So, if you have n star number of such objectives, then the degree of freedom is typically called f minus n minus n d basically of what? That is you have f number of variables free variables now, n of them so I mean ideally you would have f degrees of freedom because, these are f variables which could move in in the space, but because of the n equations they are first constrained. So, they so it is f minus n right.

So, if you have three variables and if you have two equations, then only one particular linear combination you can assign or one particular variable you can assign, but you cannot assign three variables independently to satisfy these two equations right like that. So, then it becomes f minus n and then more than that then of these f minus n some other degrees of freedom are lost because some of the variables are externally set. So, you cannot vary them.

So, then the remaining degrees of freedom are f minus n minus n d and that must be greater than the number of control objectives. So, if it is so if the number of control objectives is equal to that then your solution you will get a unique solution to the control problem, if it is more than that then you cannot satisfy it, because you have more number of equations than unknowns or and if it is less than that. Then you have some further chance of optimization that is you get put you can actually bring in some more objectives.

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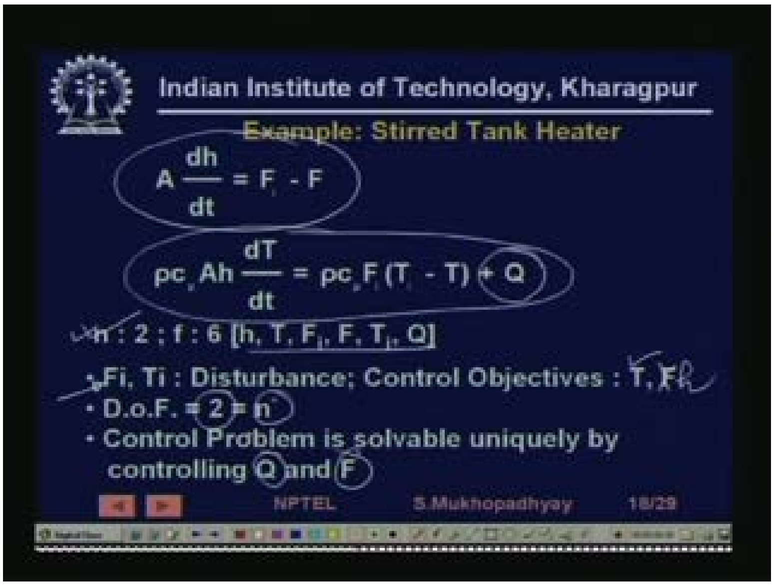

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Example: Stirred Tank Heater

$$A\frac{dh}{dt} = F_i - F$$

$$\rho c_p A h\frac{dT}{dt} = \rho c_p F_i (T_i - T) + Q$$

n : 2 ; f : 6 [h, T, F_i, F, T_i, Q]

- Fi, Ti : Disturbance; Control Objectives : T, F h
- D.o.F. = 2 = n
- Control Problem is solvable uniquely by controlling Q and F

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So, just to give you a brief example, consider a what is known as a stirred tank heater, basically a tank in which some flow is coming and you want to maintain the temperature of the tank as well as the level. So, you so these are two governing equations very easy. So, this is the level equation and this is the temperature equation.

We are assuming that we are giving some heat input, which we can control. So, the there are two equations. So, n is equal to 2 there are six variables. So, f is equal to 6 of these two are disturbance disturbances. So, F i and T i that is flow rate and the temperature of the feed. So, we assume that we cannot. So, those are lost so two are lost. So, from 6 minus 2 minus 2. So, the remaining degrees of freedom is two so that means, that it can take up to two control objectives. So, therefore, if we if you want to set if you want to set T and not F T and h by controlling Q and F this would be possible.

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Design Degree of Freedom

One degree of freedom loop

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So, this is what this is what degrees of freedom is about. Similarly, you see that sometimes typically in a control loop you can you have typical control loop that we consider actually one degree of freedom this is very important to understand.

