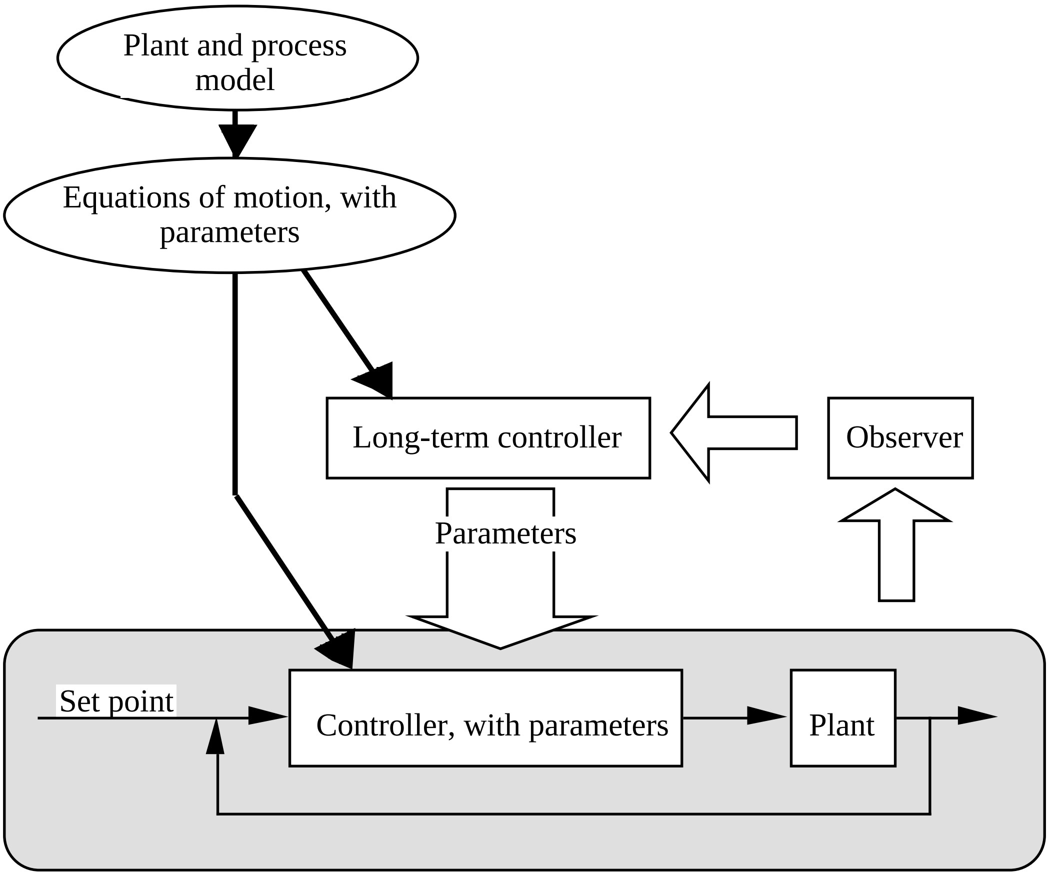
Computer Science 773

Robotics and Real-time Control

ADAPTIVE CONTROL

The purpose of adaptive control is to provide a controller with the means to adjust its behaviour according to external parameters. For example, a steering controller for a ship or aircraft is primarily concerned with short-term corrections to the steering controls as are needed to keep the vehicle on course. Over the longer term, though, the details of the controller must be adjusted to take account of changes in the prevailing wind and (for the ship) tides, and an adaptive controller would make the required changes automatically.

The general pattern is illustrated in the diagram below. The primary controller (inside the shaded box) deals with the moment-by-moment control of the plant, but the behaviour of the plant, environment, and any other relevant items are monitored by an "observer", and the results used to adjust the parameters of the primary controller. The whole system is designed from a model of the complete system.

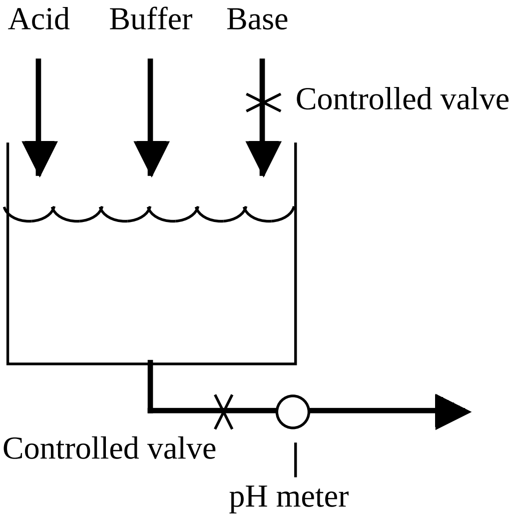


Gain scheduling can be seen as a simple example of adaptive control, but the term is usually reserved for more complex systems in which the parameters cannot simply be looked up from a table. One would speak of gain scheduling if the observer simply observed the environment (giving long-term open-loop control), and adaptive control if it observed the behaviour of the plant in action. Notice that the open arrows connecting the controlled plant, the observer, and the long-term controller themselves form a feedback loop, with the observer as the sensor.

