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Active Disturbance Rejection Control

From an Enduring Idea to an Emerging Technology

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Abstract**—**This paper introduces an emerging technology called active disturbance rejection control (ADRC), and a story that spans East to West in geography and centuries in time. Emerges from ADRC is the idea that shadowed the ancient Chinese invention of the south-pointing chariot, the idea embedded in a Frenchman' invention of isochronous governor from the early 19th Century, and the very same idea of invariance formalized in the 1939 Soviet Union. The idea was again revived in the 1990s in the form of ADRC and was soon spread to the U.S., where it took roots and gradually matured into a viable industrial control technology, as evident in the recent adoptions by major industrial concerns. Also seen in ADRC is the clashing of ideas in the history of control science, the ideas that go back to H.S. Tsien and R. Kalman in the 1950s. The origin and the making of ADRC can only be understood from the interplay of the big ideas as presented in this paper. Subject to scrutiny were the basic problems, the fundamental assumptions, and the very conception of control science itself. It is the disagreement on the very foundation of our craft that makes a paradigm-shift to ADRC seem inevitable, in theory and in practice.

I. Introduction

The problem of disturbance is as much of an engineering concern as a human concern. In the dialogue *Philebus*, Plato made note of "a disturbance of the harmony in a living creature" when "its natural condition is disturbed", and what can be done so that "a return is made to its natural condition". Ancient Chinese teachings aimed at attaining the peace in the mind that is unmoved by things outside, just as the Hellenistic philosophers strived for the state of *ataraxia*, i.e. free of disturbance. How one responds to disturbances in life plays a big part, some would argue, in one's happiness. Likewise, the quality of disturbance rejection determines, to a large extent, the quality of an automatic control system. The subject of mitigating disturbance seems to transcend the boundaries of human knowledge. Cross fertilizations among different branches would surely be beneficial.

Automatic control plays an important role in all fields of engineering, because each engineering system must deal with unexpected changes from within and without. The art of accommodating such disturbances, without constant human interventions, is what enabled the Industrial Revolution, a revolution of machines and their master, the governors. A machine needs a governor to adjust itself when "its natural condition is disturbed", just like the human condition Plato described. In contrast to the simple machines of the past, the governors of the prime movers of the 18th century were capable of sensing the controlled variables and counteracting the forces of disturbances to restore the balance automatically, much like how the basic unit of life, a living cell, copes with the elements in its surroundings. This new ability for the engineered systems to adjust itself automatically marked the beginning of the era of *Cybernetics*, or "control and communication in the animal and the machine" [1], and it precipitated the birth of "*engineering cybernetics*" [2], as an engineering science of control. But what kind of science is it?

Important to any science is the precise articulation of its basic and primary problem. At the very beginning of engineering cybernetics, this was where the two schools of ideas clashed. One school believed that the problem of control is the problem of feedback. Or to be specific, the problem of stability and optimality of feedback systems, to be studied systematically using advanced mathematical tools, because "in the classical view, a feedback control problem could be identified almost always as a stability problem" [3].

The other school of ideas disagreed with such interpretation on the ground that the very reason for the use of automatic control in practice is the presence of disturbance, both internal and external. More importantly, the mathematical model of the physical process is not to be trusted because just when you need it most, as a disturbance hits and system behavior changes unexpectedly, the model may become utterly unreliable. Therefore the basic objective of control is that the operation of the system "must not be influenced by internal and external disturbances" [2, p. 228].

The winning argument went on to become the dominant paradigm that ruled the field to this day; the dissent was soon forgotten, but the idea somehow lived on among the few, passing on from one generation to the next, one country to the other, until it comes all the way back as a competing paradigm.

This paper tells the unlikely story of how such a forgotten idea made its way back to the center stage of industrial control. What are the nature and characteristics of the ensuing technology? What kept the idea alive? How did technology come into being? What can we learn from it?

To be sure, control theory as a theory of stability and optimality of feedback systems provides us with the mathematical rigor and a valuable set of tools to study dynamical systems. Fitting it to the right problems, control theory can deliver suitable solutions, as evident in the countless papers of successful applications. What at issue is crucially important for the future of this field: how the science of control is to be understood: a system of axioms and theorems in the vein of applied mathematics? Or, an experimental science where the design principles are abstracted from practice and organized into a cohesive whole?

Our desire to understand is innate, according to Aristotle, but our conceptualization of reality often misses the mark, as shown throughout the human history. What has saved us is the spirit of modern science which puts our understanding and conceptualizations continuously under the scrutiny of

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experimental observations. In such a science there is no "self-evident" truth that is beyond doubt and therefore no place for the axioms upon which the entire structure of knowledge is to be built. The trustworthiness of a principle is measured not only by its logical soundness, but also, and especially, by its effects on practice. An engineering theory is not merely a speculation or a mathematical exercise. It either proves its worthiness to engineering practice, or ceases to be of any consequences.

The paper is organized as follows: the emergence of the new technology is described in Section II, which can be understood fully in the context of clashing ideas, as presented in Section III. The exposition of such a storied past will ease the readers into the inner workings of the technology as presented in Section IV. Finally, the paper is summarized in Section V, which by itself can serve as a white paper on the ADRC technology for those in need of a quick grasp.

II. An Emerging Technology

There is currently a surging interest, from both academia and industry, in active disturbance rejection control (ADRC). Several control journals have published, or plan to publish, special issues on the subject of disturbance rejection; several major industrial concerns have adopted ADRC in various forms in their products or production lines; several recent control conferences have seen plenary talks, workshops, and invited sessions given on the subject. ADRC seems to have captured the imagination of technologists in the field of industrial controls, a field that has been dominated for over a hundred years by PID (proportional- integral-derivative), which itself is but a variation of the Watt's flyball governor from the 18th century. Like PID, ADRC provides a genetic solution that is widely applicable. But looking closely behind ADRC, one may find new concepts, design principles, and tuning methods. In addition, ADRC can be seen as a lively idea from which particular solutions can be custom made across the boundaries of industry sectors, if the idea is well understood. To facilitate a good understanding, we begin in this section by tracing the journey of the idea and by highlighting the unique characteristics of ADRC.

A. A Long History of a Transformative Idea

ADRC can be understood at several levels, but it is first and foremost an idea that knows no boundaries of geology and time. It casted its first shadow in the ancient Chinese apparatus known as the South-pointing Chariot (SPC), a pointing mechanism used before the invention of the compass. It is made of an elaborate gear system that measures the degree of turning by the chariot and then, based on this information, counteracting it by turning the pointer on top of the chariot in the opposite direction by the same degree. The result is that the pointer always points to the same direction, regardless of the movements of the chariot. Essentially, it is an automatic control system where the output to be controlled (the direction of the pointer on top of the chariot) is not measurable but the disturbance (turning of the chariot) is! And the control action (turning the pointer) is taken based on the disturbance measurement (the turning of the chariot).

The SPC is called the first automatic control system in the world by Joseph Needham in his landmark book, *Science and civilisation in China* [4], but its underlining principle was not discussed until early 1960s when a Chinese scholar [5], Van Be-wu, discovered the connection between the SPC and the principle of invariance from the work of a French scholar, J.V. Poncelet, shown in the invention of isochronous governor [6] in the early 1800s. Poncelet studied the hunting problem in the stream engine and traced it to the lag in the governor as the cause. To overcome such lag, he proposed a spring-loaded governor where any changes in the load torque will immediately trigger a valve adjustment, before the engine speed changes. Because the governor immediately responds to the disturbance, Poncelet calls it the *isochronous governor*.

