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Engineering cybernetics: 60 years in the making

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Abstract:

The landmark book of Hsue-Shen Tsien, 'Engineering Cybernetics', gave birth 60 years ago to an engineering science of interrelations and synthetic behaviors. Clothing the bare bones of Norbert Wiener's conception of cybernetics, the book delineates for the new science the requirement (of having direct impacts on engineering applications), the aim (of encapsulating engineering principles and concepts), the problems (of analysis, design, and uncertainty), the tools (of basic and advanced mathematics), and the scope (systems that are single input and output or multiple input and output, linear or nonlinear, deterministic or stochastic). The book is a showcase of originality, critical thinking and foresights. In particular, the author calls into question the basic assumption that 'the properties and characteristics of the system to be controlled were always assumed to be known' and points out that, in reality, 'large unpredictable variations of the system properties may occur'. Sixty years later, the full spectrum of Tsien's prophetic ideas is yet to be fully grasped and engineering cybernetics, as Tsien envisioned, is still in the making.

Keywords: Cybernetics; Engineering cybernetics; Engineering science; Feedback; Active disturbance rejection

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1 Preamble

'Engineering Cybernetics' [1], according to the latest survey, 'anticipated much of the development of control after 1954' [2]. The book was written exactly sixty years ago by Hsue-Shen Tsien (Qian Xuesen), who is an 'undisputed genius' according to his mentor and colleague Theodore von Karman [3]. It is rare that a scholar of aerodynamics and jet propulsion, whose idea from 1949 eventually led to NASA's space shuttle [3], initiated a totally different field of scientific study.

The materials from the book came from 'possibly one of the first courses in control theory in the United States' [4], taught by Tsien. The book was written during a difficult period of Tsien's life when he was prevented from returning to China and was virtually under house arrest [5]. However, despite of all the hardship, this is a period in which his colleagues 'saw Tsien at his ultimate', when the 'range of problems he worked on, the rapidity with which he saw a problem, encapsulated it, solved it, published a paper on it, was truly remarkable.' [5] Shown in the book are the presence of a great mind and the field he originally envisioned.

Tsien's absence during the explosive growth of this field in the subsequent decades was a great pity and a tremendous loss. Readers of the book will find, however, that his ideas are still very much alive today, if not fully grasped. 'The prescient book by Tsien (1954)',

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said the British scholar D. Q. Mayne, 'provided a foretaste of the exciting developments of the 1960s but was probably only really appreciated in retrospect' [6]. In retrospect, the book shows what the field could have been, beyond what it has become; in retrospect, Tsien's insistence on practicality and engineering fundamentals would have provided the much needed counterbalance to the axiomatization of the field later on. Today, we gather to hear Tsien's words and wisdom once again, to peek inside the mind of a great scientist and a prophetic thinker, and to reflect on the nature of our field.

'Engineering Cybernetics' was written six years after the publication of 'Cybernetics: or Control and Communication in the Animal and the Machine', by Norbert Wiener, coincidentally in the year of his sixty's birthday [7]. The year 2014 marks the 120th birthday of Wiener, the 60th anniversary of 'Engineering Cybernetics', and the 5th anniversary of Tsien's passing. The field of automatic control owes its existence to these two intellectual giants.

The paper is organized as follows: engineering cybernetics (EC) as an engineering science is introduced in Section 2, where its aim, subject of study, and the connection between mathematical rigor and engineering know-how are discussed. Focusing on the central theme of uncertainties, some important topics of EC are enumerated in Section 3, including the principle of feedback control, the need for engineering approximations, and the cost of feedback, etc. Highlighted in Section 4 is the profound turning point in the book where Tsien questions the basic assumption made by others in the field, an assumption that, ironically, still dominates the field today. This alone makes the book a must read. The paper is concluded in Section 5 with remarks.

2 A new branch of engineering science

In this section, it is shown that engineering cybernetics is a science of a different kind: it is not about the characteristics of individual components, but how they are connected as a whole. Such relationships are inherently abstract and the tools mathematical in nature. The necessity of such a science is in encapsulating the design principles and fundamental concepts from engineering practice and in understanding, explaining, and standardizing successful engineering inventions. This will lead to, according to Tsien, an unavoidable separation in EC between the theory that is general and the practice that is specific; the theory, however, must have direct impacts to the practice.

Cybernetics, as a broad science, concerns with 'the qualitative aspects of the interrelations among the various components of a system and the synthetic behavior of the complete mechanism' [1]. The choice of name is itself interesting but it created a bit of dilemma in its translation to Chinese as 'control theory'. It shows that this new field is much more than what can be described simply as control, regulation, servomechanism, or mere feedback. The subject of study concerns with the characteristics and nature of these interrelations, biological or mechanical. At its center is the self-correction mechanism that is not only common in engineering systems but also essential to all life forms, down to their very basic building block: a cell. In order to survive, a cell adapts to its environment via the so called 'cell signaling', a name that captured the grand scheme of the generation, transmission, and reception of signals and the triggering of the subsequent actions, such as gene transcriptions and protein-making.

In engineering, the conceptualization of such interrelations, of various forms of 'signaling', came rather late. Even though servomechanisms, most notably the steam engine with self-regulation, had a long history, it was practiced rather like an art. Its governing principle proved to be elusive until WWII when servo engineers, working with communication engineers in the joint efforts on fire control, discovered that the concept of feedback and the frequency response method used by communication engineers can be applied to servomechanisms to great effects. Feedback as a universal principle in Wiener's cybernetics links various fields together and serves as the foundational concept for the new science Wiener envisioned.