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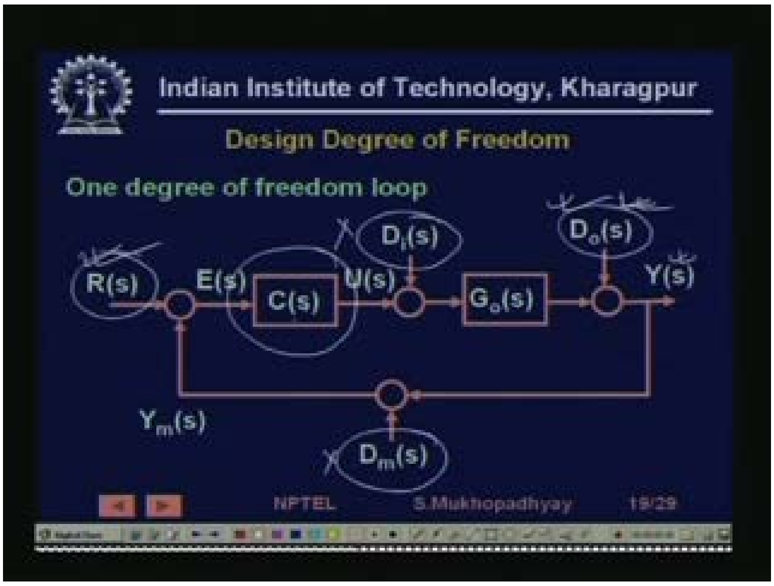

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Design Degree of Freedom

One degree of freedom loop

NPTEL S.Mukhopadhyay 19/29

So, you see that this is a typical control loop like in which several disturbances may be acting here as well as R s. So, what is that we want? We want let us say let us for the time being consider forget about these two and consider only this one. So, what do we want? We want that good set for tracking.

So, the response Y s by R s you want to share. And we want to at the same time we want good disturbance rejection. So, this response Y s by D 0 s also we want to share, but that is not possible because this is a one degree of freedom controller. So, using C s you can either you can you cannot select both of them independently right that is that is obvious from the equations.

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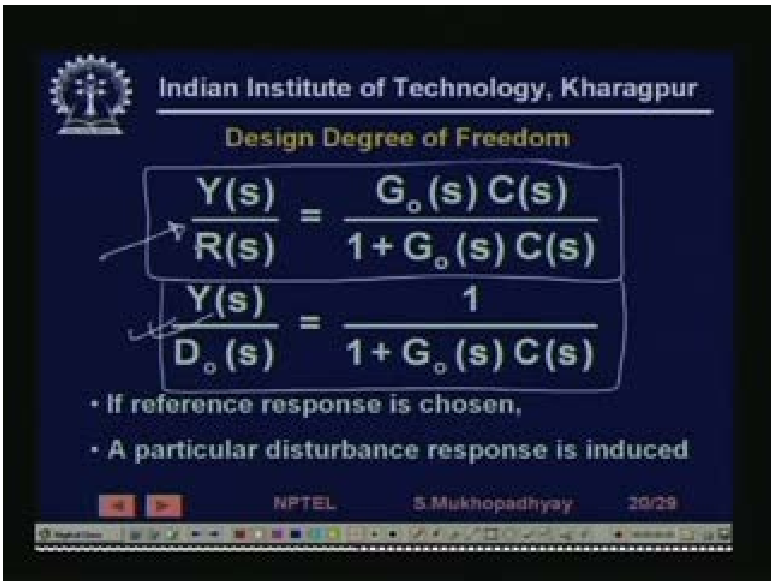

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Design Degree of Freedom

$$\frac{Y(s)}{R(s)} = \frac{G_o(s)\,C(s)}{1 + G_o(s)\,C(s)}$$

$$\frac{Y(s)}{D_o(s)} = \frac{1}{1 + G_o(s)\,C(s)}$$

- If reference response is chosen,
- A particular disturbance response is induced

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So, this is what it says, it says that this is the transfer function between Y s and R s and this is the transfer function between Y s and D 0 s. So, you see that if you choose C s this gets fixed suppose. So, you suppose, you choose D s C s to design your disturbance response then your set point response is fixed you cannot change it. So, you have only one degree of freedom you can only set the response to one variable, right? So, or vice versa if you are choosing C s to get a particular reference response then your then your disturbance response is decided.

