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Nonlinear Adaptive Control
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Week 1
Lecture 1
Basic Concepts and Nomenclature

Welcome to the NPTEL on Nonlinear adaptive control, I am Srikant Sukumar from Systems and Control, IIT Bombay. So, this is, this representative image of robotics in control of what robotics and control can achieve in the background, this is essentially a rover on Mars. So, this is sort of the combination of robotics, controls, networks, sensors, actuators and so on. So, you will continue to see this sort of a background image on all our lectures. So, let's move on to the actual content of the course.

So, this is the first week and this is the first week of our lectures. So, and this is, today is lecture number 1. So, today, we are on lecture number 1. So, we sort of assume some basic background when we are doing this course, well first is that all of you have some basic knowledge of state space representation in controls, this is typically covered in of course, in our department in course called Systems theory, but it is also covered in a second level controls course, the first level controls course is usually sort of frequency domain, Laplace transform, Root Locus and all of that.

And in the second level control course typically a lot of you study state space representation notions like linear systems, controllability, observability and so on and so forth. The second thing is that we require that all of you are sort of aware of, is the knowledge of ODE that is ordinary differential equations and basic solution techniques.

So, this sort of includes you know, things like variation of parameters solutions, existence, uniqueness, ideas of solutions. So, that is a couple of things that you definitely are required to sort of know. Then of course, we expect you to know some basic Multivariable Calculus like you know, limits, continuity, matrices and things like that. So, this is I would say a basic engineering maths course should cover all of this material. So, with this background assumption in mind, I would like to start with our actual material.

I want to also discuss to begin with what a block diagrams for an adaptive control would look like. So, a lot of you are used to see block diagrams. So, block diagram is integral to most control courses. And so, what I want to do is also to give you the same block diagram framework, what an adaptive control system will look like. So, if you see here, so, adaptive control as is mentioned here is a rather specialized sub part of nonlinear control, why usually there is a need for adaptation is the fact that a lot of parameters of our systems typical nonlinear systems are unknown.

So, lot of our examples at least in this course, will come from mechanical, aero mechanical systems, like, you know, quadrotors, robots, satellites, and so on. But of course, this is applicable everywhere, the initial probable, initial advances in adaptive controls were made by electrical engineering, infact control itself was much more popular in electrical engineering in seventies and in mathematics in the form of optimal control significantly before that, but in more recent applications, it is been the aero mechanical systems community that has found more use and actually used adaptive control in real systems.

So, and this is like I said, the reason for this is that adaptive control helps you deal with uncertainties in the system and uncertainties are probably the most common feature of any system. So, you might design a, you might have a model a state space model, just like you see here, you have a state space model for the plant and which is sort of has a general nonlinear structure in general, we assume a nonlinear structure, which is like you know, something like a summation over Lambda i f i and so on.

And then there is an output which is a summation of Mu j, g j, where f i, is a function of possibly state time and a control and similarly output is a function of the state time and also the control. So, the additional feature or additional sort of complexity in the systems that we are interested in, is that this Lambda i's and Mu j's are unknown.

So, these are some sort of unknown parameters. So, there are lots and lots of examples of these lots and lots of examples, I mean, for example, if you consider a robot, then you may have you know, damping coefficient mass inertia and so on, all of these can be unknown or all of these can be unknown quantities.

If you consider say, you have quadrotor system for example. Suppose you have a quadrotor system again, so, you have you use aerodynamic, sort of lift in order to fly the quadrotors. So, then there are parameters like lift coefficient, drag coefficients and so on, again, on top of this there is inertias, masses, that are unknown, so, there are many, many sort of unknowns that are very common in subsystems.

So, what we do is we sort of assume that the system is parametrized the parameters appear in such a way that the system is in fact linear in the parameters. It may be nonlinear in the dynamics of course, they like so, but the parameters appear in a linear manner. This is not such a difficult assumption, to be honest to justify, and you will see in the future some examples of how to deal with parameters that appear non-linearly, doing something like an over parameterization and things like that etcetera.

So, but we assume for the purpose of this course, that the parameters appear linearly. And that the parameters are constant. Parameters appears linearly, parameters constant, like I said, so if the parameters appear non-linearly there is a lot of things that can be done in terms of parameterization, in order to know alleviate this issue.

In terms of timing varying parameters, also, a lot of work has been done more recently. We are not going to look at this course, because this is still at a curriculum level and time varying parameters. I mean, sort of results in some sort of research topic still.

So, there is a still lot of research that is ongoing in adaptive control, time varying parameters is one such area, where there has been a lot of work already. But still will not have time to cover that material here. So, we have this plant, this plant works which you can see here, which is of course, now has this additional complexity that this Lambda i's and Mu j's are unknown.