Poncelet has the right idea but his method of measuring the load torque introduces unwanted dynamics, and the entire idea was dismissed as defective in 1919 [7]. It took another twenty years before the idea hopped from France to the then Soviet Union, when G.V. Schipanov conceptualized Poncelet's idea as the *principle of invariance* [8]. Implicitly, in hindsight, Schipanov redefined the basic problem of control as one of keeping the process output invariant in the presence of disturbance. He was interested in the condition under which the disturbance has zero effect on the system output, and it naturally led to B. N. Petrov's dual-channel design principle [9] where the disturbance signal is measured and used for its cancellation. It was also found that the invariance can be attained with a controller that has infinite gains, as shown in the body of work known as the sliding mode control.

Van points out that the SPC and the invariance principle, as conceptualized by Schipanov, share the same basic problem of control (disturbance) and methodology (disturbance measurement and cancellation). Interestingly, the SPC was often misunderstood as open loop control because it does not quite fit in the framework of feedback control, where the feedback, be default, refers to the measurement of the controlled variable. This leads to the ironic conclusion that the world's first automatic control system is open loop.

In the meanwhile, Schipanov's theory of invariance left a deep impression on the mind of a Chinese graduate student, Jingqing Han, studying control theory in Moscow in the 1960s, who later on became a distinguished theorist at the Chinese Academy of Sciences. Han who brought the idea of invariance back to life in the form of ADRC in 1990s and left the imprint of his unique notions of model and disturbance [10-16], which will be explained later in the paper. Soon the idea hopped again, this time to the U.S., where it took roots and, after many years of cultivation, became a viable alternative to the industry standard solution, as shown below.

B. From PID to ADRC

The development of ADRC was highly motivated by the desire to provide an alternative to PID as the dominant solution [14,15]. Despite the fast and furious developments in control theory in much of the last century, PID has remained as the tool of choice among practitioners, accounting for over 95% of industry installations [17,18]. 75% of these loops, however, is reported out of tune, wasting precious resources. Without the guidance of deep understanding, the industrial solution to the difficulty in tuning is more tuning rules, a lot of them. In fact, in what is called "the most startling statistics," there are 443 PI tuning rules and 691 PID tuning rules, for a total of 1134 rules [17,18]! Hence we have on our hand the rather awkward coexistence of mathematical rigor and precision in control theory, on the one hand, and the rudimentary and heuristic nature of engineering practice dominated by PID, on the other.

Han was among the few who took issue with the irony and he devoted the last twenty years of his life to address it. During much of this time, his work was outside the mainstream and was often dismissed offhandedly, but he persevered. Gradually, very gradually, emerged a collective recognition: the idea of ADRC works! But wait, what is the idea of ADRC anyway?

ADRC is a particular rendition of *disturbance rejection control* (DRC) as articulated recently in [19] and shown in Figure 1. DRC symbolizes the type of control systems with the primary goal of disturbance rejection; it typically consists of a controller-rejector pair: the latter estimates and cancels out the *total disturbance*, i.e. the lumped internal and external disturbances, while the former controls the enforced plant, almost disturbance-free. DRC provides an organizing principle and a platform where similarities and differences among various disturbance rejection solutions can be understood, particularly in terms of the assumption made on the process model and the nature of disturbance, as well as the method of disturbance estimation. DRC can also be seen as a generalization of ADRC to encompass most, if not all, methods of disturbance estimation and cancellation.

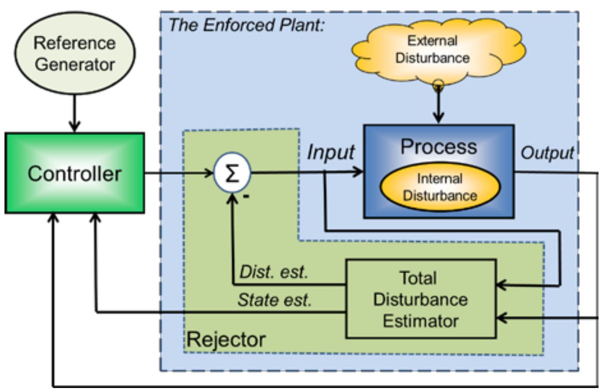

Figure 1. The Disturbance Rejection Control Platform

Unique to ADRC as a particular solution is that this controller-rejector pair requires no detailed mathematical model characterizing the input-output relationship of the process, and that the total disturbance is treated as a state, namely, the extended state (ES), which is estimated by the so called extended state observer (ESO), and is subsequently cancelled. In doing so, the process to be controlled is transformed to the enforced plant, as shown in Figure 1, typically in the form of cascade integrators. As will be explained later, the conventional concept of disturbance as something outside the process is broadened in ADRC to include the internal dynamics, and its subsequent removal makes the controller design a must simpler task. That is, the rejector takes away the messy details pertaining to each process and it makes straightforward the design and tuning of the controller. Such design principle can only come from a flash of insight, instead of deductive reasoning. It is perhaps for this reason ADRC was initially met with much doubt, as its theoretical justification lagged behind.

The first sign of the effectiveness of ADRC came in 1997 during Han's first visit to the U.S., where ADRC was first tested in motion control experiments, as was later reported in [20,21]. The tests were very successful but the complexity in tuning the nonlinear gains need to be resolved before ADRC can be deployed in an industrial setting and handled by a factory operator.

C. *The Transition from an Idea to an Industrial Technology*

A breakthrough came six years after the initial motion control test, when ADRC was greatly simplified and all its parameters were made functions of the control loop bandwidth that epitomizes the design tradeoff in practice [22]. The ensuing industrial case study funded by a major manufacturer demonstrates convincingly the advantage of ADRC, as a motion control solution, over the industry standard solutions based on PID [23]. To the astonishment of many, an even more surprising result was soon obtained when the ADRC solution replaced the time-tested PID solutions for multi-zone temperature regulation at the Parker Parflex extrusion facility in Ravenna, Ohio: in addition to significant improvement in CPI, a quality index, there is 57% energy savings across ten production lines [24]. At this point, ADRC as a viable technology became evident, as reported in the news media and product promotion materials; some chip manufacturers, such Texas Instruments and Freescale Semiconductor, have either replaced the PID with ADRC in the DSP control chips or announced their plans to do so [25-34]. ADRC as an appealing industrial solution perhaps can be explained by its unique characteristics, illustrated as follows.

1) *Almost "Model-Free" and Naturally Decoupling*

If the dominance of the PID in industry teaches us anything about control design, it is to keep the controller simple and generic, let the users tune its parameters, and don't make it model-dependent. ADRC meets all such provisions but, at the same time allows a knowledgeable user to incorporate any knowledge of the process dynamics into the design. That is, ADRC can be designed anywhere from almost model-free to fully model-dependent, as shown in the following example.

Consider a motion control problem with a second order, single-input and single-output (SISO) plant:

$$\ddot{y} = f(y, \dot{y}, w, t) + bu \tag{1}$$

Here the output y is the motor position, the input u is the motor current, the parameter b is a constant approximately known, w is the external disturbance, and $f(y, \dot{y}, w, t)$ is the *total disturbance*.