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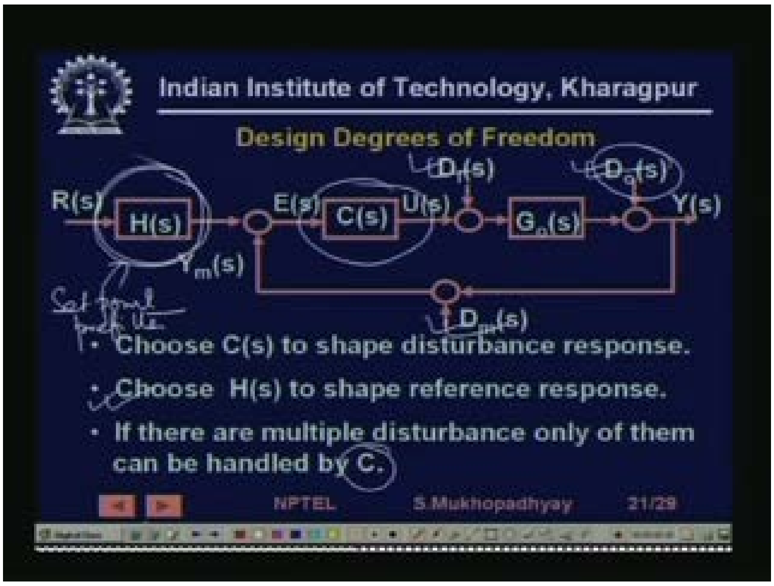

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Design Degrees of Freedom

- Choose C(s) to shape disturbance response.
- Choose H(s) to shape reference response.
- If there are multiple disturbance only of them can be handled by C.

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Now, you could improve the situation by having this. So, for example, in this case there are two degrees of freedom, why? Because, you have introduced a set point pre filter, this is called a set point pre filter. So, what you are doing is you choose C s to assign a response to D 0 s, and then once you have done that then you choose H s to assign to shape the reference response although there are constrains still you cannot have arbitrary responses realized to the structure. But still you have now created two independent avenues for shaping that reference as well as shaping the disturbance, but remember that still you do not you if you choose only one C. Then you cannot shape your shape your shape your response to D 0 and D i and D m simultaneously, you can do it for only one of them right.

So, you see these are these have to be realized to be able to choose the control structure. So, if really so this tells us that if we want to assign independent disturbance and reference set points then we cannot use the conventional control structure because that is one degree of freedom right.

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Set of Single Loop Controllers

Non-interacting process and no change in constraints

+ Tuning may be done on-line
+ No or minimal model requirements
+ Easy to fix and change
- Need to determine pairing
- Performance loss compared to multivariable control
- Complicated logic required for reconfiguration when active constraints move

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So, similarly suppose we are we have two options we actually have to simultaneously control a number of process variables. So, we have options. So, what are the options that either we could use a set of single loop controls that is manipulated variable A controls variable B, manipulated variable C controls variable D. So, A to B once single loop controller giving give feedback of B and drive A give feedback of D drive C. So, you have a number of set of single loop controllers. Compared to that you could what is the other option the other option is have one big multivariable controller which will take all the feedbacks, and which will drive all the actuators and it is a multivariable system this is more modern. So, when do you do what?

So, you have if you have non interacting processes, you see that you are actually where you are if you have a single loop controller. Then when you are trying to control one process one variable you are not you cannot take care of the fact that are there change in this variable can cause the change in another variable this fact cannot be considered. So, if there is interaction between the variable dynamics then set of single loop controllers can be very problematic and should not be used.

Similarly, you may have to maintain constraints over several of these variable, but then each controller is actually controlling only one. So, then if you have such constraints which keep changing then it is very difficult to use a set of single loop controllers. So, on the other hand tuning is very simple there are there are some plus points that is you need to you. In fact, they are used and they you can visit in various situations where there is not significant not interaction or constraints changing dynamic constraints.

So, you need your modeling requirement is low you can build models by simple experiments they are generally simplicity general plus points are simplicity. On the other hand you need to determine pairing this is very important that is which manipulated variable you will choose to set up a loop with which for which controlled variable this is called pairing you know pairing outputs to input.

