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Some Crisp Thoughts on Fuzzy Logic

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Abstract– In the past year I have been inundated with articles on fuzzy logic as well as encouraged to use it for control systems. After reading some articles on fuzzy logic control, listening to a seminar by Zadeh, and attending a one day course on Intelligent Control, I started forming an opinion about how fuzzy logic control works. I believe that there are some fundamental pieces of information not provided in most fuzzy logic control papers. When one realizes what those pieces of information are, one gets a different opinion about how and when fuzzy logic control works and when it is more practical than conventional control. I will first state some opinions on fuzzy logic and try to justify them. Once this is done, I will return to some of the articles written by proponents of fuzzy logic and use the previous understanding to shed some light on what is really responsible for the improved system performance.

1. Introduction

Before the 1992 CDC (IEEE Conference on Decision and Control), I attended a short course on Intelligent Control[1]. A small section of the day was spent on explaining fuzzy logic control. While the instructor (an unabashed proponent of fuzzy logic) concentrated on an introduction to the fuzzy logic terminology and in explaining the many wonderful things that fuzzy logic control could accomplish, I sat there trying to understand (from a control systems perspective) what was actually going on. A few things that the instructor said tipped me off and I have now settled on my own understanding of how and when fuzzy logic control works. I have bounced these ideas off of a handful of servo engineers and a fuzzy logic proponent and nobody has yet to shoot large holes in this. While this does not prove my interpretations to be correct, it does give me some belief that these insights might be helpful to others.

First, I'll make a few statements about fuzzy logic control, then I'll try to explain why I think these are true.

1) Fuzzy logic control is more useful than its detractors claim.

2) Fuzzy logic control is less useful than its proponents claim.

3) ⇒ Fuzzy logic does not generate a control law. It maps an existing control law from one set of rules into a logic set. ⇐

4) Fuzzy logic control is most useful in "common sense" control situations, *i.e.,* ones where it might be difficult to write down the equations of motion, but a human would know how to control it. Examples of this are the "truck backer upper", car parking, train control, and helicopter control problems.

5) Fuzzy logic sets effectively quantize their input and output space. However, the quantization intervals are rarely uniform.

6) ⇒ In most fuzzy logic control success stories the sample rates are incredibly high relative to the dynamics of the system. Much of their success is because of this. ⇐

[1]As opposed to ... ?

2. Explanation

I'll start with (4) and finish with (3) and the top two should become apparent from the discussion.

Most of the examples I have ever seen of fuzzy logic control being successfully applied fall into the category of things that humans do well[1, 2, 3].

- In Japan, there is a train, the Sendai subway to be precise, which is controlled by fuzzy logic. The train pulls into the station within a few inches of its target. More accurate, but nevertheless replacing human control[3, 4].
- Also in Japan, there are experiments in controlling a small model helicopter (*Spectrum, July 1992*) via radio control. The helicopter can respond to commands such as take off and land, hover, forward, backwards, left and right[2].

  Proponents assert that a conventional control scheme would be incredibly hard to design because it would be really tough to model the helicopter dynamics. The "model free" nature of fuzzy logic control makes the problem trivial.

  This might not be completely false (at least from a practical application point of view) but it obscures some key facts:

  1) The model helicopter was designed so that a human operator with a joystick could control it, *i.e.,* it was *designed* to respond well to intuitive control rules. Because of this, the helicopter has been designed to be very *robust to imprecision*. (Robustness to imprecision is one of the features that many proponents claim fuzzy logic brings to the problem. It is possible that this feature is more a feature of the dynamic system than of fuzzy logic itself. In fact, Zadeh[2] points out that fuzzy logic takes advantage of a system's inherent robustness to imprecision rather than creating a robustness to imprecision[3]).
  2) The human operator has an implicit model in their mind of the input-output behavior of the helicopter. This is how they generate their control law for using the joystick.
  3) Fuzzy logic maps the human's control law and therefore is based on the human's implicit model of the helicopter. This in turn works because the helicopter was designed to be robust to human control actions.
  4) The human being's "bandwidth" is quite low. I don't know for sure, but I would guess that it would be less than 30 Hz and certainly less than 100 Hz. Furthermore, it is unlikely that a toy helicopter, a train, or a truck would respond to anything about 1 Hz and certainly not 10 Hz. While the sample rates are not listed in the *Spectrum* articles, I would guess that they are up in the 1 to 10 kHz range. (In fact, as I looked over a set of articles on fuzzy logic control, the mention of sample rates seemed conspicuously absent [1, 2, 3, 5, 6, 7]. Since it *must* be an issue in every digital control problem and since