To establish such an encompassing science is of course a formidable task. Wiener as the instigator proves to be well ahead of his time. Most scientists, then and now, are rather narrowly focused and do not think as broadly as Wiener did. The fact that information theory and control theory grew out of cybernetics as separate disciplines is more indicative of the limitations of human mind than the nature of this science, but this is beside the point in the current paper. What's important is that Tsien immediately grasped the significance and magnitude of cybernetics.

Well established in his own field of aerodynamics and jet propulsion, Tsien saw in cybernetics something no one else did: a new branch of engineering science. Pragmatic as an engineer, well-trained as an applied mathematician, and profound as a thinker, Tsien was a rare individual, a scholar of the first degree. He possessed a deep understanding of the nature of engineering and, at the same time, was fluent in the language of advanced mathematics. In EC, Tsien made it crystal clear that this is a distinctly different type of science that 'aims to organize the design principles used in engineering practice into a discipline and thus to exhibit the similarities between different areas of engineering practice and to emphasize the power of fundamental concepts'. This is not just another 'applied science'. Instead, the principles and concepts of engineering science are abstracted from engineering practice and, in turn, make the practice more scientific, rigorous, and systematic. Tsien's prophetic vision, however, was recognized by few in his time and is mostly appreciated 'in retrospect' [6].

Cybernetics as a discipline seems to be as broad as it is vague. It is clearly quite different from other natural sciences, according to Tsien, in 'the total absence of considerations of energy, heat, and efficiency'. As a general science, it touches upon various disciplines such as physiology, psychology, sociology, and engineering, according to Wiener. However, EC as Tsien conceived is engineering-focused and clearly defined:

- 'The purpose of 'Engineering Cybernetics' is then to study those parts of the broad science of cybernetics which have direct engineering applications in designing controlled or guided systems. It certainly includes such topics usually treated in books on servomechanisms. However, a wider range of topics is only one difference between engineering cybernetics and servomechanisms engineering. A deeper and thus more important difference lies in the fact that engineering cybernetics is an engineering science, while servomechanisms engineering is an engineering practice. An engineering science aims to organize the design principles used in engineering practice into a discipline and thus to exhibit the similarities between different areas of engineering practice and to emphasize the power of fundamental concepts.' [1, p. vii].

Embedded in these words above is profound wisdom that proves to be illuminating to this day.

2.1 Direct engineering impact: a necessary attribute of any engineering science

A well-developed engineering science is the backbone to the corresponding engineering practice. 'It is not engineering if it cannot be put into practice', said Y. C. Ho [8], no matter how elegant or sophisticated it is mathematically. In other words, the progress in EC is judged based on how well it serves the design of the 'controlled or guided systems'. However, this proves to be easier said than done. To serve engineering practice, a scientist must understand what it is. From 1960s on, modern control theory evolved more or less like a branch of applied mathematics, thanks to the dominant thoughts of R. E. Kalman from the early '60s [9, 10]. Tsien's distain for empty mathematical exercises is evident throughout his book. Starting from the very first chapter, he emphasizes the connection to engineering as it is practiced and the limitations and constraints associated.

Because our understanding of the physical world is inherently limited and our knowledge incomplete, all our mathematical equations describing the physical processes are approximations. The real challenge is to deal with what these equations do not describe, to which we'll come back later in the paper. Furthermore, even when we could have detailed mathematical descriptions, simplifications may be required to make the problem manageable. The frequency response method from communication engineers is an excellent example of the importance of simplification. On the classic time domain method of E. J. Routh for stability analysis, Tsien has this to say:

- 'This method, however, is not favored by control engineers, because of the obscure manner of the variation of the Routh inequalities with the changes in the coefficients. Engineers prefer a method of analysis which uses the transfer functions written in Eqs. (4.9) and (4.10) directly without further modification; because these transfer functions are the immediate information possessed and are understood 'physically' by the engineer. Such a method was devised by H. Nyquist.' [1, p. 38].

Without such nuanced understanding Tsien demonstrated, there would be no 'direct engineering applications'. This intense focus on practicality is maintained throughout the book. Almost all theoretical developments in the book are followed by engineering examples from Tsien' own field of aerodynamics and jet propulsion. Both Kalman and Tsien were set to develop a general theory but the ways they pursued the goal could not be more different. Kalman did so as a mathematician, starting with some axioms such as the principles of causality and duality, while Tsien began with an exquisite exposition of the principle of feedback control, using a turboalternator as a case study. The readers may find that the lucidity of Tsien's account is unsurpassed in modern texts. However, at the same time, EC is not a book of engineering know-how. Rather, this is about an engineering science that is 'predominated by theoretical analysis and very often uses the tools of advanced mathematics'. The key is in how such tools are used, to encapsulate the engineering design principles, to make clear obscure ideas and hidden concepts, and to embrace 'the power of fundamental concepts'. Engineers by nature like to tinker; engineering inventions usually do not come from mathematical deductions. In requiring 'direct engineering applications' Tsien has in mind a science, a set of principles and tools, that is universal in all engineering sectors. It is for this reason that the book is not concerned with 'the actual implementation of the theory' and 'no gadget is mentioned'. And yet, the deep connection to all engineering practice is vividly there.