So, this is an interesting point and people have various methods here we did not study them, but this needs to be done. Similarly, it turns out that you have performance loss you can achieve such control such good control as you can with multivariable control. And when we have active constraints then you have very complicated logic you must have above these set of single loop controllers. You must have supervisory logic which will look at all these single loop controllers and probably carefully manipulate the set points. So, such logic such additional logic is required so all the, it is not that simple. On the other hand, if you have multivariable controllers.

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Multivariable Controllers

Interacting process and changes in active constraints

- \+ Improved performance in presence of interaction
- \+ Easy handling of feedforward control
- \+ Easy handling of changing constraints
- \- Requires multivariable dynamic model
- \- Tuning may be difficult
- \- Less transparent
- \- Failures can be very damaging

Then, in process interactions as well as constraints are handled very seamlessly. Actually, things like you know MPC model predictive control, which are very popular in the industry today are controlled methods we did not study MPC, are methods which are designed to handle multivariable processes with interactions and having constraints. So, they are all built in into the method and they are handled very efficiently all right?

So, you have significantly improved performance in presence of interaction you have easy handling of feed forward control we again feed forward is you know tends to make the system multivariable. You have easy handling of changing constraints as we have mentioned and it requires a multivariable dynamic model. Tuning is obviously, difficult much more difficult than a set of single loop controls, difficult to understand less transparent and this is the important thing that failures can be very damaging.

So, what happens is that is you know you have put you have put all the loops now in to one box. So, if that box fails then the complete controls for your process is lost. This is a, this is this needs to be understood and. So, this could be a major reliability threat having a multivariable controller. So, sometimes you need redundancies.

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Limitation due to Sensors

Sensor Noise
Sensor noise limits the closed loop bandwidth.

Sensor Bias
Sensor bias directly appears at the output

Sensor Dynamics (Thermowell)
Can be cancelled by high pass filtering.
Limited by noise bandwidth.

Sensor Nonlinearity (Orifice Meter)
Causes loop gain variation.
Can be cancelled by actuator nonlinearity (valve)

NPTEL S.Mukhopadhyay 24/29

Performance in a control loop gets can be limited either by sensor noise. Sensor noise limits the closed loop bandwidth if you increase the closed loop bandwidth the noise will go to the output. If you have sensor bias this is we have discussed exactly same bias especially in unity feedback control exactly same bias will appear at the output. Sensor dynamics you know sometimes some sensor for example, thermocouple they are not directly put in to the process they are actually put through a well. So, that well to for the temperature to for the heat to flow through the well it takes time constants and such time constant can cause stability problems right.

They can be sometimes canceled by high pass filtering, but again that will build up noise. So, there is no escape you have to pay prices. Sensor nonlinearity you know sensors if the sensors are non-linear for example, tell let us take a let us take an orifice meter sensor, it has a, it has a square root law in it is basic sensing mechanism. So, as this so if you take it as a linear sensor then what happens is that the process gain keeps changing depending on where you are operating, if you are operating at 100 percent flow then there will be one process gain, if you are operating at 20 percent flow there will be another process gain.

So, the controller gains needs to be set conservatively. So, you will have to, for stability considerations if you are setting a constant gain controller, then you need to set the gain which will work for all the processes without or all the process gains without causing oscillation. So, obviously, now the now you will set the gain low and when the process gain will become low then it will lead to sluggish behavior.

Sometimes this can be very nicely canceled by having an inverse nonlinearity in the actuator. So, that in the, so that in the, in the overall loop the sensor nonlinearity gets canceled by the actual nonlinearity actuated nonlinearity. And in fact, it happens by using valves, because valves have inverse nonlinearity sometimes we are going to see all these later.

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Limitation due to Actuators

Saturation

- Limit: Limits output Can cause windup / poor transient response/ closed loop bandwidth
- Rate Limit: Limits closed loop bandwidth

Resolution

- Digital Actuators
- Stick-slip friction
- Causes sustained oscillation in closed loop

Actuator Nonlinearity (Control Valve)

Causes loop gain variation

Can be cancelled by sensor nonlinearity (orifice)

NPTEL S.Mukhopadhyay 25/29

Similarly, for actuators you can have saturation. Saturation will actually limit transient response because, you are not you I mean how do you move system fast by giving it a lot of input and by giving it fast. So, you need good input and you need rate limits, you need high rate limits that is you can jack up the input very fast. So, if you have any of these limits then you cannot push the plant hard enough and you lose in transient response as or close to bandwidth. Similarly, it is sometimes resolution, you know some actuators cannot make small movements either because of you know stick slip motion. So, if they move it they will move and then they will again get stuck.