[2]The creator of Fuzzy Logic.

any implementation of fuzzy logic control involves using some digital processor, the natural conclusion is that the sample rates are chosen so high above the system time constants that they seemingly stop being important.)

- The train control problem, as well as the car parking and truck backer upper problem are all described by (1-4) above. So I conclude that high sample rates are an inherent part of using fuzzy logic. The seemingly unimportant high sample rate may be precisely why the simple control rules work well. Like Mr. Spock's stocking cap[3] fast sampling covers a multitude of sins. Fast sampling does lead to a greater computational burden. However, the computational cost many be offset by being able to use a simpler control law.

Look in any fuzzy logic article and you will see a picture of membership functions for fuzzy sets [1, 2, 3, 5, 6, 7]. These sets effectively quantize the interval that they are on: they span the space so that any value on the line must fall into at least one of the sets. However, they do not behave quite like what we think of as quantizers since a particular value can be a member of more than one set. The sets are typically fairly coarse in terms of what we would consider effective quantization. Combinations of these coarse quantizers provide various fuzzy conditions. The coarse quantizations and simple rules may offset the higher sample rate requirement.

An example of producing high precision output with high bandwidth, low precision computation comes from oversampled $\Sigma - \Delta$ A/D and D/A converters. Go to look at a compact disc player at any stereo store and you will find many of the new ones advertising a 1-bit oversampled D/A converter which gives 16 or 20 bit accuracy. I don't fully understand $\Sigma - \Delta$ A/D and D/A conversion, but an article I dug up (*EDN, June 29, 1989*) describes it as

> ...a servo system that attempts to balance the duty cycle of a stream of pulse-coded bits against an analog input voltage.
>
> Delta modulators perform only one bit (an unweighted bit) of digital conversion per clock cycle out of the maximum 2^{n-1} possible count of an n-bit digital word. A delta modulator therefore requires 2^n clock cycles to complete a full-scale A/D conversion.[8]

Fortunately, because of their physical simplicity, an A/D or a D/A converter using Δ modulation can run much faster with less expense. So, for the same accuracy a $\Sigma - \Delta$ modulator A/D or D/A costs less. This is why $\Sigma - \Delta$ modulators are showing up in CD players.

If the analogy holds – and I have a strong belief that it does – then this could explain when fuzzy logic control will be useful. Like a RISC machine, it uses a simpler set of logic much more rapidly than conventional control (the CISC machine in this case). For problems designed to accept a simple (*i.e.* human) control scheme, fuzzy logic control works fine. In fact it improves on the human response because of its higher sample rates. However, for a problem where the sample rate is limited relative to the system bandwidth then fuzzy logic control would fail. By this I mean that in order to achieve the same performance as a "conventional" control system the quantization level and rule complexity would have to be raised to the point where a conventional controller would be far simpler.

So finally, I come to my assertion that fuzzy logic does not generate a control law, merely fuzzy logic maps a law from one form to another.

The simple rules for train control or truck backing up are not generated by fuzzy logic control. These are already present in the mind of the human operator. Fuzzy logic merely maps the intuitive rules into a computer program. In our class the instructor said that it has been "proven" that fuzzy logic can approximate any function to any accuracy. Fine, however, control design techniques that most engineers use *generate* functions rather than approximating them. Root locus, frequency response design using Bode plots, and state space design all generate control laws. These laws are typically based on a linear model, so they give back a linear control law. Fuzzy logic maps rules based on input-output relationships that may or may not be linear. However, one could map a linear control law using fuzzy logic, although it is not clear why one would try.