2.2 The necessity of the theory-practice separation

Therefore, EC as an engineering science aims for what is common across boundaries of various disciplines: the 'design principles' and the 'fundamental concepts'. Automatic control, in over two hundred years in its history, was reinvented time and again, because the key 'design principle' was hidden in its embodiments until the 1920s when communication engineers from Bell Labs gave it the current name: feedback. It is based on this single concept that Wiener connected various domains of science, in physiology, psychology, sociology and engineering. From practice to abstract concepts, the 'justification of this separation of the theory from the practice', according to Tsien, 'seems hardly necessary'. He uses the example of fluid mechanics to show that an engineering science exists on its own, and practitioners, in this case aerodynamics engineers, hydraulic engineers, meteorologists, etc., rely on it in their daily work. In particular, EC as an engineering science looks at things 'in broad outline and in an organized way' that 'often leads fruitful new avenues of approach to old problems and gives new, unexpected vistas'.

Speaking to engineers and always with the engineering of rocketry in the background, Tsien demonstrates throughout the book how the principles are abstracted from the particular instances of design. Likewise, fundamental concepts and basic theories need to be established above the nuts and bolts of engineering activities. Moreover, this has been a struggle from the very beginning in the field of automatic control. The central concept of feedback behind Watt's flyball governor stayed hidden for over a hundred years. Clerk Maxwell, a great mathematician as he was, analyzed the steam engine using differential equations but was not able to draw attention to the key change: the modification of interrelationship, i.e., the closing of the loop. Nor did he give an engineering solution to the problem of oscillation. E. J. Routh, despite his contribution in stability analysis mentioned above, misunderstood the cause of steam engine oscillation and mistakenly suggested that it was because the governor was too fast [11].

In the progression from engineering practice to an engineering science, the initial theory-practice separation is perhaps a crucial step and should be carried out with great care and reflection. The mathematics will only make sense if it is rooted in the deep understanding of engineering practice, with all its constraints and value propositions. The importance of getting the conceptualization right, or the consequence of taking a wrong turn, is evident throughout the history of this field.

2.3 Towards a harmonic coexistence

When asked about why he likes writing about middle class America, a famous writer once said that because it is at middle the extremes clash. He might as well be talking about engineering.

Theoretical analysis and mathematics, as a tool, are central in EC and Tsien systematically introduced it, from the basic to the advanced. He takes pain to point out that, to practitioners, there is potential for mathematical difficulties but 'the matter could generally be brought down to the level of a research engineer' with 'a little reinterpretations'. To make his book readable for engineers, 'no rigorous and elegant mathematical argument is introduced if a heuristic discussion suffices'. Tsien admits that the book may look 'long-hair' to practitioners and 'amateurish' to mathematicians, but says that he will be happy if 'these are the only criticisms'. What he aims to do is to build a bridge between rigor and preciseness in mathematics on the one hand, and creativity and intuition on the other. It is in this new science rigor is balanced by utility.

The hallmark of Tsien's scholarship is his deep understanding of both engineering and mathematics. In fact, this is perhaps a minimum qualification for any researchers of EC. A mathematician alone cannot do this because he or she wouldn't know what the concepts and tools in mathematics should be used for. Harry Nyquist made the connection between the needs for stability criteria in feedback amplifiers and the techniques of complex analysis, such as the Cauchy Theorem. Likewise, practitioners by themselves are specialists, not trained to find commonalities across the boundaries of various engineering disciplines. The Wright brothers' invention of the powered flights would remain a toy without the science of aerodynamics, which gave the rational basis for the technologies that made the commercial aviation possible.

An engineering science can only grow, in a healthy way, when the rigor of mathematics and the vigor of creativity coexist in harmony. However, there is always danger: if such a science becomes dominated by pure mathematics, it would become more or less a branch of applied mathematics; on the other hand, without rigor, practice would remain a collection of rule of thumbs, such as those of the PID tuning rules. A well-known theoretician once suggested to the control community to get the mathematics right and leave the rest to the mathematics, a typical view of the field in terms of modeling and model-based design and optimization; in industrial systems, however, control loops are mostly closed today in a heuristic manner. Aristotle's golden mean, the idea of avoiding the extremes, remains elusive.

This uneasy co-existence between mathematical rigor and engineering know-how is ubiquitous, the imbalances of one way or the other is not uncommon. Moreover, the field of EC is no exception. Rigor and practicality are two opposing forces that tend to tear a field apart: on the one hand theories are looking for applications, at least those of purely mathematical problems. There are many ways to make such theories seemingly 'applicable', one of which is to make an engineering problem a mathematical one by spending excessive efforts in modeling so that the model and the real system are close enough. On the other hand, industrial control as a whole is still dominated by the trial-and-error methods and specialized solutions that are not scalable. The goal of finding universal principles and scalable solutions remain elusive to this day. In the absence of a towering figure like Tsien, finding our way back to a healthy and vibrant science is a great challenge. However, there is hope: by going back to the origin of EC, perhaps we can return to the original vision and passion of Tsien that precipitated the birth of the field in the first place.

3 Uncertainties: the central theme of 'Engineering Cybernetics'

If the contents of EC were summarized in a phrase, perhaps it would be 'dealing with uncertainties'. The problem of uncertainty is its central theme, which is discussed at several levels, starting with the necessity of making approximations in the first chapter. Uncertainties are always there if simply because engineering is practiced as an imprecise science. Cost and complexities are reduced by making approximations, which add to uncertainties that are already there: the unknown dynamics of the controlled systems and unknown forces in their operating environments.

EC is a book written for engineers with little background in advanced mathematics. It starts with an introduction on solutions of differential equation, Laplace transform, and transfer functions, followed by the discussion of engineering approximations. More than anyone of his time, he foresees the importance of the problem of uncertainty that others discovered decades later. Tsien's acute understanding and deep appreciation of the frequency response method came early in the book:

- 'Very often in engineering practice, our knowledge of the detailed structure of the system is incomplete, or if sufficiently complete, the system is so complicated as to make the theoretical calculation of the frequency response too lengthy to be practical. In such cases, it is often necessary to determine the frequency response experimentally.' [1, p. 29].