So, for such if you have such stick slip motions then the actuator cannot actuator because of resolution it keeps oscillating. So, it will move there that will that is actually too much correction it will come back, again it move there. So, it keeps on doing this and that causes you know oscillations. So, typically such resolution problems are caused either by digital actuators like step motors, or they could be caused by stick slip friction and the and the effect is that it may cause sustained oscillation in closed loop. Similarly, actuator and nonlinearity we have all ready mentioned this.

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Limitation due to Process Model

- Time delay
  - Limits gain from stability consideration degrades performance.
  - Can be corrected provided process model and delay are estimated accurately
- RHP Zeros
  - Effect like delay only
- Model Errors
  - Typically larger at high frequencies
  - Limits closed loop bandwidth

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Similarly, due to process models this we have all ready seen time delay causes stability problems and degrades performance gain has to be kept low. And if the time delay and the process parameter are known accurately then some of them may be corrected, but it is very difficult to know it accurately and the process model also keeps shifting. Right half plane 0s are like delays and model errors. So, remember that models model errors are always high in the high frequency zone. So, increasing the bandwidth you are going into the uncertain zone. So, you need to limit the close loop bandwidth such that the models are fairly accurate.

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Lesson Review

- Controller Implementation
  - Control Structure
  - Control Algorithm
  - Control Hardware and Software
- Control Performance
  - Degree of Freedom
  - Plant dynamics and constraints
  - Control Hardware and Software

So, here we have come to the review we have reviewed controller implementation and under that control structures, control algorithms we have seen the PID equations and the control hardware and the software. We have also seen looked at control performance and seen that what kind of performance can be expected is reasonable to achieve. And we have seen the various kinds of plant dynamics and constraints that can affect control performance, and we have seen the hardware and software features which will limit performance that is of course, algorithms.

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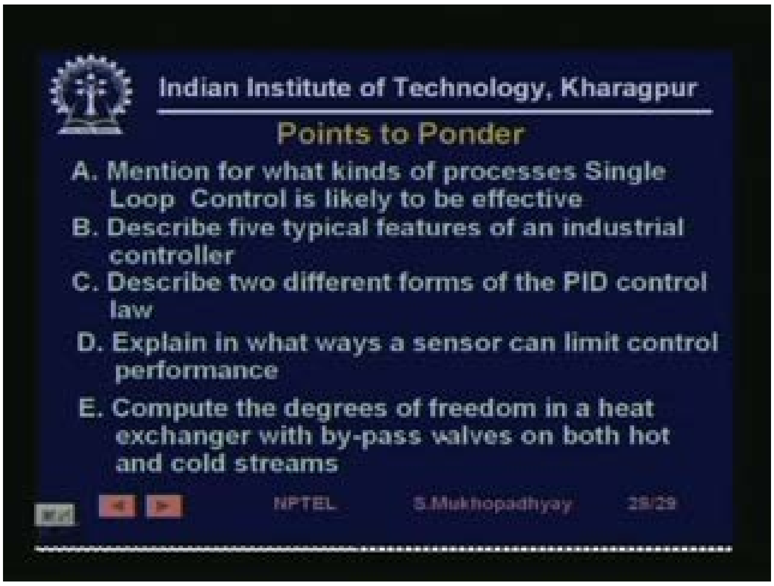

Points to Ponder

A. Mention for what kinds of processes Single Loop Control is likely to be effective

B. Describe five typical features of an industrial controller

C. Describe two different forms of the PID control law

D. Explain in what ways a sensor can limit control performance

E. Compute the degrees of freedom in a heat exchanger with by-pass valves on both hot and cold streams

So, you might ponder on these questions for example, what kind of processes single loop control is likely to be effective? So, can you give an example? Some typical features of an industrial controller, or can you state the different forms for the PID control law and make their conversion. For example three to one form three to form one we have not yet done can you look at that. Explain in what ways a sensor can limit control performance and sensor or actuator. And compute the degrees of freedom in a heat exchanger this is a nice problem. So, compute the take a standard heat exchanger with bypasses on the hot and the cold flow put valves on them and then try to compute the degrees of freedom. So, that is all for today.