ADRC is "model-free" or "model-independent" only if "model" means the detailed mathematical form of $f(y, \dot{y}, w, t)$ as a function of its variables, which is absolutely *not* required if it is estimated and cancelled, as shown in Figure 1. One may argue that even with $f(y, \dot{y}, w, t)$ unknown, eq. (1) is still considered a model because of the needed information of the order and *b*. With this in mind ADRC at best can be called almost "model-free". As will be shown later in the paper, any and all knowledge of $f(y, \dot{y}, w, t)$ can be incorporated into the total disturbance estimator for improved performance, thus making the design quite flexible for a wide range of users with different level of knowledge and skills.

For example, with the rigid body motor-driven motion in (1), the law of physics dictates that the plant is second order and b is the ratio of the motor torque constant and the total inertia, which is known. By estimating and cancelling the total disturbance, the motion control quality is made independent of internal disturbances such as the motor hysteresis, nonlinear frictions, and the external disturbances such as load torque variations. It is in this sense that *decoupling* is achieved with respect to the unknown disturbances.

Moreover, such design is naturally decoupling also for the multi-input and multi-output (MIMO) control systems. When the inputs and outputs are naturally paired, the cross-channel interference is treated as disturbance in the ADRC control loop for each pair, providing a refreshingly new solution in the area known in academia as *decoupling control*. Again, ADRC shows that it is possible to find a solution almost model-free.

On the industry side, the MIMO processes, like the one found in the multi-zone temperature regulation for extrusion, are often treated as SISO ones, which makes PID tuning quite challenging. Some resorts to tricks such as disturbance feedforward that is dependent on the intimate knowledge of the process dynamics and external disturbance. While they can be effective, setting up the control system and adjusting it as needed could be quite labor intensive, in comparison to the natural decoupling ability of ADRC. Furthermore, because of the process complexities and uncertainties, the model for such processes comes with a premium and questionable fidelity, making model-based solutions ill-suited. ADRC far surpasses the PID and model-based design in controlling this kind of processes exactly because of its natural decoupling characteristics.

2) Imposing the Will on the Physical Process

With the total disturbance $f(y,\dot{y},w,t)$ estimated and cancelled, the controller controls "the Enforced Plant" in Figure 1, which, in ADRC, is in the form of

$$\ddot{y} = u_0 \tag{2}$$

where u_0 is the output of the controller. This is the ideal dynamic imposed on the physical process by disturbance rejection, for which the controller can be predetermined and parameterized, usually in the form of the linear PD form [22]. In other words, instead of trying to figure out what $f(y,\dot{y},w,t)$ is and design the controller accordingly, the physical process is forced by the *rejector* to behave like the ideal model, which may not even be close to the physical process at all. In fact, even the order of the ideal model is enforced on the process, which can be significantly lower than that of the actual process. This is because the higher order dynamics can be seen as internal disturbance and included in the total disturbance. As shown in a recently motion control study with a low frequency resonant mode, the ADRC based control system was able to operate at a bandwidth higher than the frequency range of the unknown resonance [35], a feature that immediately captures plenty of attentions.

3) Anticipation

The author who gave PID its current form, N. Minorsky, lamented about the lack of anticipation in the PID type of design [36]. As an error-driven control strategy, PID reacts to the error, not its cause. In observing ship steering by human operators, Minorsky understood that there is a great deal of anticipation in control that was not, unfortunately, reflected in his descriptions of PID solutions. This weakness was later addressed by practitioners with the addition of the so called "feedforward" term, either from the setpoint or from the disturbance measurement. Such solutions are customized for each process and they depend on the knowledge of the process or disturbance. In comparison, ADRC is a two-layered solution that first tries to remove the cause of the tracking error, i.e. the total disturbance, and in this sense it is anticipatory. For the motion control example in (1), the total disturbance is about 180 degrees ahead of the output deviation in phase angle, in terms of frequency response, giving ADRC a significant advantage in anticipatory control. This is the reason that the ADRC solutions, such as the factory installation reported in [24], often show significant reduction in energy. The full impact on energy savings world-wide is hard to quantify but seems limitless.

4) Ease of Use

An almost model-free design, anticipation, performance improvement, energy saving, etc., these are sought-after features for any advanced control solutions. But perhaps what is more important, what will finally decide whether or not the solution will be adopted by users in industry, is the feature called "ease of use", which is seldom heard in an academic setting. The past decades have seen plenty of solutions that were supposedly better than PID. One by one they failed to compete with PID, often for the lack of simplicity and ease of use. Briefly speaking, to be a viable technology that is readily deployable as a general solution of industrial control, like PID, an advanced control must possess the following characteristics: 1) simple to implement; 2) widely applicable, 3) not model dependent, 4) significantly better in performance, 5) strongly robust, and 6) easy to use. ADRC is comparable to PID among the first three but surpasses it in the last three. The ease of use is particularly important, considering how many PID control loops are out of tune in industry [17,18].

ADRC was not a technology ready to be deployed in its early years when great performance was offset by the complexity in controller tuning, as shown in [21]. A breakthrough came in 2003, when the linear ESO (LESO) and the linear ADRC (LADRC) were developed where all controller and observer gains were parameterized as functions of the control and observer bandwidths, ω_c and ω_o, respectively [22]. In doing so, the tuning of ADRC comes down to the adjustment of the bandwidth, which is quite simple and intuitive for the users. Single parameter tuning for industrial applications is made possible by predetermining the ω_c and ω_o, relationship. And this made ADRC tuning almost trivial because the factory operators can be easily trained to turn one knob (bandwidth) to adjust the aggressiveness of the control system. Furthermore, an industrial turnkey operation, without any tuning, is finally within grasp, as shown in a recently study [37].

In particular, setting up and commissioning of an ADRC solution for an industrial control problem require four parameters to be set: the order of the enforced plant, the b constant, and the controller and observer bandwidths, ω_c and ω_o. For a particular class of industrial problems, such as motion control, it is quite conceivable that our knowledge of the plant, the physical constraints, and the design specifications will allow us to determine all four parameters *a priori*, thus allowing the turnkey operation. In case of the variable loads, the b parameter could be time-varying in a wide range, but the turnkey operation is still achievable by estimating b in real time, as shown in [37] recently and in [38] earlier.

5) Flexibility for Advanced Users

ADRC provides a flexible solution for engineers with decades of expertise in a particular industry because they can work the ADRC idea seamlessly into their existing solutions with ease, assuming that they understand the idea well.

Han repeatedly made the point in the past that if there is any model information given, it should be included in the ADRC to make it more effective. That is, the model information can be incorporated into the ESO to lessen its computational burden and to reduce the latency in the disturbance estimation. This property of the model-assisted ESO was shown and analyzed in [39]. More recently it is shown that the ESO can be applied to most existing observer-based designs in modern control theory [40]. That is, any discrepancy between the actual process and its mathematical model can be estimated and cancelled, enforcing on the plant whatever the process model for which the controller is already designed. In light of this new result, it has become clear that the DRC platform provides unprecedented flexibility across the full spectrum of control design scenarios, from knowing barely any model information to the completely model-based design.

In other words, if the model-based design principles from the textbooks are characterized as the (transparent) white box methods and the PID-based designs as the black box methods, then ADRC can be seen as the gray box in between, with an almost infinite resolution of grayness. In fact, the principle of ADRC can be incorporated seamlessly into any existing designs, industrial or academic.