Then we have a controller. Now, the question is what should be the structure of the controller the controller cannot just depend on the outputs, output is the only thing that is available. So, obviously, output is the one object that the controller can depend on. But now, the control once depends on what we call estimates these Lambda i hat and Muj hats these are called estimates of the true parameter Lambda i and Mu j.

So, the controller now depends on these estimates also. So, what adaptive controller tries to do is that it takes these measurements out and takes these measurements and it puts it into some sort of a black box for now, some sort of a black box which in turn creates an estimate for these unknown quantities.

So, that is the additional piece in this this block adaptation block is the additional block in a typical adaptive control setting that you will not find in standard nonlinear control and we denote all estimated parameters using these hats, these quantities with hats on them, denote the estimates of the true parameters and then these estimates are in turn fed into original controller, and the controller uses not just the outputs measurements, but also the Lambda hats and Mu j hats, that is the estimates of the true parameter values it also takes in a reference signal this is always the case there always has to be a reference signal.

So, the plant is trying to follow all the outputs of the plant required to follow some kind of reference, and so that reference system is also input. So, with the reference the Lambda hat Mu j hat and the measurements the controller then generates an algorithm which is sent into the plant through an actuator and then of course, you have the outputs again and the cycle goes on and on, this is a typical feedback system structure.

The only difference again, like we said before is that there is an adaptation block. So, this adaptation block is what is rather critical. For all adaptive control without the adaptation block, there is no adaptive control. You hear a lot of a lot of folks, who do parameter tuning not, not parameter tuning, but gain tuning, and they take a typical PID control and then they take a P gain, I gain and then they tune these gains based on some kind of performance metrics.

So, these are like some kind of time varying days and then they tend to call this adaptive control, but this is not true, this is not adaptive control. Adaptive control is primarily for the case when you have unknown parameters in the plant or uncertainty is in the plant. So, so, that is what we sort of summarize here typically in an adaptive controller, typically in the nonlinear control, you have states outputs and some input u reference signal r. The objective is usually for the y that is your output to track the reference r.

So, this are some examples, trajectory tracking in robotics. So, this is usually called the tracking problem always remember this word, because we keep using this word in this course, again and again. This is called tracking problem tracking problem, why because the output or the states or whatever be it are tracking reference trajectory. So, if there is no reference trajectory, then you want all your states, or all your outputs to get to 0. This is called a stabilization problem.

So if you want y or x to go to 0 as t goes to infinity. This is called a stabilization problem. But what we are typically interested in tracking problem. Similarly, you have a setpoint temperature in H VAC that is air conditioning systems, that if you want to achieve a particular vehicle speed in an automatic cruise control that also falls under the category to tracking problem and because you want to achieve a particular speed irrespective of what the road conditions are that is if it is, if the, it is an upward incline or a downward slope does not matter, you still want to remain at a particular speed alright. So, that is the idea of a tracking problem.

Now, I mean as is obviously evident we do not actually use all the states and we did not use all the states in order to do tracking. Not all states are in fact quite to track a signal this is very obvious, very obvious in any sort of problem. For example, if you think about being say this for example, your air conditioning system just an AC in your home or just think of an AC in your home what is it that you want to track, you want the room to track something like a setpoint say 25 degrees. Suppose you want your room to be at 25 degrees centigrade.

So, this is what you want to track. Now, now, remember the air conditioner that you have in your home, has many states, in fact if I had to model a AC it has many states, it has electrical elements. So, obviously there are states like you know for example, the x will be say voltage, current then there is a compressor. So, obviously there is pressure, maybe input, output pressure, then there is of course temperature, this is not just the temperature of the at the output that is of the room, but this can also be temperature at different points in the air conditioning system.

So, there are many many states, I mean, I have just given you say 4 or 5 states already, but if you want to do more and more careful modeling in of course, you will have more and more states. But the fact is we are not concerned with all the states tracking a particular set point, we as a user are interested in only the output temperatures to track a set point.

That is it, we only want the output temperature to track a setpoint. Now, this is of course, achieved by using, by setting the room output temperature. So, when we say room temperature, usually you can imagine that the air conditioner in my home is not measuring the temperature at every point in the room, anything fancy like that.

All it does is it has a sort of thermostat at the end at the exit of the air conditioner. And it simply uses that to measure what my output temperature from the AC is, it is not really measuring the room temperature, the basic air conditioning systems. Of course, if you wanted to make a very very fancy air conditioning system, which actually does what it promises.

Then the AC will have to come with many many temperature sensors that have to be mounted all corners of the room and then it somehow it maybe takes the average of that temperature and uses that to infact control the air conditioner better, in that case you will have probably better or more equitable distribution of sort of temperature, but usually this is very difficult to do. And that will not just require multiple temperature sensors; it will also require multiple outlets for the AC.