In other words, the uncertainties are unavoidable because: 1) the limitation of our knowledge, which is always incomplete; and 2) the limitation of our design methods, which tends to break down if some details are not left out. Hidden in the engineering approximations is the constraint of cost in all aspects of engineering. Engineers know that 'there is no free lunch' and that all gains come with a cost. Engineering is practiced on a delicate balance of performance and cost, the understanding of which is crucial for any theoreticians. For example, if a linear controller designed based on approximation meets the requirements, one has to justify the cost of further developing a nonlinear controller for performance gains. This is why the frequency response method of Bode and Nyquist, based on linear approximations, was preferred by engineers over the differential equation method of Maxwell. In feedback amplifiers, for example, the nonlinear dynamics is the cause of the distortion to be removed but the cost of modeling it and designing a model-based feedback linearization or dynamic inversion could hardly be justified. This is because, as it turns out, a simple output feedback can solve the problem without any knowledge of the amplifier dynamics. In feedback, engineers found the solution to the problem of uncertainties, as a general engineering design principle.

3.1 Feedback control: the principle of self-correction amid uncertainties

Feedback as a concept in communication originally described the signal flow from the output of a circuit back to its input. By reversing the sign of this feedback signal and multiply it by a small gain, it was found that the distortion caused by nonlinearities in the amplifiers could be greatly reduced. It was later found extremely helpful in conceptualizing the practice of servomechanisms that dates back to James Watt's flyball governor. For over a century, scholars struggled to encapsulate the design principle behind the automatic control of the steam engine and to offer alternatives, without much success [11]. The main reason, in retrospect, is perhaps that the principle was never clearly stated, nor its weakness. Even in today's textbooks, the principle of feedback control, the principal reason why feedback control is necessary, is not always explained with clarity.

Using the turboalternator as an example, Tsien elucidates the concept of feedback like no others. Consider

$$I\frac{\mathrm{d}y}{\mathrm{d}t} + cy = x(t), \tag{1}$$

where $y(t)$ is the speed deviation, I is the inertia and c is the damping due to the windage loss. The task of control is 'to balance the torque generated by the steam turbine and the torque absorbed by the alternator, the load torque'. The balance is not perfect and 'there is always an error torque, $x(t)$', since the load torque is usually unknown or fluctuating. This, in a nutshell, is the problem of automatic control: the imbalance brought by unknown forces. The engineering solution is that 'we cause the steam-throttle opening to depend not only on the load but also on the speed deviation y'. This 'so-called closed-cycle control' changes (1) to

$$I\frac{\mathrm{d}y}{\mathrm{d}t} + (c+k)y = x(t), \tag{2}$$

where 'the accelerating torque is reduced by the amount ky, and the ratio of steady-state speed deviation to the error torque is $1/(c+k)$', down from $1/c$. Note that this reduction in error is achieved in the absence of the knowledge of both the windage loss and the error torque. Moreover, it is here a general principle is encapsulated, namely the principle of feedback control or, to be clear, the principle of self-correction amid uncertainties.

In equations (1) and (2) Tsien makes the principle of feedback clear for all to see: by reversing the chain of causality, by making steam-throttle opening respond to speed deviation, the self-correction is made possible, the balance is restored, and the desired 'synthetic behavior' is realized. Amid the uncertainties in the damping and the load variations, the system adjusts its action (steam valve opening) for the desired outcome (small speed deviation), all by itself! This self-correction principle has dominated the industrial control for over a century in the form of PID (proportional-integral-derivative) controller where the original term, ky, in equation (2) is complemented by the integral and derivative terms of the deviation. The PID controller is just the embodiment of the principle of feedback control!

It is equally straightforward to see that if we do have the knowledge of windage loss or load variation, there is no question that such knowledge should be used in determining the control action, to make the restoration of the balance more efficient. Such clarity, originated by Tsien, makes the connection almost trivial among various engineering solutions such as feedforward (of the two kinds: set point and disturbance), load estimation, disturbance estimation and cancellation, etc. This puts on display the power of fundamental concepts!

3.2 Two different uses of feedback and the cost of feedback control

Having stated the general principle of feedback control, let us make clear the distinction between the feedback circuit in communication engineering and the feedback control in control engineering, because there is a tendency by many to overlook it. First of all, feedback in the feedback amplifier is that of the output, the purpose of which is to linearize the circuit that contains nonlinear elements; feedback in the turbogenerator above is that of error, the purpose of which is error-correction. As such, it is quite foreseeable that the goal of control can be met even with severe nonlinearities in the closed-loop system, where the goal of the feedback design in amplifier is to linearize it. In fact, as Tsien points out later in the book, the optimum solution of feedback control is often a nonlinear one and we should embrace the nonlinearity, as opposed to avoiding it.

Secondly, unlike the feedback amplifier, automatic control in engineering practice is usually not entirely dependent on feedback. For example, as Tsien mentioned, the steam-throttle opening in turboalternator is set based on the normal load and is automatically adjusted based on the speed deviation caused by the unknown load change. The feedback-only dogma in the textbook solutions overlooks this important distinction. As though Tisen saw this coming, he further emphasized the nature of the control action by introducing the combined open- and closed-loop structure of J. R. Moore [12], as shown in Fig. 1.

