For submission to the IEEE
Control Systems Magazine (June, 1999).

Some Crisp Thoughts on the Fuzzy versus Conventional Control Debate

Daniel Y. Abramovitch
Hewlett-Packard Laboratories
1501 Page Mill Road, M/S 4U-12
Palo Alto, CA 94304 USA
E-mail: danny@hpl.hp.com

1 Introduction

I admit it. I haven't looked at fuzzy control in over 4 years. It wasn't always that way. About 6 years ago I was starting on a new disk drive project where analyzing and compensating for actuator pivot friction would be a major contribution [1, 2]. Not certain of what technology would help, I noticed a lot of press about fuzzy logic and fuzzy control. I then struggled for months to get a clear understanding – to get a straightforward explanation – of how fuzzy logic and fuzzy control actually worked. Eventually, a series of events and discussions led to a series of notes and these notes when not shot down became the basis for a paper [3] entitled, "Some Crisp Thoughts on Fuzzy Logic". Probably the least technical and most widely read document I have ever produced (available on the web at http://www.hpl.hp.com/personal/Danny_Abramovitch/pubs/), it made a good case to my managers for my not pursuing any more work on fuzzy control. However, I still had a passing interest in the field and so when Dr. Linda Bushnell, chair of the CSS History Committee, suggested a at the 1998 CDC debate between Professors Lotfi Zadeh and Michael Athans on fuzzy versus conventional control, I set about to make certain that I could attend. As part of the History Committee, I was in a good position to be a slightly educated "fly on the wall" for this event. What follows is this fly's impression of what transpired, what was said and what it addressed. Also, as the debate and its aftermath triggered some new understanding for me, I will try to pass these along.

There were 3 portions of the debate that I was privileged to attend: the dinner beforehand, some videotaped interviews, and the debate itself. The dinner was held Tuesday evening. We requested the interviews with Professors Athans and Zadeh at the end of this and conducted these Wednesday morning. Professor Gene Franklin generously agreed on short notice to be our interviewer. The debate was then held on Thursday morning.

This report will proceed as follows: Section 2 will discuss the pre-debate activities. Section 3 will give a report on the debate itself. From there, I will switch from a reporter's voice to that of an editorial writer. Section 4 will give some brief analysis of what was said by the proponents. Section 5 will offer a possible view that explains the paradox of the success of fuzzy control and some somewhat surprising (at least to me) predictions for the future.

2 Pre-Debate Activities

Several interesting things became apparent during the dinner and the interviews. First of all, Athans and Zadeh are close friends. Lotfi Zadeh was on Mike Athans' thesis committee at UC Berkeley. He actually helped get Athans into the optimal control field by translating Pontryagin's papers from Russian for the Berkeley control crowd. Furthermore, he introduced Professor Athans to his (Athans') wife, Rita Almeida Ribeiro, now a professor in the Computer Science Department at the University of Nova Lisboa in Portugal, who does fuzzy linear programming for decision support systems. (At that time she was doing a postdoc with Zadeh.)

More relevant to the debate was the posturing of the participants like armies maneuvering for position before a battle. (As Sun Tzu [4] says, the battle is won before the armies take the field.[1]) Thus, the maneuvering took the form of trying to cast the scope of the debate. Professor Athans tack was clearly to keep the debate narrow to one of conventional versus fuzzy control for problems in which either one is applicable. Professor Zadeh, on the other

[1] Therefore the skilful [sic] commander takes up a position in which he cannot be defeated and misses no opportunity to master his enemy.

Thus a victorious army wins its victories before seeking battle; an army destined to defeat fights in the hope of winning.

hand, was clearly interested in broadening the debate to include task control – areas that tend to require rule based control. While the discussion was very courteous, the intent was obvious: to choose the playing field that would favor their side of the debate. An interesting result of this was the realization that Zadeh was already choosing not to contest a key point that I expected Athans to hammer away at: for any standard control problem, one could always outperform fuzzy control using conventional – albeit quite sophisticated – control. Zadeh instead was going to try to focus the debate to areas that are hard to model and quantify, for which heuristics play a key role. In that area, he clearly was hoping to convince people that fuzzy control provided a means of integrating rule based control with conventional methods.

