Fuzzy Control as a Disruptive Technology

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It is worth elaborating a bit on the fundamental assumption that fuzzy control underperforms conventional control, yet is used increasingly in applications. After viewing the debate tape (the tape is available from the IEEE History Center, http://www.ieee.org/history_center/, for a nominal fee) several times, I can assert that this assumption is consistent with what both Professors Athans and Zadeh had to say; that is, while some may object to the assumption that for every fuzzy controller there is a conventional controller that can outperform it, Zadeh never directly contradicted such assertions by Athans. Likewise, while some may claim that fuzzy control's successful application in products has been largely overstated, Athans never directly contradicted assertions to that effect by Zadeh.

For ease of visualization, I will use an analogy Athans generated to make his final points. Presenting a slide in which he used a Ferrari to represent conventional control and a donkey to represent fuzzy control (see the debate report), he described the notion of fuzzy control as follows: If the Ferrari was going down the highway and one had this little donkey get out and push, the Ferrari would go faster. His point is well taken; however, his use of the analogy completely ignores the reasons why one might want a donkey. The donkey is useless on the highway but quite helpful when one drives off the road—to pull the Ferrari out of a ditch. Furthermore, on a dirt path, it may make no sense to use a Ferrari when a donkey would suffice. In controls parlance, driving into the ditch would be akin to those times when our modeling ability breaks down and we have to add some heuristics. The dirt path could be those toy class problems where the sophistication of the feedback law is not nearly as important as the fact that feedback has been added to the system.

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Given that there seems to be no strong argument against the statement that for a given problem, conventional control can outperform fuzzy control, why is it that fuzzy control algorithms are going into so many applications? This apparent contradiction was resolved for me by a talk on disruptive technologies given at HP Labs by Professor Clayton Christensen of the Harvard Business School. Christensen's talk was based on his research, summarized in a book titled *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* [2]. I believe that the model he presents explains why, despite its apparent flaws, fuzzy control is flourishing in the applications arena.

To explain this properly, let's first look at Christensen's model of a disruptive technology versus that of a sustaining technology [2]:

Most new technologies foster improved product performance. I call these sustaining technologies. Some sustaining technologies can be discontinuous or radical in character, while others are of an incremental nature. What all sustaining technologies have in common is that they improve the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued. Most technological advances in a given industry are sustaining in character. An important finding revealed in this book...
is that rarely have even the most radically difficult sustaining technologies precipitated the failure of leading firms.

Occasionally, however, disruptive technologies emerge: technologies that result in worse product performance, at least in the near-term. Ironically, in each of the instances studied in this book, it was disruptive technology that precipitated the leading firms' failure. Disruptive technologies bring to market a very different value proposition than had been available previously. Generally, disruptive technologies underperform established products in mainstream markets. But they have other features that a few fringe (and generally new) customers value. Products based on disruptive technologies are typically cheaper, simpler, smaller, and frequently, more convenient to use (p. xv).

Does any of this sound familiar? It should. If we take Athans's well-studied attack on fuzzy control at face value and assume that on any highway his Ferrari will whip the donkey, why is it that so many people are buying donkeys? Perhaps it is that in very human time constants, we cannot often tell the difference between a donkey solution and a Ferrari solution, so we buy the one that is cheaper and can go more places (the donkey).

In every example Christensen gives in his book (personal computers versus minicomputers, transistors versus tubes, etc.), the new disruptive technology underperformed the existing technology and was thought to have little use. However, some firms saw that they could open up new markets with the cheaper technologies and eventually overtake the existing technologies in the traditional markets. This ability to overtake traditional technologies was based on the common phenomenon that engineers can improve technology at a more rapid pace than the user can make use of it, as shown in Fig. 1, which is reproduced with permission from The Innovator's Dilemma, p. xvi [2]. Because of this, the underperforming technology eventually catches the curve for what the user needs without ever having to catch the curve for the original technology. Furthermore, because the disruptive technology has some advantage in the market (typically it is cheaper), it is the one that gets chosen. A Ferrari is a beautiful machine, but many more people buy Toyotas. This is the simple class of problems Athans referred to as toy class problems, and while these are quite trivial compared to most classical control problems, they open up a whole new set of applications for feedback loops. The fact that some technical performance metric could have been improved another 10-20% by some optimized controller rarely plays into the consumer's calculation for two reasons:

- First, the incremental improvement is small compared to the fundamental improvement of adding feedback. Thus, the product makers may see little use in reworking their new designs.
- Second, and perhaps more important, conventional control engineers have rarely entered into these toy class problems and thus have left the field uncontested for the fuzzy control engineers.