6) Robustness

Robustness, or ruggedness, is highly valued in industry where any miscue of control system could result in system shutdowns. Robust control, as an academic discipline, strives to address the problem of model-mismatch in a model-based design framework. Instead of solving such problems, ADRC reframes them, with new notions of model and disturbance. Instead of asking whether performance and stability can be maintained when the process dynamics differs from its model, ADRC asks whether or not such discrepancy can be removed all together; instead of asking how to incorporate the robustness constraints into the control design process, ADRC asks whether or not we can disregard the detailed dynamics of the process in control design. In essence, instead of answering the question of robust control, ADRC changed it.

The question to be answered now is, for example, to what extent the uncertainties can be removed by the rejector? The engineering success indicates that ADRC can handle with ease a large range of uncertainties and it calls into question the necessity of having a detailed mathematical model of the physical process as the point of departure in control theory. In fact, through ADRC the problems of control can be casted in an entirely different light and ADRC itself can be best understood through the clashing of ideas over the course of history of this young field, to which we turn next.

III. A History of Clashing Ideas

The history of science is full of clashing ideas and competing paradigms. A scientific paradigm is defined as "universally recognized scientific achievements that for a time, provide model problems and solutions for a community of practitioners" [41, p. xlii]. It is how the questions are framed and the assumptions are made. Occasionally, someone else comes along and brings a different set of questions and premises. Such is the case in the science of control, where the questions in the prevailing paradigm are centered around stability and optimality, with the investigations premised on the detailed mathematical model of the physical process. All investigations start with such model and ultimately return to it. What can be done outside the accurate and detailed mathematical model pales in comparison to what can be done within it.

This model-centric cosmic view started with Maxwell in 1860 [42], brought to the center stage by Wiener in 1948 [1], and has continued to dominate the academic field of control theory to this day. The emphasis of this new science, as explained by Wiener and further articulated by Newton et al in 1957 [43], is to make systematic what previously a haphazard, trial-and-error, and empirical engineering practice of control system design. Modern control theory came into its own, perhaps not by accident, at the beginning of the space race and benefited from the strong and lasting government support in the U.S. It grew rapidly and furiously for much of the second half of the 20th century. In recent years, with research funding for control theory dried up and the industry practice still dominated by PID, the field now has to justify its existence. In 2011, the IEEE Control System Society published a comprehensive report titled "The Impact of Control Technology"[44], enumerating across the industry sectors particular instances of advanced control solutions, each is specifically design to address a particular class of problems, but none is threatening the dominance of PID as a general solution.

Reconnecting theory with practice has been the subject of numerous articles and conference sessions, such as [45], in the last few decades. But amid all such chatters the gap grew wider, indicating, perhaps, a fundamental and not yet well understood problem at the foundation. Such problem is not unique to control. Concerning the field of economics, renowned economist R. H. Coase once said

> "Economic theory has suffered in the past from a failure to state clearly its assumptions. Economists in building up a theory have often omitted to examine the foundations on which it was erected. This examination is, however, essential not only to prevent the misunderstanding and needless controversy which arise from a lack of knowledge of the assumptions on which a theory is based, but also because of the extreme importance for

> economics of good judgment in choosing between rival sets of assumptions." [46]

Likewise, control science may also have "omitted to examine the foundations". The model-centric paradigm in academia and the PID-only world of industrial control can both benefit from "rival sets of assumptions", ones that would shake up the dormant practices and misguided research. In fact, Prof. Åström reminded us, in his plenary talk at the 2012 American Control Conference, that "We should not forget about the foundation because then the tower will tumble"[47].

As control theory marched forward as a branch of applied mathematics, perhaps it could have heeded to the warning of John von Neumann:

> "As a mathematical discipline travels far from its empirical source … it is beset with very grave dangers. It becomes more and more purely aestheticizing"[48].

Does this resemble the current state of research in our field? Is mathematical sophistication, if not elegance, valued more in modern control theory than the practical utility? What could be the grave danger ahead? Prof. von Neumann explains that one grave danger is

> "that the discipline will become a disorganized mass of details and complexities. In other words, at a great distance from its empirical force, or after much 'abstract' inbreeding, a mathematical subject is in danger of degeneration"[48].

Prof. von Neumann might as well be speaking of control theory. This departure from the empirical force and subsequent "abstract inbreeding" could perhaps explain the loss of the "holistic view" Prof. Åström described [47]. It is now appeared that the persistent gap between theory and practice in control science is indeed a symptom of a much deeper problem in the foundation. Finding our way back to the source, to the "empirical force", is an arduous journey that requires a collective effort and all hands on deck. But where do we start?

"Before men can build a successful theory in any field of science they must be clear what it is that requires explanation" [49]. Likewise, let us ask what is it that requires explanation in the field of control? Perhaps the early work of Trinks [7] and Tsien [2] in distilling the fundamental principles of governing from engineering practice could help us get back on track. What distinguishes them from others is the penetrating scientific mind that sees way below the surface of trivial details. More importantly, they show us that the basic principles of control are discovered from engineering practice, not deduced mathematically from some unexamined axioms. So first, to the principles we go.

A. A Mysterious Design Principle

The first holistic view of the field of control, or governing as it was called back then, was given by Prof. W. Trinks at the then Carnegie Institute of Technology in 1919, in the book titled "Governors and the Governing of Prime Movers"[7]. "As far as I was aware, there exists to-day no other book of any consequence on governors and governing in the English language", he said, referring to the book as one of "essentials and principles". They are important because, according to Trinks, practice changes but engineering principles do not change. Trinks was determined "to dig out that which is essential."

"In the evolution of the art of governing, many principles have been used, but one by one they were discarded", according to Trinks, until just one left: the Watt's principle of flyball governor. But even this "has been pronounced defective and faulty, because to cause the governor to act, it necessitates a change in the quantity to be kept constant". That is, despite the works of the scholars of the first rate, such as Maxwell and Routh, the principle behind the Watt's governor remained elusive. Without a clearly articulated and validated principle, more mathematics wouldn't help. In fact, the early mathematical analysis of the governor pioneered by Maxwell and Routh led to misunderstandings and "absurdity", according to Trinks. In particular, Routh stated in 1905 that "The defect of a governor is, therefore, that it acts too quickly, and thus produces considerable oscillations of the speed in the engine." But in reality, says Trinks, the opposite is true: the oscillation is due to lag in the governor and the remedy is "in making it act more quickly" [7, pp. xviii]. It is therefore quite evident that mathematics alone cannot make up the lack of understanding of fundamental principles, and abstraction of principles from tedious details cannot be replaced by mere mathematical exercises.

But in this intellectual endeavor of conceptualization, the field of control is not alone.

> "Often it is only after immense intellectual effort, which may have continued over centuries, that humanity at last succeeds in achieving knowledge of a concept in its pure form by stripping off the irrelevant accretions which veil it from the eye of the mind" [50]

says Gottlob Frege, and the search, started by Trinks, for the basic principles of governing would go on for another 35 years before H.S. Tsien came to the scene.