Also finalized was the debate format. It was to contain 15 minute opening statements by each of the participants. This was to be followed by a question and answer session where a panel member would ask a question to one of the participants and they would have two minutes to answer. The other participant would then have one minute to rebut. As this would take a minimum of 3-4 minutes per question and as there were 4 panelists, it was determined that each panelist would get at least 1 but not more than 2 questions. The panelists had been chosen to have equal representation from the conventional control side (Karl Åstrom and Gene Franklin) and the fuzzy control side (Reza Langari and Demitre Filev). The participants would then have 3 minutes each to give closing statements. After dinner, the panelists met to go through their questions and make certain that a fair spread of questions would be asked. We also determined to start the session 15 minutes early at 8:15 am to allow a few more minutes for the debate.

The next morning we were able to interview Professors Zadeh and Athans and capture them on video tape. Professor Franklin agreed to serve as the interviewer after Tuesday's dinner and Linda Bushnell and I each made videotapes. Most fascinating about the interviews was the history that each of these people represented, and how the criss-crossing paths of careers and lives had had its effect on what we now simply think of as control theory. I mentioned earlier that it was Lotfi Zadeh who translated the Russian optimal control papers for his cohorts at Berkeley and that Athans happened to be a student there. He spoke Russian because he spent the first 10 years of his life in what is now known as Aizerbajan, at that time part of the Soviet Union. His father was a correspondent for an Iranian newspaper who had been posted there. (Imagine the ripple effect on modern control theory if Professor Zadeh's father had been posted elsewhere.) The interviews set a good backdrop for the debate, and these will be available on the same tape as the debate from the IEEE History Center for a small fee to cover the cost of reproducing and sending the tapes.

3 The Debate

The debate itself opened with the general welcome and introductions by Professor Douglas Birdwell, the General Chair of the 1998 CDC, followed by opening statements from Athans and then Zadeh. It was obvious that Athans had come quite prepared to tackle the specific question of whether fuzzy control could outperform conventional control in well known control problems. He had clearly done his homework and made the case very strongly that in the end, most of these problems could be solved with much better results from a conventional control perspective. He broke down fuzzy control into two categories:

- 1st Generation (Momdani): Rule based feedback control with the rules being interpolated by fuzzy sets and
- 2nd Generation (Takagi-Sugeno): Fuzzy augmentation of crisp control laws.

In the first generation systems he claimed that this was only really good for toy class problems. Furthermore, he said that since there was no inherent explicit model used to derive the rules, it was hard to say much about the performance or stability of the system. He also noted that this first set of fuzzy rules based controllers implement a human's control law and therefor have a built in assumption that the human is a good controller. He said that if that was the case, control theory never would have been developed. It is precisely because the human is a poor controller in many situations that we need control theory. Because of this, he claimed that fuzzy control is bad for high performance feedback control problems.

The second generation, he claimed, was oriented around overcoming such objections and focused on using fuzzy logic to "interpolate" between several good conventional control designs, and then find a Lyapunov function for the whole system. He claimed that this was ad-hoc at best, performed poorly, and in fact could be outdone by most gain scheduling methods. During his closing remarks his final point was brought home with an analogy where he showed a drawing of a Ferrari and next to it he had a drawing of a donkey. He asserted that fuzzy augmentation of conventional control was akin to having this Ferrari (conventional control) speeding down the highway and claiming that by having the donkey (fuzzy control) get out and push, the Ferrari will go slightly faster.

One of his main objections to fuzzy control was that it did not use fuzzy logic's method of capturing uncertainty (which he liked). In fact, he said that he often found it hard to find the connection between fuzzy control and the principles of fuzzy logic as developed by Lotfi Zadeh.

Next came the opening statement by Professor Zadeh. He said that Professor Athans painted quite a picture, but he could not recognize fuzzy control in that picture; that the picture was not connected with reality. He immediately noted the large number of books on fuzzy control, including the recent one by Passino and Yurkovich [5], and stated that if the audience members took it upon themselves to read these books, they would see that many of the issues that Professor Athans had brought up were taken care of. He then stated that he wanted to take a broader view. He asked the question, "What is fuzzy control?" and then produced a slide which listed a series of papers that he and others had written over the years, starting with his 1965 paper introducing the concept of fuzzy sets [6] and ending with the Mamdani and Assilian paper [7] that is considered the first true fuzzy control paper. He said that the principle concepts in all of his early papers were *linguistic variables* and *fuzzy if-then rules*, and that the "seminal" paper by Mamdani and Assilian applied these concepts to the control problem.

Crisp Control	**Fuzzy Control**
differential equation based	rule based
start with system equations, goals, & constraints	start with human solution
provides certain tools	*adds to* those tools

Table 1: Professor Zadeh's delineation of fuzzy versus conventional control.