What seems to be the newest feature of fuzzy logic control is that because the borders are fuzzy, more than one logic state can be true to some degree. This allows for a smooth transition between one control action and another, since they can both go on but at different activation levels – what control engineers call gain. Quite often control systems have different operating regimes. Handling the transitions between these tends to be ad hoc. Things which are already ad hoc are perfect candidates for using fuzzy logic. Thus, fuzzy logic might be a good solution for smoothly switching a control system from one operating regime to another. In the transition, both control laws would be active, but their outputs would be scaled by the how much the system is in one regime or another. Of course, this means that both control laws would have to be run in parallel during the transition. Whether or not this takes up too much processor time for the sake of a smooth transition depends upon the DSP and sample rate, etc.

If what I have written makes sense so far, then it is pretty clear that fuzzy logic control has its limitations. Very few fuzzy logic proponents will admit this or even truly explain why fuzzy logic control works well when it does. (The latter part is more disturbing to me but is part of any overly hyped new technology.)

However, if you have bought the previous pages, then it is clear that fuzzy logic can be useful in quite a few more situations than its detractors would have you believe. Any application in which there is human "interaction" and "control rules" is a candidate. These are problems where the difference between good and bad is not binary. Quite often what constitutes acceptable performance in a servo system is such a problem. When we test the system's frequency response, we may know that a particular response is "good" or "bad", but the range between these can be quite large. How do we classify the systems in between? The concepts of fuzzy logic provide a clue. Another application might be in deciding when recalibration of an instrument or device is necessary. Many places where the system dynamics are substantially slower than the available sample rate are also candidates for fuzzy logic control. In each of these, however, the above understanding can be used to determine whether or not fuzzy logic simplifies or complicates the control design.

3. Reexamining the Evidence

Since I wrote the above section, a few things have happened which have strengthened my belief in its validity. First of all, I have passed the above text in front of every control engineer and fuzzy logic proponent I could get my hands on. None of them has found the fallacy in the argument. Secondly, an article written by Bob Pease entitled "What's All This Fuzzy Logic Stuff, Anyhow?" came out in *Electronic Design*[9]. In his article, he rails against the hype and empty claims being made by promoters of fuzzy logic. I sent him the above text and since then he has passed other articles on fuzzy logic and the draft of "What's All This Fuzzy Logic Stuff, Anyhow (Part II)?" to me[10].[4] I have realized that using the previous section as a framework, it is possible to explain away much of the hype in fuzzy logic articles and provide an explanation of when and why it is effective. Thus, the following section will examine some other fuzzy logic control papers and the claims made by

[3] In "The City on the Edge of Forever".

[4] Much of the following discussion was inspired by replies and elaborations I had to specific points Bob was making in the draft of "What's All This Fuzzy Logic Stuff, Anyhow (Part II)?" Again, I am using the previous section's understanding as my framework for these points.

their authors from the perspective of the previous section's understanding.[5]

The more articles I read about fuzzy logic control, the more I become convinced that there are several mentalities at work here. The reason for this is the wave of new interest in an old field. Suddenly, fuzzy logic has attracted much media attention as the key to productivity, better control systems, and saving the planet. All the same claims were once made for adaptive control. In the 1950s, adaptive control was the big hype, with "a lot of enthusiasm, bad hardware, and nonexisting theory."[11] The algorithm technologies which have followed as saviors of the planet include, among others, artificial intelligence, expert systems, and neural networks. Now it is fuzzy logic's turn.

A very possible model for what is going on is that there are several types of fuzzy logic proponents here. First, there are those (like Zadeh) who have labored in relative obscurity on this field for years. Typically, these are not people who are making any outrageous claims. They have done good work, expanded the field and will probably continue to do so for years to come. Next there are the people who may not have a deep theoretical understanding of fuzzy logic, but have actually used it in a few practical situations to do some good work. The video image stabilization scheme and the train control problem are both cases where people have done very nice practical work using fuzzy logic[4].