Thank you very much.

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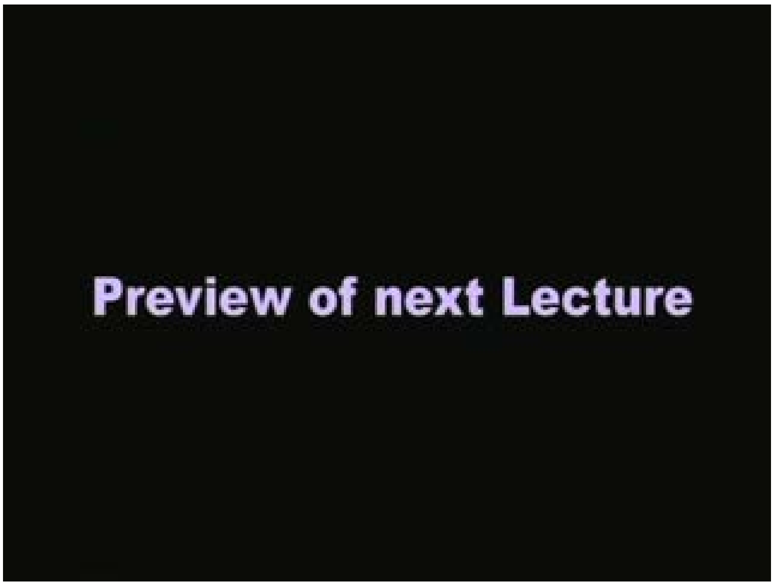

Preview of next Lecture

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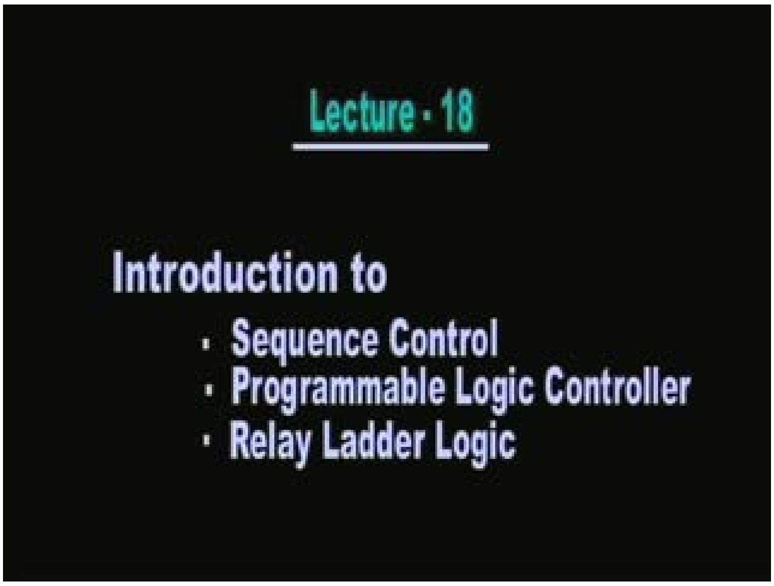

Lecture - 18

Introduction to

- Sequence Control
- Programmable Logic Controller
- Relay Ladder Logic

Good afternoon.

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Lesson 18

Introduction to

- Sequence Control
- Programmable Logic Controller
- Relay Ladder Logic

NPTEL S.Mukhopadhyay 2/33

We are going to start lesson 18, which is on a new subject it is a new module on sequence control. So, we are going to have our first introduction today on sequence control, on the kinds of controllers that are used for sequence control namely programmable logic controllers or TLCs. And we are going to take a first look at the programming languages, the languages which are used to specify control programs for TLC’s.

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Instructional Objectives

After learning the lesson students should be able to

A. State three differences between analog control and sequence control

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So, as usual we will first look at the instructional objectives. So, after learning the lesson the student should be able to state three differences between analog and sequence control, this is important, because traditionally an electrical or manufacturing or chemical engineering student is typically exposed to analog controls.