AN EXAMPLE : A NEUTRALISATION CELL.

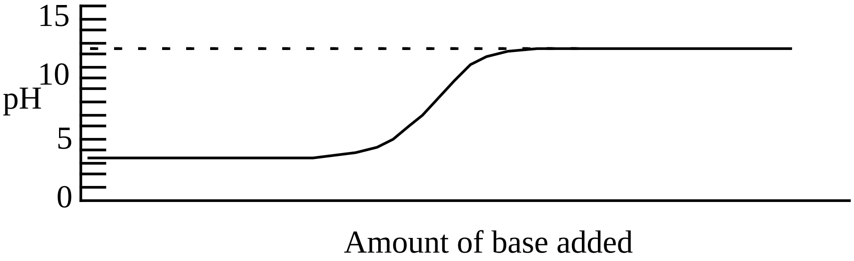
This is a very brief summary of an investigation reported in the literature; see the reference below for more details if you're interested. I've simplified it quite a bit, but I think I've retained all the important bits. I suspect that the system is contrived to the extent that it would be possible to measure various useful parameters better, but in any case it gives a good testbed for the adaptive control method.

The plant is quite simple, and is shown in the diagram below. There are three feeds into a reaction vessel, carrying acid, base, and buffer solution.(They are 0.003M nitric acid, 0.003M sodium hydroxide, and 0.03M sodium bicarbonate solutions.) The acid and base flow rates, and the outflow rate, can be regulated by the system (though the acid rate is not controlled in this investigation), but the buffer flow rate is regulated manually. The reactants are mixed in the reaction vessel, and the liquid level in the vessel is measured. The pH of the liquid (a measure of alkalinity) is measured in the outflow pipe. The task is to maintain the pH in the tank at a set level.



The system has several features which make it very difficult to control, and standard control methods do not give satisfactory performance. The main sources of trouble are the nature of the neutralisation process, the difficulty in measuring the buffer concentration, and the late measurement of the pH.

The **neutralisation process** is very non-linear. (That's why titration can be a very precise measurement technique.) In the absence of a buffer, the change of pH as base is added to acid in the concentrations used in the system looks something like this :



Clearly, the rate of change of pH is far from constant throughout the process.

The **buffer** is intended to reduce the range of the pH change, but it doesn't significantly improve the linearity. In effect, it squashes the curve vertically to a degree determined by the buffer concentration. The immediate effect on the pH of adding more base is therefore determined by the current pH and the buffer concentration. Unfortunately, it is comparatively difficult to measure the buffer concentration in the reaction vessel, so it must be estimated from the various flow rates and other measurements.

The **pH measurement** is precise, but its position in the outflow means that the current pH value is never known precisely. Such a time delay is important if it is long enough for significant changes to take place in the controlled system; in this system, the rate of change of pH depends on the system state, and can be very large if the buffer concentration is low.

Many results are presented in the paper; I'll describe only one set. These are experiments with various sorts of controller, all using the same conditions. The acid flow rate is kept constant, and the buffer flow rate is changed every 30 minutes through the sequence 0.55, 1.2, 2.0, 1.0, 0.2, 0.55. (This was the second try; in the original sequence the buffer was turned off completely during the fifth period, and the simpler controllers couldn't cope at all. The large oscillations predicted in the comments on pH measurement were very obvious !) The points at which the buffer flow rate is changed are marked by noticeable steps in the graphs of base flow rate, and by perturbations in the pH graphs. The set point for the pH is 7.0; this is normally supposed to be the pH of a neutral solution (though strictly the value depends on temperature), so one might expect that a constant rate of addition of base would be required to neutralise the constant flow of acid. In fact, the picture is a little complicated by the buffer, which is slightly alkaline, so rather less base is needed if more buffer is supplied; this effect is clear in the graphs.

RESULTS.

In each case shown below, the left-hand graph is the rate of addition of base set by the controller, and the right-hand graph is the corresponding measured pH at the meter.

FIRST SET : PI control.

Except for the initial state, the controller never manages to gain control of the system in half an hour at any of the settings. Adjustments are always in the right direction (apart from some oscillatory behaviour near the end of the experiment), but the system never settles down.

SECOND SET : Non-adaptive nonlinear control.

In most cases, control is much better than with the PI controller; control is reestablished quickly after any change in conditions, and fluctuations thereafter are small. Control is poor only when the buffer feed rate is very low, when there are strong oscillations.

THIRD SET : Adaptive nonlinear control.

Control is better overall than with the non-adaptive case, especially with the low buffer feed rate. Even here, the performance is not perfect, but the improvement is very clear.

COMMENTS.

The bit I've missed is the mathematics; if you look at the original paper, you'll see why. It isn't particularly difficult mathematics, but it's very fiddly. It's also unavoidable, though, because you need the model to do the adaptive control. That's why people are interested in techniques like neural networks, where a detailed model of the plant isn't necessary.

REFERENCE

M.A. Henson, D.E. Seborg : "Adaptive nonlinear control of a pH neutralization process", *IEEE Trans. Control Systems Technology* **2**, 169-182 (1994).

Alan Creak,
March, 1998.