B. The Emergence of Control Science and the Centrality of Disturbance Rejection

The landmark book, *Engineering Cybernetics,* by Caltech Prof. H.S. Tsien [2], formally established the field of control as an engineering science in 1954. Like Trinks, Tsien "aims to organize the design principles used in engineering practice into a discipline that thus to exhibit the similarities between different areas of engineering practice and to emphasize the power of fundamental concepts", and "to grasp the full potentialities of this new science by a comprehensive survey of the whole field" [2, pp. viii]. The book "anticipated much of the development of control after 1954" [51], according to Åström, and its impact on control theory in general, and to ADRC in particular, was recently discussed in [52].

The power and clarity of the mind were on full display when Tsien finally put the mystery of the Watt's principle away, using the speed control of a turboalternator as an example. The essence of the speed regulation, he explains, is really the balance between the torque generated by the steam turbine and the torque absorbed by the alternator. Its solution consists of two part: the *open-cycle* control that "could be done by measuring the load and by opening the steam throttle accordingly", and the *closed-cycle* control, where "we cause the steam-throttle opening to depend not only on the load but also on the speed deviation"[2, p.35]. In other words, the control action has two parts, not one as in Trinks' early exposition. One is determined by the load and the other by the speed deviation. Trinks' version of the Watt's principle misses the "open-cycle" control component, which makes the principle seem "defective and faulty. It's a misconception still prevalent today.

The open-cycle control initially achieves the torque balance, according to Tsien, and the closed-cycle control maintains the balance amid load variations. That is, the essence of feedback control is feedback correction. This would resolve the difficulty Trinks mentioned earlier. To focus only on the feedback correction and ignore the open-cycle control is a bias that is still prevalent in control theory. It also missed an important part of engineering practice where the limitation of the feedback control in the PID is mitigated by the use of open-cycle control based on the process knowledge, or feedforward. A common knowledge among practitioners is that a well-constructed feedforward control makes the system less dependent on the feedback control. Theory is yet to catch up on that.

Moreover, and this is profound, Tsien made it clear that the source of the imbalance is the disturbance torque. In fact, Tsien made the problem of disturbance central in *Engineering Cybernetic* and left his imprint on the notion of stability:

> "Stability of any control system means that the design performance of the system will be obtained even with the presence of internal and external disturbances. We have seen how this requirement is satisfied in the case of conventional servomechanisms and other more general control systems in the preceding chapters. 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." [2, pp.228]

By convention, disturbance is taken as something external to the plant. Tsien appears to be the first person to give the notion internal disturbance and this has had a profound effect in the making of ADRC decades later, as we shall explain shortly. The primary objective of control, according to Tsien, is to achieve "stable operation", which is synonymous to rejecting the internal and external disturbance.

After a comprehensive survey, Tsien pointed out a common flaw in control theory at the time:

> " In the previous chapters we have discussed the design principles of control systems with increasing degrees of generality and complexity. However, one basic assumption 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." [2, pp.214]

But this assumption doesn't stand, he said, because "large unpredictable variations of the system properties may occur", such as in 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". "But at just this critical situation", he goes on to say, "our prior knowledge of the airplane performance is rendered useless by the ice deposition." The irony is that how can a control system depend on the knowledge it doesn't have?

In articulating the principle and objective of control, in setting the foundation and framing the question for the science of control, Tsien left us with the seminal ideas for the paradigm of control science: 1) the objective of achieving "stable operation" and the notion of stability; 2) the notion of internal and external disturbance; 3) the premise that a control system cannot rely on the mathematical model of the physical process.

Tsien left U.S. shortly after the publication of his book and never returned. His insight on the basic principle of feedback correction, his challenge of the basic assumptions of model-based design, and his focus on disturbance rejection were all largely forgotten, until another 35 years had passed, as we shall see in Section IV. In the meanwhile, the problem of fire control in WWII brought together control engineers on the one hand and electronics engineers from Bell Labs on the other. The work on feedback systems by Black, Bode and Nyquist from Bell Labs gave control engineers a powerful concept in feedback and an effective and practical stabilization method in frequency response method, which later became the central piece in what is known as the *classical control theory*. Through Wiener's popular book [1] the term feedback became household name and the search for the fundamental principle seems to have finally reached its destination. A well respected control historian, O. Mayr, declares in 1970 that this whole field of control is based the single idea of feedback [53].

C. The Turning Point

The field of control took a turn towards mathematization in the late 1950s, signified by the book of Newton et al in 1957 [43] and the paper by Kalman in 1959 [54]. The former declares that we are done with the trial-and-error design procedure, where there is "no criterion for terminating the sequence of trials." Instead, "the design objective is to minimize (or maximize) the chosen performance index" [43, pp.v]. Two particular indices were chosen: the integral-square error is used for system with the "transient input signals", now called set points or reference, and the mean-square error for the "stochastic input signals".

The idea of analytical control design in [43] was reinforced by Kalman's *Principle of Duality* [44], by which the optimal control solution is to be found by solving the problem of optimal filtering, which has already been obtained in the context of Kalman Filter. Given the worldly success of Kalman filter in signal processing, it is only a matter of time before similar success of mathematical rigor is repeated in the field of control, so they believed.

Amid the excitements at the beginning of the so called "golden age" of control [51], control as applied mathematics, control theory in an axiomatic framework and the deductive reasoning become pillars of the modern control paradigm and the dissenting point of views such as those of, Tsien's, were summarily ignored. So was the evidence gathered by practitioners that contradicts the basic assumptions of Kalman.

One glaring example is the work of Graham and Lantrop [55], a meticulous study that conclusively rejects the integral square of error as a viable performance index for automatic control, published six years before Kalman's seminal paper. It is appalling that such hard evidence from a painstaking study by highly qualified engineering researchers was not even acknowledged. The difference in the nature of governing from that of filtering and signal processing was never scrutinized and Kalman's Principle of Duality was taken at its face value.

H. Bode himself suggested in 1960 that the two fields, control and communication, joined in a shotgun marriage by the necessity of fire control during WWII, are fundamentally incompatible and should go their separate ways because "they are obviously quite different in fundamental intellectual texture" [56]. Horowitz saw, in 1975, the state-space based linear regulator design originated as "highly naïve and incomplete in the practical context", and it "has led to enormous misplaced research effort on problems, although mathematically interesting and challenging, are irrelevant and trivial in the practical engineering context"[57]. Concurring with Tsien, Horowitz points out that "a basic central reason for using feedback" has been lost: the existence of disturbance, noises and parametric uncertainties in engineering practice.

Such defect in the foundation of modern control theory would come back to haunt the field for the years to come. An example reported in1978 show that when it comes to the guaranteed margins for LQG regulators, "there are none" [58]. Likewise, it was shown twenty years later that the so called "optimum and robust controllers, designed by using the H_2, H_{inf}, l^1, and μ formulations can produce extremely fragile controllers, in the sense that vanishingly small perturbations of the coefficients of the designed controller destabilize the closed-loop control system" [59]. Ironically, the H_2, H_{inf}, l^1, and μ formulations were supposedly the answer to the uncertainty problem Horowitz raised earlier. The misconception of control problems, the lack of scrutiny of basic assumptions, and unwillingness to entertain opposing point of views all contribute to the decades of wasted resources and they continue to haunt the field today. This is perhaps the type of "grave danger" von Neumann warned earlier [48].