For example, who in their right mind would design an LQG controller for a vacuum cleaner or a washing machine? No one. However, both of these applications have benefited from the inclusion of simple feedback, implemented as fuzzy control. For such simple control problems, the dynamics are trivial. In such cases, it is quite obvious that simple rule-based control is enough to improve the performance of this dynamically simple yet highly useful product.

Thus, although there are still plenty of markets for conventional high-performance control, it is those who put feedback loops on all sorts of consumer products that will increasingly own the market for control applications. This, in turn, will be where the research gets funded. If one accepts the view of fuzzy control as an underperforming solution that opens up different applications for feedback control, one must call it a disruptive technology. If that is the case, it will eventually outpace conventional control in the marketplace, not by being a higher end technology, but by being a lower end technology. (If 20 years ago I had stated that personal computers would drive minicomputers out of business, people would have said I was crazy.)

Looking back at Fig. 1, we see that it is some set of sustaining technologies that allows a disruptive technology to displace the conventional technology in the market. But, one might ask, what set of technologies would allow fuzzy control to displace conventional control in more applications? Perhaps fuzzy logic opens up the world of control to a set of engineers whose primary training is in programming. Obviously, this can have its advantages, but for a large set of relatively benign applications, these might be the people chosen to implement feedback. Perhaps the if–then–else rule-based structure allows a more natural way to address some discrete event dynamic system controllers, as speculated by Professor Gene Franklin. As Zadeh says, “Time will tell.”

My own understanding is that although it is hard to predict the future, a look at the past indicates that inexpensive sensors and computation have been key to allowing fuzzy control to enter many markets. (It is ridiculous to put a $1000 optical sensor on a consumer washing machine.) Micromachining, one of the key trends in

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**Fig. 1.** The impact of sustaining and disruptive technological change.
technology today, will enable large numbers of inexpensive sensors and actuators in the near future.

As micromachining makes cheap sensors more pervasive, the entire structure of control problems may change. In combination with cheap computation, the day is not far off when it will be entirely practical (for many applications) to assign a sensor to every significant energy storage state of a system. When that happens, the control problem decreases considerably. LQG becomes LQR, a highly robust algorithm. Much of the sophisticated machinery may have far less applicability in such a world. Many sophisticated control problems may be reduced to toy class problems.

(I am old enough to have written programs both on early versions of personal computer operating systems and on mainframes. In the mid-1980s, PCs were considered toy machines by many people. The operating system (OS) itself had none of the sophistication of mainframe or minicomputer operating systems. It was clear from any interaction with the system that any design that had been done on the OS was largely heuristic. However, as sustaining technologies have made PCs more powerful and the needs for operating systems have increased, the design methods used have come full circle. While some may question the efficacy of the latest PC operating systems, the designs are clearly far closer to the sophistication of mainframe operating systems than to those that ran on the old PCs.)

Some may say that this is cheating, that it redefines the control problem, fundamentally changing it [1]. Although this is true from a control theory perspective, from a systems view, one cares less about the theory used than about a product’s performance and cost. Thus, if redesigning the system to trivialize the control design problem produces a better product, that is the path to choose.

The control algorithms that take advantage of such improvements need not be fuzzy. However, currently it seems that the practitioners of fuzzy control are the ones looking for such shortcuts in control problems and opening up new markets for feedback systems. Thus, after all this time, this debate has crystallized my belief that those of us who practice “conventional control” have three choices:

- Continue to pound away at fuzzy control’s substandard performance for any “real” control problem and ignore the new markets they are creating for feedback.
- Blindly follow the crowd into fuzzy control, abandoning all we know about conventional control.
- Begin to explore the application of control (whether fuzzy or conventional) to the new market areas that the fuzzy control folks have opened up for us.

I believe the first choice is analogous to sticking with mainframe computing. Just as there will always be a niche for mainframes, there will always be a place for high-performance control systems. However, if feedback loops for consumer systems become prevalent in the market, these high-performance systems will increasingly be thought of as niche products.

The second choice is quick and easy but has long-term peril if we abandon everything we know about dynamic systems. In fact, as feedback loops on consumer products become more prevalent, they will be applied to systems with more complicated dynamics. It will be the knowledge and discipline of conventional control that help ensure the functionality and safety of these consumer products.

I wish to suggest that the future of control lies along the third path—that there are many new applications crying for some decent feedback. I do not believe there is a real barrier to entry for conventional control in consumer products. All that is required is the will to do it. However, to repeat a point made earlier, if conventional control engineers do not apply their skills to these low-end problems, the vast majority of the money will be made by those who do.

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References