Consider the amount of knowledge available on the controlled system, there are two extremes: 1) there is perfect knowledge upon which the control can be established, open-loop, and no feedback is needed; 2) no knowledge is available and the control action must be calculated solely based on the error-feedback. The reality, of course, falls somewhere in between and the control laws are established accordingly, as shown by Tsien and Moore.

What is implicit in Tsien' description of the principle of self-correction becomes very clear in Moore's configuration. For fast response, the feedback loop requires high bandwidth, and therefore high gains, which tends to destabilize the loop and amplifies sensor noises. The question is how to design a control system with a fast response and a low feedback gain. Moore's solution in Fig. 1 combines the feedback loop with an 'Open cycle controller' which is approximately the inverse of the controlled system. That is, the 'Open cycle controller' inverts the known dynamics of the controlled system for fast response; the uncertainties in the dynamics are handled by the feedback loop.

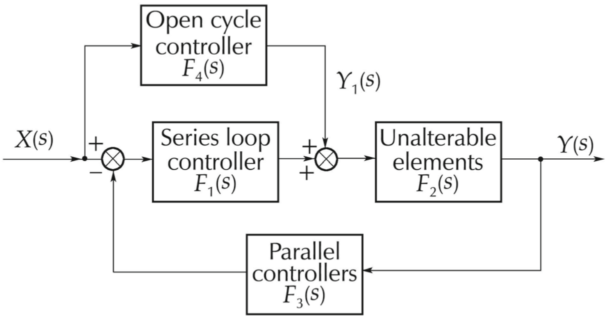

Fig. 1 The combined open- and closed-loop control loops (as appeared in [1]).

In today's practice, the 'Open cycle controller' of Moore is called feedforward and it plays an important role; in the context of the orthodox control theory, however, it is deemed as primitive and not worthy of much discussion. The system in Fig. 1 is engineered to make its output follow the command efficiently, economically, and reliably. By adding the open cycle controller, the system is more efficient because much of the lag in the feedback loop is avoided; it is more economic because, by lowering feedback gain and still getting the fast response, the cost of feedback is reduced; it is more reliable because the lower gains will likely lead to better stability margins and lower noise levels in the control signal, thereby reducing the wear and tear of the actuators. The popular high gain solutions, ubiquitous in the control literature, are fine as long as they come with a clear understanding of the cost of feedback and the vulnerability of the feedback-only solution.

Fig. 1 is an excellent example of how engineers, with clear understanding of the physics of the controlled system, could masterfully modify the interrelations among system variables to obtain the desired 'synthetic behavior'. EC is intended as the foundational theory that makes possible the sustained technological growth, like what the science of aerodynamics and jet propulsion did to aviation. To build a success engineering science, the scientists, instead of inventing mathematical problems, should study the inner workings of successful engineering systems and should try to encapsulate the underlying principles, such as the principle of combined systems for example, that are universal. They must be, in a sense, students first with immense curiosities in how engineering is practiced.

3.3 Stochastic uncertainties and optimum solutions

Tsien noticed that the uncertainties in control system are sometimes stochastic in nature and this can be seen in examples such as 1) the fatigue stress in a structure subject to random input disturbances; 2) lift on airfoil due to fluctuating air turbulence; and 3) the random forces in servo systems. For systems with random uncertainties, the task of design is somewhat different from the deterministic systems. Assuming that the stochastic properties of the random signals are given, such as the mean and deviation, the task is now to design an optimum controller, i.e., a controller that on average performs the best based on a predetermined criterion. For solutions to such problems, Tsien repeatedly points to the 'optimum servo design for a specific purpose and specific input' pioneered by Boksenbom and Novik [13] and notes that it is 'one step beyond the mere requirement of stability and other qualitative criteria of servomechanisms in the previous chapters'. Compared to the conventional servo design, this new design method 'is guaranteed to give the optimum performance'. Tsien cautioned, however, that 'this comparison has meaning only if we know specifically the desired performance' and 'strict insistence on the best performance must come after a clear understanding of what constitutes optimum control behavior. Therefore, when we do want an optimum control system, we naturally should have the information to define sharply the design criteria'. It is unfortunate that such great foresight went largely unheeded.

Largely for the sake of mathematical elegance and convenience, the linear quadratic (LQ) cost function became the most popular one in modern control theory. Such criterion proves to be extremely useful in filtering, such as the Kalman filter and the adaptive filters, but its adoption as the criterion for the purpose of control system design was widely accepted in academia without much scrutiny, even though there was clearly clear evidence against it. In 1953, two Air Force engineers, through a meticulous set of extensive experimentations performed on analogue computer, conclusively showed that the LQ cost function is among the worst in selecting the best transfer function that yields fast response without much overshoot [14]. In other words, given a set of transfer functions and the task to find the one with the critical damping, the LQ cost function failed miserably, casting doubt in its suitability for the purpose of control. Furthermore, some three decades later, researchers found that the LQ solutions lead to stability margins that are essentially nonexistent [15] and that the resultant control system is fragile, in the sense that a smallest variations in the controller parameters could lead to instabilities [16].

Together, these results point to a simple fact: the much celebrated LQ optimal control, from the extension of Kalman filter and the principle of duality, may not be a good fit as a general design principle for control engineering practice. Ignored for decades were Tsien's insistence that 'we know specifically the desired performance' and that 'we should naturally have the information to define sharply the design criteria'. The LQ criterion could be great for the purpose of noise filtering but obviously not so for that of control. The vast literature on robust control reflects the collective efforts by researchers from the '80s to the present in addressing the deficiencies in the LQ methodology, with limited success. A detailed assessment is beyond the scope of this paper.