D. The March towards the "Pure Theory" of Control

The paper, "On the General Theory of Control Systems" [54], "initiates study of the pure theory of control, imitating the spirit of Shannon's investigation". Here Kalman refers to the paper by Shannon, "A mathematical theory of communication" [60], the founding paper of information theory. Curiously, while Shannon begins by stating that "the fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point", Kalman would have none of it. Likewise, there is no mention by Kalman what a control system consists of and how it is configured, in parallel to what Shannon did for the communication system. Such lack of articulation of both the basic problem and the nature of the engineering systems is calls into question the connection between Kalman's general theory and engineering practice.

The significance in Shannon's theory, according to Kalman, lies in the "discovery of general 'laws' underlying the process of information transmission" and these laws are like laws of physics except "the laws governing man-made objects cannot be discovered by straightforward experimentation but only by a purely abstract analysis guided by intuition". In other words, the general laws of control must be mathematically deduced in an axiomatic system to which the modern control theory would become. The trouble, however, is that no one stated just what the axioms were and under what assumptions the reasoning was to proceed. When R. H. Coase said:

> "Economic theory has suffered in the past from a failure to state clearly its assumptions. Economists in building up a theory have often omitted to examine the foundations on which it was erected." [46]

he might as well be describing the field of control science.

Kalman's paper set the cornerstones for modern control theory with the concepts of controllability, observability, optimality etc. and the principles of causality, duality etc. The belief that the laws governing man-made objects are not obtainable from experimentation went unchallenged, even though it goes against everything we know about the great inventions in the field of control, from Watt's governor to Sperry's PID. Somehow, in the search for the general laws, a science of man-made objects was deemed not suitable as a subject of study of man-made hypothesis and man-made experimental verifications.

Engineering Cybernetics as Tsien envisioned is quite different: 1) that the task is to distill the design principles and organize them in a cohesive whole, by using advanced mathematics; 2) that the basic problem of control is to achieve "stable" operation where the output tracks the command without deviation in the presence of internal and external disturbances; and 3) that the control design cannot be dependent on the mathematical model of the process dynamics, which could change significantly unexpectedly during operation, as discussed earlier.

The much needed debate between the two opposing visions of Tsien and Kalman would never take place, as Tsien departed U.S. in 1955, under trying circumstances [61] and Kalman's idea of pure theory became the blueprint for modern control theory. To argue that this is the true cause of the theory-practice gap is beyond the scope of this paper, but, in the true spirit of modern science, nothing can escape scrutiny for long. Any engineering science, in particular, must continue to justify its validity on empirical ground, on its utility to practice, or risk becoming obsolete. In fact, the most exhilarating work in science comes when the reigning paradigm becomes obsolete and is replaced by a competing paradigm. If Tsien's seed ideas are sound, the question is not if but when and by whom they will be revived.

IV. The Making of ADRC

By 1980s, it has been over two decades since the inception of the "pure theory" and, given the "primitive" state of industrial practice that hadn't changed much since the invention of PID decades ago, doubts began to creep in. Y.C. Ho, for example, wondered aloud if the science of control should be an experimental one [62]. But the most serious challenge by far came from Jingqing Han, one of the founding members of the Laboratory of Control Theory, established in 1962 at the Institute of Mathematics, Chinese Academy of Sciences [63]. Assessing the state of control theory at the time, as Trinks and Tsien did in their own time, Han asked bluntly whether the control theory as we know is a doctrine of control or a doctrine of model [10] (the English translation of the paper can be found in [63]):

> "The last 30 years in the history of control theory is known as the era of modern control theory. Scholars, from different perspectives, describe the characteristics of various phases in this era and give outlook for the future development. To us, however, such characteristics can be abstracted as the "doctrine of model". The modeling of control system, the analysis of the model, and finally seeking of the control law based on such model form the pattern of the thought process in this era." [10]

Then he turned to the dominance of PID in industry and the gap between theory and practice:

> "In the 70s, many scholars of modern control theory expected that the new accomplishments and methods would displace PID regulator, attributing the dominance of PID in industry to the lack of knowledge in modern control theory. It has been 20 years, however, since the entrance into industry by those schooled in modern control theory. Yet, PID is still here, still hanging on tenaciously. It is the model-based control design that has met great challenges in engineering practice. Robustness, at the onset, is a big problem. On the other hand, for complex system, such as those in robotics, the model representation has become ever more complicated, to the extent of a 'disaster of model'" [10]

Using the practice of guidance and regulator design as examples, he postulated that there must be another way, "beyond the confine of mathematical models". To make his point, Han used a classical problem in guidance:

$$\begin{cases} \dot{p} = v \\ \dot{v} = a + u \end{cases} \tag{3}$$

where u is the control signal, p is position, v is velocity, and a is the so called "inherent acceleration" and is affected by the various state-dependent nonlinearities.

It is at this point in the paper when Han shows a crucial flash of insight: that the control design can be carried out without the knowledge of a, and that a can be estimated:

> "To improve accuracy, it is sometimes necessary to estimate $a(t)$ but it is not necessary to know the nonlinear relationship between $a(t)$ and the states variables. Here, we are not concerned with the nonlinear plant's global dynamic characteristics. Rather, the focus is on how to control its transitory process based on the real time information." [10]

Han noticed that, in guidance, engineers didn't design control laws once for all, covering the entire envelop of operation globally. That will be overly ambitious and unrealistic given the uncertainties in the system. Rather, the problem of guidance is to overcome the "inherent acceleration" that is local in time, without knowing its global characteristics, or description as a function of the state variables. Instead of modeling, the guidance engineers have shown that the system (3) can be very well controlled by estimating and compensating a locally in time.

In a nutshell, Han articulated a great design principle hidden in the art of guidance and brought it to light at a higher level of abstraction: that all control systems can be designed this way. This is what Tsien meant earlier when he said that "an engineering science aims to organize the design principles used in engineering practice into a discipline … to emphasize the power of fundamental concepts" [2]. Such design principle would have never been derived from mathematical analysis, as in Kalman's pure theory, which insists on having the detailed mathematical expression of a as the starting point for any investigation. The guidance engineers discovered the design principle through experimentation, in the spirit of nature science, even though their method is often dismissed as "trial-and-error" and not systematic or scientific. But what exactly the fundamental concept did Han extract?

A. The Concept of Extended State

It took Han another six years but, incredibly, he made a conceptual leap that is as elegant as mystifying in 1995 [11]. Note that many physical processes involving motion can be described by (3) where a is the part of acceleration not accountable in terms of the control signal u. It could be a nonlinear, time-varying function of the state variables and is treated variously, in control theory, as problems of nonlinear control, robust control, adaptive control, system identification, time-varying system, etc., respectively. In the true spirit of experimental science and after extensive simulation studies and experiments, Han made a crucial discovery: that a as the lumped effect of all disturbances, internal and external, can be treated as an additional state and estimated as one. He denoted such state as the *extended state*. In other words, the second order system of (3) would have three states: p, v, and a and this is unheard of.

But how can the quantity a in (3) be called a state? In Kalman's original definition, "the state is the minimum 'record' of the past history needed to predict the future behavior" of a dynamic system [54]. In other words, a dynamic system remembers, by its state, what happened in the past. By this standard no one could have called a in (3) a state. There is a significant body of work, however, on the reduced order state observer where the aim is to reduce the number of states for the sake of simplification. No one has ever increased the order of the state space model beyond its original number of states, like using a third order state space model to describe a second order process in (3).

Generally speaking, *the extended state (ES)* is the extension of the state definition to the total disturbance, which, in a dynamical system, is defined as the lump effect, to the system at the input channel, of both the unmodeled dynamics, i.e. the internal disturbance, and the external disturbance.