He sought to draw distinctions between crisp control and fuzzy control, which are reproduced in Table 1. He emphasized that fuzzy logic compressed data by using linguistic variables and that this is what humans do so well. He said that fuzzy control accepted the fact that a solution may not work always for every situation, but was happy with a solution that worked many, many times. He drew a parallel to the computer science paradigm where there are many practical and useful solutions that are understood not to work all the time in every situation.

He showed a sanitized quote from Rudy Kalman which viciously opposed the concepts of fuzzy logic. He said that he and Kalman had been riding on the same train for a while, that he (Zadeh) had gotten off, but that Kalman was still on that train. He said that many others were still on that train.

He then spoke about all the applications that were being completed using fuzzy logic and gave a count, based on an Internet search, of the growing number of papers that are based on fuzzy control. He posed the question to the audience, "Do you really think that all these people are stupid? Do you think they do not know what they are talking about?" which he then answered with a, "No I think not."

He was at his strongest when he pointed out that control systems people really need to get away from thinking about what he called "set point control" and get more into the "task control" of replacing human functions. He ventured into dubious territory from there, though, when he used driving a car as an example of task control and claimed that humans drive a car "with no measurements and no computation". He strongly stressed that fuzzy control is not a replacement for but an *addition to* conventional control.

The question and answer period followed with the fuzzy control panel members asking questions of Professor Athans and the conventional control panel members asking questions of Professor Zadeh. As time remained, Professors Zadeh and Athans each fielded one more question. I will give a synopsis/paraphrasing of the questions and the answers below. As I am "compressing data" using "linguistic variables", there may be some loss of the original meaning. However, that's what the video tape available from the IEEE History Center (URL: http://www.ieee.org/history_center/) is for.

Professor Franklin for Professor Zadeh: In Professor Zadeh's talk and in many papers it seemed that fuzzy control was a methodology for implementing a control scheme when one already had a scheme in their head. Did this make it something of a programming language?

Professor Zadeh: Professor Zadeh replied that there was much more to fuzzy control than that. He said that one started with the fuzzy rules in their head and then used the "calculus of fuzzy if-then rules" to implement them. So he agreed that in that sense it was a bit like a programming language. However, there were many books and papers that show how the field was now moving towards automatic rule generation.

Professor Athans: (Laughed and then said:) "I agree with Gene." ... He did not see a normative, descriptive, process in existence (for fuzzy control design).

Doctor Filev for Professor Athans: He noted that many of the applications of fuzzy control were task control systems rather than set point control problems. What were his feelings about fuzzy control in this context?

Professor Athans: Professor Athans stated that generally, his remarks were limited to fuzzy feedback systems. His response seemed to be that as one moved closer to the man-machine interface, he

had less problem with fuzzy techniques. However, he thought that most of these applications threw away any sense of methodology in favor of a fuzzy interpretation.

Professor Zadeh: Professor Zadeh's response was to tell the audience to look at the statistics on the numbers of papers and books out there. Professor Athans looked at a small set of papers. He said the field was moving towards task oriented control. Classical feedback theory had little to say about this.

Professor Åstrom for Professor Zadeh: Professor Åstrom stated that while he had not read all the papers out there on fuzzy control he had read quite a few of them. In these papers there was something quite mysterious and that is the whole notion of *model free* control system design. Did Professor Zadeh really believe that one can develop effective control systems without any use of differential equations?

Professor Zadeh: Professor Zadeh emphasized that he did not regard fuzzy control as a replacement for classical control, but an addition to it. When Professor Åstrom requested a clarification on the model free assumption, Professor Zadeh said that there was no differential equation model, but instead a fuzzy model in the designer's head.

Professor Athans: Professor Athans agreed that there should be a mathematical model. He referred to the thousands of papers and applications as, "a waste of human effort". He had a problem with folks luring students into doing control by showing them some simple fuzzy feedback rules. He did not think that they were getting a good idea of what control was all about.

Professor Langari for Professor Athans: While admitting that many of the applications of fuzzy control are in low order, overdamped, process control applications, he asked Professor Athans if he would agree that fuzzy control methods provide a semantically transparent way for people to address control problems.

Professor Athans: His answer was largely, that maybe this is true for some simple problems, but how can this possibly be extended to large scale or multivariable systems? It all fell apart then. He said telling someone that if they know a few simple fuzzy rules that they know control design is analogous to teaching someone how to use a stethoscope and to take blood pressure and having them think that they were now a brain surgeon.

