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On the centrality of disturbance rejection in automatic control

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ABSTRACT

In this paper, it is shown that the problem of automatic control is, in essence, that of disturbance rejection, with the notion of disturbance generalized to symbolize the uncertainties, both internal and external to the plant. A novel, unifying concept of disturbance rejector is proposed to compliment the traditional notion of controller. The new controller–rejector pair is shown to be a powerful organizing principle in the realm of automatic control, leading to a Copernican moment where the model-centric design philosophy is replaced by the one that is control–centric in the following sense: the controller is designed for a canonical model and is fixed; the difference between the plant and the canonical model is deemed as disturbance and rejected.

1. The problem of disturbance

Disturbance, as defined in the Oxford Dictionary of English, is "the interruption of a settled and peaceful condition". If engineering is understood as the process of creating an apparatus to serve the human needs, the "settled and peaceful condition" of such an apparatus is the primary concern and the subject of study in the field of automatic control. For example, the apparatus of obtaining mechanical power from steam long preceded the device of automatic control, i.e. the flyball governor that ensures the "peaceful and settled condition" of a constant engine speed, not interrupted by various changes in the operating condition.

There are two distinct areas of study here: (1) the invention of the apparatus to meet the human needs; and (2) the problem of keeping such an apparatus operating in "the settled and peaceful condition", i.e. the problem of automatic control. This paper is concerned with the latter in a way most general and encompassing. By definition, it appears that the *problem of automatic control* in various domains of applications is reducible, in essence, to the *problem of disturbance*. Understanding automatic control in this manner may give us a refreshingly new outlook and deep insight into the nature of the discipline, beyond its tradition of mathematical rigor. In a way, the strength of a control system is not different from that of a human mind: when disturbed by an adversity, how severely is it interrupted and how fast does it return to a "peaceful condition"? Similarly in industrial processes, the quality of a control loop is measured by how tough it handles the adversities, i.e. the changes in dynamics, the interferences of unknown forces, etc., collectively known as uncertainties. In this paper, the notion of "*disturbance*" is taken in the most general sense to denote those uncertainties that tend to *disrupt* the working of an apparatus or an organism.

Understood as such, disturbance is what tends to interrupt a nominal course of actions, whether it is a machine or an organism. The problem of disturbance is a problem not just in engineering, but life in general. It is the nature of the interaction between any organism and its environment, and it matters, in terms of survival. It is for this reason that a humanistic approach is taken in this paper, following the trails of ideas and inventions throughout the history of automatic control, the exposition of which will lead to a more comprehensive understanding of the conceptual framework, premises, methodology, and the domains of applications. The end goal is to make the integration seamless between the universal concepts, methods, and solutions of automatic control on one hand, and the idiosyncrasies of particular domains of engineering on the other hand. It is through such integration that practitioners will be able to take advantage of various disturbance rejection techniques freely in solving the pressing problems of today. The need for doing so was articulated some 40 years ago but still rings true today:

> "Many scientists are busily at work in laboratories and universities, searching for more advanced control concepts. The principles they are discovering, however, could never realize

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their full worth if they are not communicated to the people who must apply them. Control problems arise in the plant must be solved in the plant. Until plant engineers and control designers are able to communicate with each other, their mutual problems await solution." [1]

The questions remain: (1) is there an advance control concept that worth sharing? (2) If so, how can it be communicated to "the people who must apply them"?

Our thesis is therefore quite straightforward: the mutual problem of plant engineers and control designers, which has awaited solution, is the problem of disturbance and it should be the focus of the study in automatic control, the foundation of which begins with the very notion of disturbance, to which we now turn.

2. The evolving notion of disturbance

Like any branch of science, the current generation of researchers in automatic control inherited a particular point of view, an implicit paradigm and an assumed value judgment from the previous generations, the protégés of which continue to shape this discipline from their positions in academia. In the true spirit of science, all points of view, including and especially, the ones that have been dominant, must be continuously reflected upon and judged for relevance and validity. All theories must be scrutinized and verified in practice; cherry picking of evidence to support a particular view, while unavoidable, must be discouraged. "We must be mindful of foundation", as Prof. Astrom recently advised, or "the building might fall" [2]. Our understanding must be absolutely clear concerning the basic concepts, such as the meaning of *disturbance* or *rejection*, before a solid foundation of automatic control is built.