Note that the unmodeled dynamics in the total disturbance may be unmodeled by purpose, to remove the dependence on the model by the controller that Tsien so disliked. In fact, with the definition of ES, the basic problems in various branches of control theory, including modeling, robust and nonlinear control, adaptive control, etc., are transformed to the problem of disturbance estimation and cancellation. This is Han's singularly most significant contribution to the field of control and it provides a completely "new, unexpected vista".

Han's bold conceptualization was much ahead of his time and was met mostly with suspicion initially. But the utility of his ideas and the advantages they provide over the existing technology led the practitioners to embrace the idea first. In turn, the visible and verifiable industrial success changed the tenor of intellectual discussions: instead of asking whether or not the concept of ES is sound, the question has gradually become why does it work so well? What is the rationale behind? How do we prove it mathematically? Such questions remind us what the control science was supposed to be, in the vision of Tsien some 60 years ago: to articulate and organize the design principles from engineering practice, so that they can give us "new avenues of approach to old problems" and "new, unexpected vistas." But how did Han do it exactly?

B. The Luenberger-Han Observer

Although the conceptualization of the extended state is traced to Han's 1989 paper, the general solution of its estimation was not given until six years later, in a paper titled *The "Extended State Observer" of a Class of Uncertain Systems* [12]. The words extended state observer (ESO) were put between quotation marks because there was no such thing at the time. The ESO was given in [12] for a general, n^{th} order system, but it is illustrated here, for the sake of simplicity, in terms of the 2^{nd} order system in (1). With $x_1 = y$, $x_2 = \dot{y}$, and $x_3 = f(y, \dot{y}, w, t)$, the state space equation of (1) is

$$\begin{aligned} \dot{x} &= Ax + Bu + Eh \\ y &= Cx \end{aligned} \tag{4}$$

with $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ b \\ 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

and $h = \dot{f}(y, \dot{y}, w, t)$.

The system (4) happens to be observable, meaning that the all states can be estimated with a properly constructed state observer. This is crucially important because it allows, in terms of guidance for example, the "inherent acceleration" to be estimated from the available signals of u and y. The original form of ESO employs the nonlinear gains, for which a special case can be seen in the form of the Luenberger observer of (4)

$$\begin{aligned} \dot{z} &= Az + Bu + L(y - \hat{y}) \\ \hat{y} &= Cz \end{aligned} \tag{5}$$

as described in [22]. It is a simplification of the Han's original ESO in [12], with the linear gain vector L replacing the nonlinear observer gains.

The linear ESO (LESO) in (5), as effective and simple as it is, should not be taken as a formula for all problems. For example, if for a particular problem we do have model information in the form of h in (4), then this information can be added to (5) for a more informed LESO, one which takes the knowledge of the plant dynamics into consideration:

$$\begin{aligned} \dot{z} &= Az + Bu + E\bar{h} + L(y - \hat{y}) \\ \hat{y} &= Cz \end{aligned} \tag{6}$$

where $\bar{h}$ is the part of h that is given [39].

Han's originality is on full display in ESO: to overcome the limitations of the model-based modern control theory, he makes use of its crown jewel, the state space representation and the Luenberger observer, to estimate the total disturbance in real time so that the control design can be liberated from the constraints of having the detailed mathematical model. In other words, he used what was the model-based state observer in an ingenious way to arrive at a design that is mostly model-free. To commemorate the creativity of Han, the author suggests that the ESO be called Luenberger-Han Observer, or LHO.

Three years after he solved the puzzle of total disturbance estimation with LHO, Han finally put together the complete package: active disturbance rejection control (ADRC) [13,14], to which we now turn.

C. Active Disturbance Rejection

For the system in (1), the LHO in (5) provides three state estimates: $z_1 \approx y$, $z_2 \approx \dot{y}$, $z_3 = \hat{f} \approx f(y, \dot{y}, w, t)$, and the control law

$$u = \frac{u_0 - z_3}{b_0} \tag{7}$$

where b_0 is the estimated value of b in (1), reduces (1) to the enforce plant in the form of

$$\ddot{y} \approx u_0 \tag{8}$$

With most of the uncertainties and complexity of the original system in (1) now removed, controller design for (8) becomes straightforward, with either the nonlinear PD from [12], or a simpler and easier to tune linear PD from [22]. Ironically, the model-based methods can also be put to full use here.

Note that (8) is just one example of the enforced plant. It is an ideal plant in the sense that the input-output relationship is that of pure integration. For various model-based designs, they can be integrated seamlessly with ADRC by using the existing model as the enforced plant and treat any difference between the model and the actual dynamics as extended state to be estimated and cancelled. The same idea applies to other disturbance observer based designs where a nominal plant model is assumed and the external disturbance is the object of estimation and cancellation. Therefore, the DRC platform in general and ADRC in particular provide a unified framework where various disturbance problems can be addressed, the past methods can be organized, and the design principles can be discussed.

D. Key Design Principles

With the total disturbance estimated and cancelled, the objective of "stable operation" is now finally attained. Emerged from the long process in the development of ADRC are several key design principles.

1) The Smooth Reference Principle (SRP)

Popular as it is in academic settings, step command is seldom used in industrial settings for good reasons. In tracking, the reference, i.e. the desired output trajectory, must be carefully generated to make it physically feasible for the output to follow. It also helps to keep the tracking error small. This is the idea behind the reference generator in Figure 1 and it is widely practiced in industry under different names, such as motion profile in servo systems or soft start in power electronics. In addition, the trapezoidal profile and the s-curve are used often in motion profile to save energy and to avoid actuator saturations. Han is very much aware of such practical considerations and he suggested a simple and clever reference generator called the tracking differentiator, as a component in the original ADRC configuration [12]. It is shown in [22] that this tracking differentiator can be replaced with the industry standard trapezoidal profile, which is more familiar to engineers. In any event, it is important that a smooth reference is generated for the output to follow.

2) The Bandwidth Parameterization Principle (BPP)

It was emphasized early in the ADRC literature that both the controller and the ESO use nonlinear gains to maximize its performance. Nonlinear gains are more powerful and flexible and they generally outperform the linear gains. But there is a trade-off: nonlinear gains make the control system more difficult to tune and to analyze. LADRC with LESO is proposed in [22] for better ease of use, particularly when all controller and observer gains are parameterized as functions of the control bandwidth, ω_c, and the observer bandwidth, ω_o, respectively. Such parameterization is crucially important in industrial applications because it enables the so called "one parameter tuning", where the machine operator just needs to turn one knob, more aggressive or less so, in tuning ADRC. As the result, ADRC solutions are vastly easier to use than those based on PID. Moreover, the parameterization technique does not preclude more powerful solutions using nonlinear gains. In fact it helps to establish the starting point in search of the optimal nonlinear gains.

3) The Generalized Separation Principle (GSP)

The most important design principle emerges from ADRC is that the controller and rejector, as shown in Figure 1, can be designed separately. That is, the tracking and regulating (disturbance rejection) are effectively decoupled. The rejector forces the plant to behave like an ideal model for which the controller is designed. And this principle applies to a wide range of process: nonlinear, time-varying, highly uncertain, and multi-input and multi-output (MIMO), etc. This principle was originally discovered by Han, although not articulated, in his extensive simulation studies, first validated in a theoretical study reported in 2007 [39] and later confirmed by others, see, for example, [65-73]. There is still a long way for the theoretical advance to catch up with the practice of GSP. The progress has accelerated in recent years as ADRC's success in industry has become more evident.