Professor Zadeh: Again, he took issue with Professor Athans trivializing all the books and papers on fuzzy control and implying that all those people are "stupid". He said that he believed that in the not-to-distant future fuzzy control would be a standard part of a controls curriculum.

Professor Franklin for Professor Athans: He said that everyone remembers the advent of optimal control in the form of the LQG controller and all the hype that surrounded that. Could Professor Athans compare and contrast the hype around LQG in the 1960s with the hype around fuzzy control in the 1990s?

(At this point, the room was laughing, since Professor Athans made his name in optimal control in the 1960s.)

Professor Athans: (After some hemming and hawing.) He thought that the hype for LQG was a necessary step. There were some problems with LQG at the beginning, those have been taken care of. He had a LQF slide (Linear Quadratic Fuzzy) where he said that while one can cast this problem, it is intractable. The difficulty was not philosophical, it was mechanical. There was no practical way to do it.

Professor Zadeh: Professor Zadeh said that he thought LQG and fuzzy control were two different beasts. He thought that LQG was a useful procedure in a very narrow set of problems while fuzzy control addresses a much wider set of problems. He predicted that fuzzy control would continue to grow and that more books, papers and applications would show up. (At this point, Professor Athans noted that "it grows like a plague", prompting a quick laugh and reply from Professor Zadeh.)

Professor Åstrom for Professor Zadeh: Professor Zadeh's paper count slide showed an exponential growth in the area of fuzzy control and things with an exponential growth tended to flatten out at some point. When did he see the growth in fuzzy control flattening out?

Professor Zadeh: He first noted his respect for Professor Åstrom, noting that he had always been fair. He then said that fuzzy control will continue to grow in importance. He said that its name may disappear, but it would move into the mainstream. This might take some time.

So much for the report on what transpired. This document now transitions from a reporter's view to an editorial. What follows are my own particular opinions on what was said (in Section 4) and my views on how fuzzy control will impact control applications (Section 5). The

opinions are my own, but I have made some effort to sanity check them before foisting them on the reading public.

4 Analysis and Opinions

I spoke with one of my friends after the debate and asked him what he thought. He responded, "They're both right," and started laughing. I think he made a good point and it was in line with what I perceived before the debate. Each was maneuvering to an area where the other could not oppose them in the debate, assuring that they could each "be right". Generally speaking, it seems that they were both able to choose their battlefield so that they could not be defeated.

However, as the debate wore on, some apparent fallacies started emerging. I think it is worth going into these. However, the comments are the subjective opinions of one individual and deserve to be treated as such.

4.1 Comments on Professor Zadeh's Talk

Professor Zadeh's presentation seemed to be a similar one to many that I have seen him give in the past few years. Essentially, it was to give a history of his interaction in the field, to play up all the successful applications of fuzzy logic and fuzzy control, to give a paper count showing that lots of folks were publishing work on fuzzy logic and fuzzy control, and to urge control systems people to think in terms of task oriented control and not just set point control. His strongest points seemed to be in emphasizing that fuzzy control is not a replacement for but an addition to conventional control and that linguistic variables offer a large amount of data compression. For the most part, it would be hard to argue with much of what he said, but there were 4 areas where I felt obliged to take exception.

4.1.1 There are a lot of books on fuzzy control out there. Read them and you will see that the problems Professor Athans talks about have all been addressed.

This seemed to be a common thread: that if we read all of the fuzzy literature, we would believe these problems to be addressed. However, I must submit that it is not the job of the audience to go out and convince ourselves. It is the job of the debaters to argue their points directly. Perhaps this can't be done on every item, but it should be done on at least a few. It seemed that more often than not, Professor Zadeh relied on the tactic of saying that some document was seminal and addressed some set of these issues. I would have preferred it if he had gone into the specific document in question and shown us exactly where it addressed one of Professor Athans' concerns. This he never did.

4.1.2 Proof by paper count is no proof.

Professor Zadeh made a big point of noting the growing number of papers published in the area of fuzzy logic and fuzzy control as if this constituted some sort of proof. As MIT Professor Robert Gallager, the previous day's plenary speaker, pointed out, the increasing number of papers in any area is no indication of an increase in the amount of knowledge in that area. In fact, all it indicates is that the density of knowledge per paper is going down. (Most eloquently, he summarized it as: "We are not in the information age. We are in the data age. The amount of information being produced is relatively constant, but we are being overrun with data.")