So, these things are done using H VAC systems. But you can imagine this is too complicated and as engineers we of course, make approximations when such kind of complicated setups are not possible. Therefore, the AC is a single unit it contains a temperature sensor just at the outlet and it measures that temperature it is used that is what is the temperature of the room and this temperature y is only one of the states of the air conditioning system? Only one of the states of the air conditioning system and therefore, like we said we almost never need to track all the states this should be rather obvious.

So, as I stated already we have the standard assumptions that these Lambda i's and Mu j's, appear linearly, even though the system is nonlinear, the parameters appear linearly, further we have that the parameters are constant. So, this is of course, evident the linearity is evident in 2.1, 2.2, again which is simply rewriting what we had in the block diagram.

So, these equations are simply rewriting whatever we had in the block diagram, nothing new that. So, the question is can we still make the output y track a reference r of t, by prescribing a control. So, here of course we say that the control is allowed to depend on also the estimates for the unknown parameters.

So, this is the important part in adaptive control, now lot of you may have also seen in some form robust control, which is another way of dealing with uncertainties. So, uncertainties are dealt with in two different ways one is using a robust control and other is adaptive control. So, there is, there is a bunch of differences in robust control there are no estimates.

The first important thing to remember is that in robust control, there are no estimates of any parameters, if there is a uncertainty, it is classified as a, sort of structures and unstructured uncertainty and it is dealt with as is, the second is it because there are no estimates. You can expect I mean, I do not know, you should not expect that there will be true tracking performance. So, only bounded performance guaranteed, only bounded performance is guaranteed here. What does it mean? It means that you will never truly track a signal, you will only remain in a bounded neighborhood. So, this is a rather important point.

So, if I make a sort of xy axis and say I have some kind of robot for which I have a reference signal like this, typical robust controller will only guarantee that you remain somehow in a neighborhood, as you can see that I have made it, I have drawn using a thick line to indicate that you will sort of remain in a neighborhood of given whatever uncertainties in the system structured and unstructured and so on so forth.

On the other hand, with an adaptive controller suppose you have start at some. Offset suppose you are start with some offset, but with an adaptive control, you are guaranteed to converge to the true trajectory. Why is this? It is not free nothing is free nothing is free. This is because we construct estimates for the Lambda i's and Mu j's. And these estimates are used in the controller robust control does not do this.

It does not use any estimates it does not design a control base obviously, it just says that you are given a controller. Then there are these uncertainties. What happens to the system performance in the presence of uncertainties with the nominal controller? In adaptive control, you don't even use a nominal control.

So, in designing estimate for the unknown parameters is that you are adding additional dynamics to the controller, when you are adding additional states to the system. Lambda i hats and Mu j hats and infact additional state, obviously there is more computational burden. So, the question if you can take in this computational burden, then you can construct these estimates, you can make a controller which depends on these estimates, so that you can drive the measurements or the outputs to the desired values.

This is not done robust control, it is not a more a simpler sort of setup, where you say that, alright, I do not have access to that much computational power. So, I am simply going to take a nominal controller I am going to simply analyze I will call robust control analysis method because it takes a nominal controller, the control design has nothing special in it, it is designed based on the absence of uncertainty and then you simply analyze how, what kind of boundedness what kind of bounds you will get, so, typical robust control will actually give you some estimate of this width, will give you some estimate of this width.

The other thing is a robust controller typically assumes knowledge of parameter bounds, without parameter bounds, there is no way to give bounds this here, without parameter bounds, you cannot give such kind of bound here. So, therefore, the robust control assume knowledge of parameter bounds, adaptive control does not.

So, these are sort of the key differences between robust control and adaptive control, not free. So, robust control seems to be doing something which I would call analysis, what is adaptive control is actually doing control, because you are adding some elements, you are adding an estimator, you are adding control, which is probably more complex, which lies on this estimate.

So, this is what we need to remember. Alright, that is sort of, the end of what we want to talk in this lecture. In the next lecture, we will go towards what are the myths, typical myths and temptations. So, we jump right into the mathematics of things. So, this is of course, a very, very mathematically oriented course, back soon enough, you will start seeing connections with real systems.

And so, the hope is that you can actually pick up a real system eventually, and use what you learned in this course in order to do adaptive design. So, what is it that we talked about today? We saw that adaptive control adds an additional block of an estimator in the system. So, here we estimate unknown parameters, there are standard assumptions, the parameters are expected to appear linearly in the plant dynamics.

The parameters are of course, expected to be constant for the purpose of this course. Then the control is designed which is of course, depending on these parameters. So, gets as opposed to robust control, you get exact tracking. While in robust control you get only approximate tracking that is you converge to a neighborhood of your reference signal. And you are not required to know, the bounds on the parameters. You do not need any uncertainty bounds in adaptive control. Thank you very much for listening.