Specifically, disturbance rejection is a ubiquitous term used in control theory and it is one of the many design considerations in textbook techniques from loop-shaping to H_∞. It has essentially become an academic jargon and is used freely without a second thought. In reality, the word "*disturbance*" takes on different meanings as it is used in various contexts, often unknowingly. It often refers to a disruption coming from an external force, as, for example, wind gust acting on an airplane; in some other cases, however, it may not be entirely clear whether the disruption is coming from within or without. People seldom, if ever, ask "what do you mean by disturbance?" or "in what sense a disturbance is said to be *rejected*?"

Going back to the Oxford Dictionary of English again, the word "*disturb*" means "interfere with the normal arrangement or functioning of", from which "*disturbance*" is inferred to as something abnormal, not part of the original plan, but tends to disrupt it. It is used synonymously with *uncertainty* an automatic control system is designed to deal with. "If there is no uncertainty in the system, the control, or the environment, feedback control is largely unnecessary" [3], said renowned control theorist R. Brockett. If one is only concerned with the type of the uncertainties that tend to "interfere with the normal arrangement or functioning of", then the problem of uncertainty is no different from the problem of disturbance and will be denoted so in this paper for the sake of simplicity and clarity.

As in any human endeavor, a lot of what is being done stems from habits, consciously or otherwise. It is a habit that the problem associated with the uncertainties internal (external) to a physical system is denoted as the robustness (disturbance) problem. In fact, such robustness problem has become a dominant theme in modern control theory and the topic of endless books and papers; the disturbance problem, on the other hand, is narrowly defined and is treated without much fanfare. The real world, however, does not draw a line to separate internal uncertainty from the external one. In a robot manipulator, for example, what would one call the problem caused by the coupling among various joints? To each joint the disturbance coming from other joints are external but to the robot as a whole all joints are internal.

Treating the coupling among joints in a robot manipulator as robustness problem presupposes the detailed mathematical model of it, which could be quite nonlinear and complex. This practical hindrance led researchers to a shortcut: to each joint, the coupling force from other joints can be estimated in real time and canceled, resulting in a much simpler and more effective solution called disturbance observer (DOB) [4]. But by habit, the notion of disturbance used in the framework of DOB distinctly refers to something external, even though the solution equally applies to disturbances that are state dependent, thus creating an awkwardness in articulating exactly what kind of uncertainties with which the method deals.

This conceptual ambiguity was resolved once for all by Han in his landmark paper of 1989, which for the first time put forward the idea that, for the purpose of controlling a physical process, linear or nonlinear, having a complete mathematical model is both impractical and unnecessary [5]. Physical system, Han believes, can be controlled without a mathematical model because the information it needs can be extracted from the input–output information. Han went on to open a new front of automatic control and spent the next two decades cultivating it [6–8]. This new area of research is known as active disturbance rejection control (ADRC), with the "disturbance" referring to both internal (state dependent) and external forces that are unknown.

The work of Han demonstrates that many boundaries in control theory are artificial, reflecting not the nature of automatic control but our limitations in comprehending it. Such boundaries include those that divide the systems as linear and nonlinear controls, internal dynamic uncertainty and external disturbance, time varying and time invariance, etc. In fact, all these problems can be seen as one and the same: the problem of disturbance, if the word "disturbance" is allowed to take on the more general meaning described above. Perhaps the most unique contribution from Han's work is his notion of disturbance, which includes uncertainties both internal and external to the physical process [6–8]. A more detailed account will be given later in this paper.

Taking it one step further, the term *disturbance* can now be used to denote the difference between what the system is and what it is should be, whether this difference belongs to the internal or external uncertainties. But "*what it should be*" seems problem dependent, vague and fleeting; it seems tied to the particular system of interests, not easily describable as a universal concept.

With a penetrating insight, Han gave answer to this puzzle in 1979 by showing that under reasonable conditions, all linear and nonlinear systems can be reduced to the cascade integral form that he termed "canonical form of feedback systems" [9], which is denoted in this paper, for the sake of convenience, as Form Han (FH). In other words, most systems, linear or nonlinear, with state feedback, can be transformed into FH, based on which control design can be standardized. Therefore, FH becomes the point of departure for all design methods because various types of physical systems, once they are reduced to FH, are identical dynamically and can be controlled by a standard, fixed controller.

Note that FH anticipates much of the later, more complete, work on generalized control canonical form for linear and nonlinear systems by M. Fliess and others. See [22] for details and references therein. In particular, Han discussed in [9] the problem of transforming a general nonlinear system to the control canonical form by the use of input-dependent state transformation, to which Fliess gave a rather expanded account a decade later [22].

Han also gives us an alternative answer to the above question of "what an ideal plant should be". Using FH as the ideal plant,