4.1.3 The repeated statements that humans drive and park cars without measurement or computation are obviously flawed.

To use one of Professor Zadeh's phrases, "obviously flawed" is the sanitized version. Obviously, humans make measurements using our eyes (position, velocity and acceleration), our hands (force sensing), and our guts (acceleration, jerk). Much of the decision making we do may be suboptimal, but some cognitive activity is going on. The form of the measurement and the computation may not match what is done in classical system theory, but this does not mean that measurement and computation are not going on.

I am not certain why Professor Zadeh would make such a statement, since he must know that it is false. The issue is not with Professor Zadeh, making such a statement before a group of trained control systems engineers who will immediately see through it. Rather it is the repetition or quoting of such statements to less seasoned audiences that can cause problems (or simply get extra research funds). I think that statements such as this hurt the case for fuzzy control, since they make the rest of the control community think that fuzzy control people either aren't thinking straight or are intentionally trying to deceive. Neither option looks very good to the technical community.

4.1.4 He claimed that "nobody is suggesting that conventional control be replaced by fuzzy control".

Of course, this neglects the fact that when I last looked at fuzzy control that is *exactly* what was being suggested by fuzzy proponents. Perhaps this validates some of what Professor Athans is saying in that such suggestions of replacing conventional control have disappeared.

4.2 Comments on Professor Athans' Talk

Professor Athans stuck to a good plan: stay only on the subject area of comparing fuzzy control to conventional control in areas where a conventional control solution already existed. By doing so, he was able to make the point that in any one of these areas, conventional control could outperform fuzzy control. He really stuck with the case that for high performance applications, the human is typically not a good controller and thus fuzzy control produces underperforming control systems.

This is hard to argue with. However, I do feel that he is missing a large point, and that is that many of the new areas where feedback can be applied are what he calls *toy problems*. In these applications, simply the addition of feedback yields tremendous benefits to the consumer of the product and thus these products are successful without being necessarily high performance. In other applications, replacing the human controller with an automatic controller that has a higher sample rate essentially improves the performance for the user. 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 importantly, conventional control engineers have rarely entered into these toy problems, and thus have left the field uncontested for the fuzzy control engineers.

4.2.1 The Ferrari with donkey analogy is largely correct

. . . in that there is very little help that the donkey can give the Ferrari when the Ferrari is on the highway. However, to stay with the analogy, this completely misses the reasons why you might want a donkey. You don't need one on the highway, you need it when you drive off the road – to help pull you out of the ditch. For example, fuzzy augmentation of conventional control is usually derived from the "intelligent control" area which tries to combine rule based control with numerical control. I interpret the fuzzy augmentation of conventional control as a carry along donkey, to help you maneuver between highways when there is no well defined road. In that sense then, the donkey can help quite a bit. Furthermore, in some environments, all you really need is a donkey, and it would be foolish to spend money on a Ferrari. More will be said about this notion in Section 5.

5 Fuzzy Control as a Disruptive Technology

Given that there seems to be a consensus 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 in a talk given at HP Labs by Clayton Christensen of the Harvard Business School on the subject of disruptive technologies. Professor Christensen's talk was based on his research, summarized in a book [8] entitled, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. I believe that the model that he presents explains why despite all the apparent flaws, fuzzy control is flourishing in the applications arena.

In order to properly explain this, I first need to go into Professor Christensen's model of a disruptive technology versus that of a sustaining technology.

> 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. (See [8], page xv.)

Does any of this sound familiar? It should. If we take Professor Athans' 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).

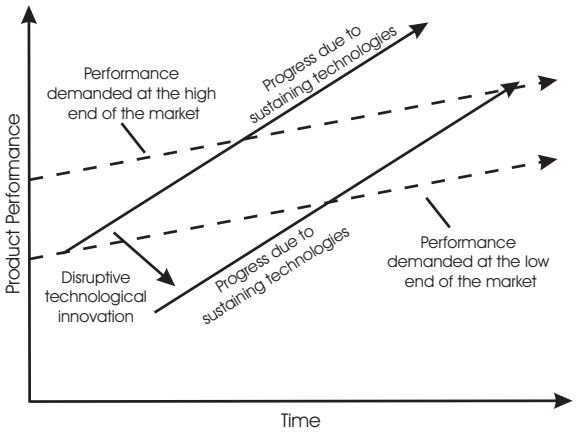

Figure 1: The Impact of Sustaining and Disruptive Technological Change.

In every example that Professor 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 the traditional technologies was based on the common phenomena that engineers can improve technology at a more rapid pace than the user can make use of it, as shown in Figure 1, reproduced with permission from *The Innovator's Dilemma* [8], page xvi. Because of this, eventually the underperforming technology 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 that Professor Athans referred to as *toy problems*, and while it is true that compared to most classical control problems these are quite trivial, it is also true that they open up a whole new set of applications for feedback loops.