Another kind of stochastic uncertainties Tsien concerns with is noise and it leads to the introduction of Wiener-Kolmogoroff filter, or Wiener filter as it is commonly called. The integral cost function based on the mean-square error is introduced, together with 'a very important assumption' that the noise is a random function with given stochastic properties and that the signal is relatively weak compared to the noise (otherwise the noise can be ignored). Based on the calculus of variations, Tsien introduces the Wiener filter, in the transfer function form, that minimizes the mean-square error. This of course anticipates the famous Kalman Filter, which gives a more numerically efficient solution in the state space form. Note that Kalman filter is designed to deal with the uncertainties in the measurements and process with given stochastic properties, and that an accurate mathematical model of the process is assumed given. With foresight, Tsien calls into question such assumptions in the context of control, to which we now turn.

4 The turning point

If the first 14 chapters of the book cover the basics and give a comprehensive survey of the field in 1954, Chapter 15 marks the turning point of the book and it begins with:

- 'In the previous chapters we have discussed the design principles of control systems with increasing degrees of generality and complexity. However, one italic was made throughout the treatment: the properties and characteristics of the system to be controlled were always assumed to be known . . . . The control design is thus based upon this knowledge of the properties of the system.' [1, p. 214. emphasis added].

This 'basic assumption' is a huge problem because, as Tsien explains, 'large unpredictable variations of the system properties may occur', such as the case of 'the flight of an airplane through icing weather condition', when 'the aerodynamic properties of the airplane can be profoundly altered, and altered in an unpredictable way, by ice'. 'However, at just this critical situation', he goes on to say, 'our prior knowledge of the airplane performance is rendered useless by the ice deposition'. In other words, if control system is designed to cope with the unexpected changes, with our lack of knowledge in the controlled system, then how can the control theory be based on such an assumption?

What Tsien pointed out was a paradox most scholars did not see at the time: the basic problem in feedback is the problem of uncertainties and this basic assumption would assume the problem away. Tsien makes no attempt to hide his doubt about 'this seemingly elementary requirement for control design', elementary because it 'is tacitly assumed in the previous chapters'. According to this point of view, an automatic control system works like this:

- 'The feedback merely conveys the information on the state of the output to the 'computer'. The computer then uses its built-in knowledge of the system properties to generate the 'intelligent' control signal.' [1, p. 214].

However, anyone with a rudimentary understanding of how feedback control actually works could see the falsity. The principle of feedback control, as Tsien explains earlier, makes no such requirement of the 'built-in knowledge'. The whole point, whether in steam engine or turboalternator, is to implement a self-correction mechanism so that the output deviation from the set point is reduced. Tsien questions any control systems that rely on the 'built-in knowledge' because the systems are always in a flux and any such knowledge will tend to be unreliable, sooner or later.

To be sure, there is a place for model-based theory of control, mostly in analyzing and justifying engineering solutions. Good engineering practice needs to be understood and standardized so that it can be scaled in mass. For example, the Wright brothers' invention of the powered flight is only the first step towards commercial aviation. The theory of aerodynamics is an important bridge in between. The theory of servomechanism is another example. It is mostly a method of analysis, however, and the design is still pretty much an art.

For Tsien to go beyond the basic assumption in the 1950s, the alternatives were quite limited, beyond what is now known as the problem and method of 'extremum seeking', i.e., continuously adjusting the control actions for the purpose of obtaining the 'optimum operating conditions', all without the detailed knowledge of system dynamics. This particular technique has grown into a distinct research field, a recent survey of which can be found in [17]. The limitation of such a solution does not in any way make less significant the problem itself, the pursuit of which led to new concepts and principles. The later development of adaptive control seems to be but one narrow interpretation of this idea, assuming a given model with unknown or varying parameters. Another related development that gains steam in recent time is the so called 'data-driven' methodology, where the controller is more or less 'model-free' and control actions are computed based on the information obtained from the measurement data. Finally, the challenge of Tsien is fully addressed by Jingqing Han in the context of active disturbance rejection control, to which we shall turn shortly.

4.1 The concept of stable operation amid internal and external disturbances

Standing at the most basic level of control theory is the concept of stability. Using linear differential equations with constant coefficients as an approximation of the steam engine dynamics, Clerk Maxwell reduced the problem of stability to the location of the roots of the characteristic polynomial, to determine whether the output is diverging or converging from any initial conditions. E. J. Routh extended Maxwell's work to higher order systems.

However, the word stable means in English 'not likely to change or fail; firmly established', according to the Oxford Dictionary of English, and stability means 'the state of being stable'. This is of course an extremely desirable quality of any engineering systems and the concept of stability used by Maxwell is but a subset of it. The ultimate goal in engineering design is to build a system that is 'not likely to change or fail' amid significant amount of uncertainties in and outside the system. Tsien says:

- 'Stability of any control system means that the design performance of the system will be obtained even with the presence of italic. For optimalizing control systems, the essential part of the operation is the proper coordination of the input drive with the output behavior, so that the output stays within a close neighborhood of the optimum. This operation must not be influenced by internal and external disturbances. When this is achieved by a good design of the system, we have stable operation.' [1, p. 228. emphases added].

What he suggests is that the concept of stability should retain its engineering implications and represent the desired quality to be attained amid unknown forces, internal and external. It echoes the definition of stability by communication engineers in the 1930s, as the ratio of the change in amplification and the change in the parameters of the circuit [18], but in a much broader range.