4) The Gray Box Principle (GBP)

The GBP stands for the idea that however much you know about the physics of the process to be controlled, you should use it to your advantage. It is a happy medium between the white box of model-based modern control paradigm and the black box of the PID-based industrial control paradigm. In the full spectrum of automatic control, PID occupies the lower end with the run of the mill problems and trail-and-error solutions; the model-based designs find themselves at high end of the spectrum where the benefits of modeling outweigh their high costs. ADRC is perhaps the first low-cost but high-performance, gray box alternative to both. The grayness comes in various shades, reflecting the depths of knowledge of plant dynamics, all of which can be used in design to improve performance and to reduce cost. In general, the more knowledge is added to ADRC, the better the results.

5) The Observer Synchronization Principle (OSP)

All control systems have a certain amount of transport delays in the plant, or the controller, or both. When the delay is pronounced, it is the chief cause of the problem of "ringing" or "hunting", as it's variously called by engineers. For the state observer based design, such as the Luenberger-Han observer, it is of paramount importance that the observer has its inputs synchronized in time.

There are two methods of synchronization. The first is to make sure that all signals are delayed by the same amount as they enter the observer [74]; the second method of synchronization is to cancel the delay with prediction, for which there are two means: 1) by using the Taylor series expansion with higher order derivatives of the disturbance obtained by using the generalized PI observer [75] or the generalized ESO [76]; or 2) by combining the well-known Smith-Predictor with ESO [77]. None of these methods is ideal because there is no ideal solution when it comes to time delay. We must learn to live with the limitations it brings to control design, particularly in the performance-stability margin tradeoff.

E. Disturbance Rejection Control: a Unified Platform

As Tsien and Horowitz wisely pointed out to us decades ago [2, 57], and as it was further articulated in [19], the basic problem of control is to reject disturbance, internal and external. Outside the mainstream, generations of researchers, scattered geographically, have put their minds to this problem. There has been a lack of awareness of disturbance rejection as a distinct field and a lack of framework in which all results can be organized, categorized and connected. As a result, researchers worked individual problems in isolation, not aware of the general framework or each other's work, past and present. The emergence of ADRC as a technology provides the impetus for a unified platform of disturbance rejection control, as shown in Figure 1.

As a distinct field, disturbance rejection control has become increasingly vibrant in recently years, with ADRC as a spearhead. The DRC solutions, however, are by no means limited to ADRC. A complete overview of the field is beyond the scope of this paper but the interested readers are referred to the papers in [78-93] and three recent books in [94-96] for further reading. By this paper, together with [19], we hope to present a DRC platform on which all previous work can be organized under one umbrella, for the purpose of facilitating further growth and avoiding redundancy.

Perhaps the most critical component in the DRC platform is the disturbance observer. As shown in [64], the state and disturbance observers developed over the years can be arranged in terms of: 1) the dynamic structure (the kind of model) assumed for the plant, 2) the required information that goes into the observer (input signals), and 3) the implementation equation (linear-nonlinear, state space–transfer function, continuous-discrete). However scattered in time and geography, all past work can be sensibly understood and reconnected in systematic manner in the DRC framework.

Earlier work in DRC was heavily influenced by the model-based design paradigm and the disturbance estimation is limited to that of external disturbance. The trend has taken an interesting turn in recent years, in parallel to the evolution of ADRC. Perhaps emboldened by Han's conceptualization of total disturbance, researchers began to treat the dynamics of the plant as something not to be modeled, but to be rejected like a disturbance, thus making control system performance independent to the plant dynamics to some extent. For example, the recent work on model-free control (MFC) [93] uses an algebraic method to compute and cancel the total disturbance. Another example is the adoption of ESO in the form of extended high-gain observer [73], where the design principle of ESO is supported by rigorous mathematical analysis. A generalized PI observer (GPI), based on ESO, was proposed to estimate multiple extended states [75]. A different kind of disturbance estimator, also capable of estimating unmodeled dynamics, is proposed in [92].

The unified framework of DRC as shown in Figure 1 can also help us better understand the work in the past and use its full potential. Early researchers might not realize that some methods of estimating the external disturbance, such as the one in [81], can actually estimate the internal disturbances as well, as shown more recently in [97]. It is such power of connection that will unite an otherwise scattered field of disturbance rejection control. It also provides a reference point by which the basic concepts of control theory can be reexamined and reintegrated with our renewed understanding of the science of control.

V. SUMMARY

When it comes to control system design, the practitioners, such as those in the field of robotics and motion, may have a dilemma: on the one hand they need a solution that is simple, powerful, robust, and easy to tune; on the other hand, such solutions are nowhere to be found, given the complexity and uncertainty in system dynamics and the limitations of control theory. In many occasions they rely on their ingenuity and intimate knowledge of the machine to come up with novel and powerful solutions. But, frequently pressed by deadlines, they often resort to the default solution of PID and the trial-and-error method of tuning. There is, however, an alternative: active disturbance rejection control (ADRC), an emerging technology that has found its way into motion control DSP chips and process control PLCs. What might be more intriguing is the deep rooted idea behind ADRC that took centuries to germinate and grow. In a presentation that is both historical and philosophical, the evolution of this idea is on a vivid display in this paper, leading to a new paradigm to guide our practical and theoretical investigations. Here is a transformative idea that has traveled between the East and the West, spanning centuries if not millenniums. It challenges the principles and the premises that have been taken for granted in the field of automatic control since its inception.

We begin with the notion of disturbance rejection control, a distinctly different platform for which ADRC, as a technology, is but a natural outcome and illustrative example. Tracking and regulating (disturbance rejection) are naturally decoupled when disturbance, more broadly defined to include unmodeled dynamics, is estimated and cancelled, thus making the controller design almost trivial. This gives us a solution just as ordered: simple, effective, robust, and easy to tune, with special appeals to the fields like robotics where a detailed, fully authenticated model is both out of reach and, as it is turned out, unnecessary.

Control design, in theory, revolves around the mathematical model; in practice it is dominated by PID. ADRC proves to be a viable alternative to both. In theory, with complications from the uncertain dynamics and external disturbances effectively removed via disturbance rejection, the physical process is forced to behave like an ideal model for which the controller is predetermined and easily tuned. In practice, ADRC competes with and surpasses PID as a generic solution that takes user a matter of minutes to tune and commission, in addition to the gains in performance and energy savings. The simplicity and effectiveness of ADRC technology is the testament to the power of the idea.

In addition to the short term gains from the new technology, the great challenge in further development of ADRC across all industry sectors is for the users to reconcile the idea of ADRC with the knowledge of control theory and process dynamics so that they can find creative, tailor-made solutions for specific engineering problems. To facilitate such integration is the main aim of this paper. The case of ADRC as an emerging technology can be made with diagrams, equations, examples, and explications of its characteristics; the case of ADRC as a new paradigm for the science of control requires a good deal more efforts to make: reliving the history of clashing ideas in automatic control, revisiting how the existing paradigm came into being, and reexamining the basic problem, the rudimentary concepts, and the fundamental design principles at the foundation of control science. In doing so, we hope, the theory of automatic control will once again empower the practice with creativity and productivity.

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