In between the mathematical world of the long term researchers and the practical world of those that would implement fuzzy logic control schemes there is a significant gap in understanding. This is where I believe that the hype has its best breeding ground. There are two types of individuals in this area: those that know why and when fuzzy logic control works but refuse to actually tell the world, and those that do not know but are blindly following the hype. The argument for not giving a concise explanation of a new technology is as follows: The physics of the underlying control problem does not go away, no matter how we reorganize the bits on the computer. How we affect the underlying problem is governed by the nature of the problem, what type of sensors and actuators we have, and how quickly we can apply them (sample-rate). If one makes a clear explanation of why and when fuzzy logic control works people in general – and the organizations that fund research in particular – will no longer be mystified by the topic. Once the magic disappears, then funding organizations will see the limitations of fuzzy logic control just as they see the limitations of every other type of control. This would make it harder to get large amounts research funds, and there is considerable pressure on young researchers out of graduate school to get research funds.

The latter group which does not understand what is going on often make the wildest claims. In retrospect, many of these claims tend to be the glassy eyed, "You don't have to know anything about the problem," type claims that seemed to follow every overhyped new technique. Adaptive control in the 1960s did this, as did robotics in the 70s and early 80s, AI, expert systems, chaos theory, neural nets, and now fuzzy logic. It reminds me of a discussion that occurred when I worked for a short while at a defense contractor. A bright young coworker came into my office. At that time (about five and a half years ago) , neural networks was the rage and many people were wondering, "How do we get in on this great new technology?" He had just been at a short course on neural networks, and was wondering what I (as someone with a controls background) thought of them. He had this glassy-eyed, "I have seen the prophet," look in his eye. When I was noncommittal, he pointed out that, "Well, its been *proven* that the network will *converge* and *solve* the Traveling Salesman Problem." To which I asked, "What converges? Do the tap weights converge? Does the solution converge? What converges?" The glassy eyes filled with panic as he mumbled something and left. He never talked to me about neural networks again. It was as if he had been admiring the Emperor's new clothes and I had asked, "What specific clothes are you referring to? I don't see any. What clothes?" I think much of the flocking to fuzzy logic without an understanding of why they work is the same thing. ("The Japanese have done amazing things!") Until Peases article[9] in the public eye, "What's All this Fuzzy Logic Stuff, Part I", and the notes I had distributed internally to HP I saw nobody willing to say that they thought the Emperor was naked.

A fundamental truth remains: The physics of the underlying problem does not go away, no matter how we reorganize the bits on the computer. Anybody who tells you something different is naive or lying.

3.1 The Model Free Assumption

Quite a lot has been said about the *model-free* nature of a fuzzy logic control system. The notion is that rather than trying to construct these complicated dynamic models for a system, the *"simple fuzzy rules"* allow the designer to design a control system. Of course this hides the notion that buried in those *"simple fuzzy rules"* is an implicit model of the system. I believe that no intelligent action is possible without a model. This concept crosses many fields. James Burke makes this point quite clearly in, "The Day the Universe Changed", (PBS Series and companion book):

> Science, therefore, for all the reasons above, is not what it appears to be. It is not objective and impartial, since every observation it makes of nature is impregnated with theory. Nature is so complex and so random that it can only be approached with a systematic tool that presupposes certain facts about it. Without such a pattern it would be impossible to find an answer to questions even as simple as 'What am I looking for?'[12]

Babies don't talk because they have no communication model. They can certainly exercise their voice boxes, but they have no input/output relationship between wanting to communicate and making specific sets of noises with their mouths. As they build up their model (i.e. their vocabulary) their communication skills go up. (The book *Cultural Literacy* has a more general schooling view of this[13].) Most gymnasts cannot play tennis. Why? Certainly they have the physical skills. Yet, they lack the model for how tennis is to be played. Their physical ability may allow them to pick up the game faster than a couch potato (interpret this as better sensors and actuators), but they still have to acquire the models for moving their feet and arms appropriately to hit the ball.