The most significant is the term internal disturbance. In the context of control theory, disturbance usually designates the unknown forces external to the controlled system. The concept of disturbance first appeared in Chapter 5 where 'an arbitrary disturbance $V(s)$ is introduced between the servo and the engine to account for the accidental outside influences'. This denotes obviously the external disturbance and the design goal is to make it 'noninteracting' with respect to the output variable. The concept of 'internal disturbance' by Tsien is fascinating because for the first time the unknown forces internal to the system is called disturbance. In a nutshell, the fundamental problem of control engineering is reduced to the problem of disturbance rejection [19, 20].

All engineering systems are 'open', meaning that they are subject to the influences from their environments. Taking the icing condition in an airplane for example, the combination of external conditions such as moisture and temperature may cause great changes to the system behavior, rendering useless the knowledge (model) of the system dynamics under normal conditions. What Tsien emphasizes here is that even so, even under such extreme conditions, a goal of control design is to make the system performance invariant. Again, Tsien sees far into the future of the field. The problem of disturbance has caught the attention of many researchers lately and much promising work has been done. But first, Tsien's illuminating distinction between general principles and specific solutions needs to be introduced first.

4.2 General design principles vs. specific engineering solutions

Tsien carefully distinguishes the general design of a specific type of systems, such as 'the theory of conventional servo mechanism', and a specific design of a general type of systems, such as the perturbation theory as applied to linear systems with time-varying coefficients. Most design methods from control theory are of these two types. In engineering practice, however, the daily activities are dominated by finding specific solutions to a specific type of systems; unless a new principle can be encapsulated from such solutions, they have little to contribute to science. The ultimate goal is to find general design principles for a general type of systems, of course, and this leads us straight to the dominant solution in industrial control today: PID.

PID is ubiquitous as an engineering solution and is quite straightforward and general in principle: the control action is made a linear weighted sum of the present, past and future trend of the output deviation, or error. Incorporating the terms of the error behavior in the past and future, it is a simple generalization of the feedback control principle discussed by Tsien earlier in the book. Its popularity has been enduring among practitioners because it is simple to use and it applies to most dynamic systems encountered in practice: linear or nonlinear, time-invariant or time-varying, known or unknown. Its shortcomings are also very obvious: the limitations of the control law; the complications associated with the integral action, and the noise issues associated with the derivative action, etc.

For many years PID has been used as the benchmark against which other designs are measured. However, due to the lack of understanding in general vs. specific solutions, the comparison in most cases is unfair, when a specific design, whether it is based on mathematical model, fuzzy logic, or neural network for a particular system, is matched against a general design, PID. For the comparison to be of any value, any rival design principle must be general, simple to implement and easy to tune, and not dependent on the plant model. Next, a general design principle is briefly introduced as a follow up to Tsien's formulation of the problem of stable operation in the presence of internal and external disturbances, and as an alternative to the solution of extremum seeking.

4.3 Moving beyond the basic assumption

Over the last six decades, scores of scholars have recognized and addressed the fundamental mismatch between the basic assumption and the engineering reality, with solutions ranging from fuzzy logic, artificial neural network, and various 'model-free' approaches, including the more recent trend of 'data-driven' methodology. In the meanwhile, PID has continued to dominate the engineering practice and practitioners have seen little incentives to abandon it, until very recently when the active disturbance rejection control (ADRC) of Jingqing Han [21–24] appeared on the scene.

Picking up where Tsien left off, Jingqing Han renewed the critique of the basic assumption in 1989, pointing out that an effective control law must exist independently of the plant model and the information the controller needs does not have to come from a global model of the plant dynamics [23]. Instead, such information can be extracted from the input-output data, local in time. In a manner similar to the 'continuous sensing and measuring' Tsien discussed, Han points to an alternative design principle to achieve stable operation: the internal and external disturbances are estimated from the input-output data and cancelled out by the control action, leaving to the controller a well-behaved dynamic system without much uncertainties. In other words, the behavior of the controlled system is first changed through disturbance estimation and cancellation so that its operation is itself stable, in the original meaning of the English word.

This principle of ADRC is general and applicable to most problems found in engineering practice. It is summarized by Han as:

- 'Active disturbance rejection control (ADRC) can be summarized as follows: it inherits from proportional-integral-derivative (PID) the quality that makes it such a success: the error driven, rather than model-based, control law; it takes from modern control theory its best offering: the state observer; it embraces the power of nonlinear feedback and puts it to full use; it is a useful digital control technology developed out of an experimental platform rooted in computer simulations. ADRC is made possible only when control is taken as an experimental science, instead of a mathematical one. It is motivated by the ever increasing demands from industry that requires the control technology to move beyond PID, which has dominated the practice for over 80 years.' [22].

In the true spirit of the experimental science, Han discovered through computer simulations and engineering practice that, for the purpose of control, most physical systems can be approximated by the bare bone integrator model, i.e., the input-output relationship can be approximated as chained-integrators and all else can be seen as either internal or external disturbances, in the words of Tsien. By estimating and cancelling such disturbances, the 'stable operation' is attained.

In ADRC, a general design principle for a general type of systems, as a viable alternative to PID, is conceived. It is not a model-based solution for a specific system and it transcends the artificial boundaries between systems that are linear and nonlinear, time-varying and time-invariant, deterministic and stochastic, with known and unknown dynamics. By gain parameterization based on the bandwidth, the ADRC solution is further engineered to make it even easier to use and to tune by novice users [19, 20]. Through a careful process of validation, ADRC has already been productized by the industry giant, Texas Instruments, in what appears to be a massive replacement of PID by ADRC in industry [25, 26]. The problem of internal and external disturbance raised by Tsien 60 years ago is finally addressed in a practical manner.