For example, who in their right mind would design a LQG controller for a vacuum cleaner or a washing machine? Nobody. However, both of these applications have benefited from the application of simple feedback, implemented as fuzzy control. For such simple control problems, the dynamics are trivial.[2] In such cases, it is pretty obvious that simple rule based control is enough to improve the performance of this dynamically simple, yet highly useful product.

Thus, while there are still plenty of markets for conventional control applications, *it is the people 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, then 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 that I was nuts.)

Looking back at Figure 1 we see that it is some set of sustaining technologies that allow a disruptive technology to displace the conventional technology in the market. One might ask the question as to 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 whos primary training is in programming. Obviously, this can have its down sides, but for a large set 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 Franklin. As Professor Zadeh says, "Time will tell." My own understanding is that while it is hard to predict the future, a look at the past indicates that inexpensive sensors and computation have been key components allowing fuzzy control to enter many markets. (One cannot put a $1000 optical sensor on a consumer washing machine. It has to be cheap.) One of the key trends in technology today is micromachining which will enable large numbers of inexpensive sensors and actuators.

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 completely practical (for many applications) to assign a sensor to every significant energy storage state of a system. When that happens, the control problem reduces 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[3]. Some may say that this is cheat-

[2] I like to say they have the dynamics of a rock.

[3] I am old enough to have written programs on both early versions of personal computer operating systems and on mainframes.

ing, that this redefines the control problem, fundamentally changing it [3]. From a control theory perspective, this is true. However, 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, then this is the path to choose.

Nothing says that the control algorithms that take advantage of such improvements must be fuzzy. However, it seems that it currently is practitioners of fuzzy control who are looking for such shortcuts in control problems and opening up the new markets for feedback systems.

So 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 for feedback that they are creating;
- blindly follow the crowd into fuzzy control, abandoning all what we know about conventional control; or
- start 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 one that is quick and easy, but that has long term peril if we abandon everything that we know about dynamic systems. In fact, as feedback loops on consumer products become more and more prevalent, they will be applied to systems with more complicated dynamics. It will be the knowledge and discipline of conventional control that helps ensure that these consumer products function and are safe.

I wish to suggest that the future of control lies along the third path; that there are lots of new applications crying for some decent feedback. I do not believe that 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 the people who do.

Back in the mid 1980s, personal computers were considered toy machines by many people. The operating system itself had none of the sophistication of mainframe or minicomputer operating systems. It was pretty 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 have become more powerful and the needs for an operating system have increased, the design methods used have come full circle. While some may question the efficacy of the latest PC operating systems, it is very clear that the designs are far closer to the sophistication of mainframe operating systems than they are to those which ran on the old PCs.

6 Acknowledgements

I wish to thank Dr. Linda Bushnell, and Professors Gene Franklin, Reza Langari, and Michael Athans for some very helpful commentary and insights.

References

[1] D. Abramovitch, F. Wang, and G. Franklin, "Disk drive pivot nonlinearity modeling Part I: Frequency Domain," in *Proceedings of the 1994 American Control Conference*, (Baltimore, MD), pp. 2600–2603, AACC, IEEE, June 1994.

[2] F. Wang, T. Hurst, D. Abramovitch, and G. Franklin, "Disk drive pivot nonlinearity modeling Part II: Time Domain," in *Proceedings of the 1994 American Control Conference*, (Baltimore, MD), pp. 2604–2607, AACC, IEEE, June 1994.

[3] D. Y. Abramovitch, "Some crisp thoughts on fuzzy logic," in *Proceedings of the 1994 American Control Conference*, (Baltimore, MD), AACC, IEEE, June 1994.

[4] S. Tzu, *The Art of War: Translated and with an Introduction by Samuel B. Griffith*. London, Oxford, New York: Oxford University Press, 1971. ISBN 0-19-501476-6.

[5] K. M. Passino and S. Yurkovich, *Fuzzy Control*. Menlo Park, CA: Addison-Wesley Longman, Inc., 1998. ISBN 0-201-18074-X.

[6] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, pp. 338–353, 1965.

[7] E. Mamdani and S. Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller," *International Journal of Man-Machine Studies*, vol. 7, no. 1, pp. 1–13, 1975.

[8] C. M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston, MA: Harvard Business School Press, 1997. ISBN 0-87584-585-1.