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Book review

Real-Time Optimization by Extremum-Seeking Control, Kartik B. Ariyur and Miroslav Krstić, Wiley, 2003, US$ 64.95, ISBN 0 471 4685 9 2

According to the traditional approach to control:

– first, we *identify* a system, i.e., test how it reacts to different controls and, based on the reaction, design a model that describes the system's behavior;
– then, the apply the known optimal control techniques to the resulting model and produce the optimal control strategy.

This procedure makes perfect sense in many real-life situations: if we want optimal control, e.g., optimal fuel efficiency or optimal output, we need to find out how exactly the systems reacts to different controls, so the time and money spent on identification pay off.

In many real-life situations, however, the plant (= controlled system) exists only for a short period of time, or it exists for a longer period of time but its parameters change fast. Examples of such situations include close formation aircraft flights or combustion engine control, where the parameters of the plant change with the minor changes in the atmospheric conditions and/or in the characteristics of the fuel. In such situations, we have no time for a proper identification, we must instead use some model-free control technique. One of such techniques is extremum seeking control described in this book.

In extremum seeking control, crudely speaking, we add high-frequency perturbations $A \cdot \sin(\omega \cdot t)$ to the control u, filter out the frequency ω part of the system's response x, and use this part in a feedback loop to update the control. Let us illustrate this idea on a simple example of a single-input single-output system in which $x = f(u)$ for some unknown function u. Our objective is to find the control u^* for which the output $f(u^*)$ has the largest possible value. We can safely assume that the current control u_c is reasonably close to u^*, so that in this vicinity, we can ignore cubic and higher order terms in the dependence of f on u and only keep quadratic terms: $f(u) = f(u^*) + (1/2) \cdot f''(x^*) \cdot (u - u^*)^2$, where $f''(u^*) < 0$ (since we have a minimum). If we substitute the perturbed signal $u = u_c + A \cdot \sin(\omega \cdot t)$ into this formula, we get the expression

$$x = f(u^*) + \frac{1}{2} \cdot f''(u^*) \cdot (u_c + A \cdot \sin(\omega \cdot t) - u^*)^2.$$

One can easily see that in the resulting expression for x, there is only one term proportional to $\sin(\omega \cdot t)$: the term with an amplitude $A_x = A \cdot (u - u^*) \cdot f''(x^*)$. Thus, if we set up a feedback loop in which $\dot{u}_c = k \cdot A_x$ for some $k > 0$, we then conclude that for the difference $\Delta u \stackrel{\text{def}}{=} u_c - u^*$, we have $\Delta \dot{u} = -C \cdot \Delta u$, where $C \stackrel{\text{def}}{=} k \cdot A \cdot |f''(u^*)| > 0$. So, Δu decreases with time as $\exp(-C \cdot t)$ and, thus, the resulting control u_c reaches the desired maximum level u^* really fast.

It turns out that a similar idea can help optimize more complex multi-parametric non-linear systems. Due to simplicity and easiness-of-implementation, this idea was actively used until the late 1960s, when complex optimization algorithms replaced it. It has recently turned out that in my applications, this idea still works well.

The book describes different implementations of this idea, with stability proofs showing that for a large class of systems, this methods really leads to a stabilizing control. The second part of the book contains practical applications of this idea, ranging from anti-lock brakes to bioreactors to formation flight to combustion engines and compressor control.

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