To be sure, there is plenty of work in the literature addressing the problem of disturbances, including different ways of estimating, attenuating and rejecting such disturbances. Disturbance compensation is also one of the key design considerations in the robust control framework. The uniqueness is in Tsien's original conception of dynamic uncertainty as internal disturbance and in Han's follow up solution in ADRC. With a simple 'reinterpretation', the mathematical difficulty involving nonlinear, unknown, and time-varying dynamics is now seen as a problem of signal processing and information extraction, in the true spirit of cybernetics.

Glancing over the topics of the recent control journals and conferences, as well as the directives of various funding agencies, one could not help but ask if the cybernetics of Wiener and the engineering cybernetics of Tsien are making a comeback. It is perhaps not a coincidence that an 'IEEE 2014 Conference on Norbert Wiener in the 21st Century' will be held in Boston this summer. From networked control system, to cyber-physical system, to data-driven design, the engineering reality makes it a compelling case that the basic assumption of the past era did not hold back then and certainly does not hold now. A paradigm shift in the science of control is long overdue.

4.4 The legacy of 'Engineering Cybernetics'

In retrospect, EC did not quite unfold as Tsien envisioned. The basic assumption, called into question by Tsien, the selection of design criteria based on mathematic convenience, which he cautioned against, etc., all became pillars in the modern control era. Today, the science of automatic control as taught and researched is quite different from the engineering science he had in mind, as evident in the most recent and comprehensive review [2]. Some wondered if automatic control is a science at all [27]. It is therefore full of contemporary significance that we trace our steps back and see where the divergence originated.

The era of modern control theory began with the landmark papers of R. E. Kalman around 1960. Kalman made it clear that his work 'initiates study of the pure theory of control, imitating the spirit of Shannon's investigations but otherwise using entirely different techniques' [9]. Moreover, the 'pure theory of communication and control', according to Kalman, 'resembles mathematics, rather than physics'. This is because 'the 'law's governing man-made objects cannot be discovered by straightforward experimentation but only by purely abstract analysis guided by intuition gained in observing present-day examples of technology and economic organization'. In his paper of 1962 [10] in the proceedings of the national academy of science, Kalman made it clear that 'for mathematicians or theoretical physicists, the natural definition of a dynamic system is the axiomatic one' and he proceeded to give the axioms 'expressing the Principle of Causality' as 'an extension of newtonian mechanics'. This has become the foundation of the modern control theory, taught at universities around the world today. Kalman summarizes the modern control paradigm as '1. Get the physics right; 2. The rest is mathematics' [28]. In other words, give me the mathematical model and everything can be derived mathematically from there.

To be sure, Kalman's general theory of control yields profound insights and useful tools for linear systems. For example, controllability and observability are fundamental concepts for linear system theory, as the pillar of modern control theory. The state observers give us new means to extract additional information from the input-output data that would be otherwise inaccessible. Furthermore, the Kalman filter provides numerically efficient solutions for the Wiener filter problem. The difference between Tsien and Kalman, however, is in how the problem of control is conceptualized.

As Tsien points out, the basic tenant in control engineering is that the physics of dynamic systems is elusive, that our knowledge of it is always incomplete, that our design must be able to withstand a great amount of uncertainties. To assume otherwise, to deduce control laws from a set of equations, pretending it to be the accurate depiction of physical entities, would just give us another set of equations that can only control the previous set of equations, and not much else.

Furthermore, in EC, Tsien sees a much broader picture of an engineering science, primarily concerned with the 'interrelations and synthetic behaviors'. Today, as interrelations multiply and system behaviors becoming ever more synthetic, engineering desperately needs guiding principles and design philosophies to deal with the problems that arose in 'networked control systems', 'cyber-physical systems', among other trendy names. What these problems share in common is what Tsien pointed out in the 1950s: that it is uncertainties, i.e., the internal and external disturbances, that require our most dedicated attention. More than ever in the history of control, it is the general design principles and fundamental concepts that need to be encapsulated, a new foundation to be built. The nature of the problems facing us today is that of cybernetics: interconnections, interrelations, synthetic behaviors, not modeling and optimization as it has been narrowly interpreted for over a half century. The time has come for the rebirth of engineering cybernetics and renewal of its original ideas, and it starts with a revisit of Tsien's book of 1954.

5 Conclusions

'Engineering Cybernetics' is a book of penetrating insights and original ideas. Tsien set to 'grasp the full potential of this new science by a comprehensive survey of the whole field'. Most of the topics covered in the book later grew into separate branches of control theory, such as linear system, nonlinear system, filtering, stochastic control, optimization and optimum seeking, etc. With this landmark book, the grand vision of Norbert Wiener finds its embodiment in a new engineering science.

In 'Engineering Cybernetics', readers find a pristine exposition of the collections of ideas, concepts, principles and methods as a cohesive whole, with masterful conciseness and clarity. More importantly, the book shows, in the true spirit of science, that all assumptions, explicit or otherwise, must be made accountable in engineering. The turning point in the book is where Tsien goes beyond the model-based theory of servomechanisms and argues for the necessity of a new design principle for a general type of system where the properties and characteristics of the controlled system are largely unknown. It is here a deep connection becomes visible between Tsien's 'Engineering Cybernetics' and the later work of Jingqing Han on ADRC. In fact, the burning question first posed by Tsien in 1954 was renewed by Han in 1989 [23], followed by two decades of intense research on the ADRC solution, crystalized in Han's last paper in [22].

Sixty years have passed, but Tsien's words are as relevant today as when they were written. His vision may be forgotten, but only at our own peril.

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