Any general behavior trend constitutes a model, whether explicit (e.g. dynamic systems model) or implicit (i.e. as encompassed in the fuzzy logic rules). In fact, the much maligned PID rules are typically based on a very loose model of the system: a rigid body mechanical system with reasonable sampling rates and not too many nonlinearities. This loose model, plus the fact that only the position is measured, accounts for much of the "lack of performance" of such a system. Improve the model, add extra sensors and you can get a kick-butt controller using PID because this comes much closer to being a full state feedback controller (at least for a rigid body mechanical system).

3.2 Sample Rates and Nyquist Criterion

Another general idea that seems to permeate the fuzzy logic control hype is the notion that someone with very little skill can design a controller using fuzzy logic, while using classical control takes years of training. In fact, one fuzzy logic proponent, Professor C. Vibet, made this claim and then went on to say that:

> In fact, the advantages and disadvantage of fuzzy systems result of the fact that fuzzy logic represents a decision making process. In control field, this provides a wide range of viable ways to solve naturally control problems while a basic knowledge about Nyquist criterion and lead-lag compensation networks is not needed.[*sic.*][14]

[5] This presumes some acceptance on the reader's part of the previous section.

Whether or not one allows someone with minimal skill to design a control system typically depends upon the consequences of the system's failure. (This is roughly analogous to trusting an 8 year old with a Super Soaker filled with water, but not with an Uzi. The consequences are considerably different.) There are probably quite a few systems for which one would have to design a really terrible controller to make something go wrong. However, a nuclear power plant or the space shuttle are not examples of such systems.

Coupled with this is the notion that one need not worry about sampling rates in general, or the Nyquist rate in particular. I have yet to see a single fuzzy logic paper where the sample rate has been listed. Every physical system has physics that govern its dynamics.[6] The physics of the underlying system does not change simply because we choose to use a different computer algorithm. Any time we use a digital computer (such as a DSP or fuzzy logic chip) to control a system, we are sampling the system response. The Nyquist rate fundamentally governs how fast we need to sample to do control. The use of fuzzy logic has not made this go away. You can use an ostrich approach to the Nyquist Sampling Theorem (i.e. stick your head in the sand and pretend it doesn't matter) but this is a recipe for disaster. (Of course, if the system is always sampling very fast relative to the time constants of the system then the Nyquist Rate can be ignored since the system is always complying anyway. However, that is a different kettle of fish.)

For virtually any sampled data control system (where the controller actually does something) and for any type of control algorithm, if you allow me to change only the sample rate I can make it fail by sampling too slowly. The performance of sampled data systems are inherently tied to some minimal sampling rate. No reorganization of bits on the computer will change this simple fact.

3.3 Extra Sensors

One of the themes that has pervaded my discussions with Bob Pease has been the notion of using extra sensors. The recent *Scientific American* paper by Kosko and Isaka[4] makes quite a few statements which attribute every bit of a system's improvement to fuzzy logic. I believe that these authors should know better and therefore have done a disservice to the field. Among other things they discuss both the train control problem and the fuzzy logic washing machines. In talking about the train control application they write:

> The most famous fuzzy application is the subway car controller used in Sendai, which has outperformed both human operators and conventional automated controllers. *Conventional controllers start or stop a train by reacting to position markers that show how far the vehicle is from a station.* Because the controllers are rigidly programmed, the ride may be jerky: the automated controller will apply the same brake pressure when a train is, say, 100 meters from a station, even if the train is going uphill or downhill.
>
> In the mid-1980s engineers from Hitachi used fuzzy rules to accelerate, slow and brake the subway trains more smoothly than could a deft human operator. The rules *encompassed a broad range of variables about the ongoing performance of the train, such as how frequently and by how much its speed changed and how close the actual speed was to the maximum speed.* In simulated tests the fuzzy controller beat an automated version on measures of riders' comfort, shortened riding times and even achieved a 10 percent reduction in the train's energy consumption.[4]

The italicized sections give away a key omission by the authors. The conventional controller only used position feedback. The fuzzy logic rules used more sensors including acceleration (how often the speed changed), velocity, and the position information. So it did better. In other words the designers of the fuzzy logic control system added a new DSP and some extra sensors and then claim to do better than the position feedback loop. Well, if you allow me to do conventional control with extra sensors and a better DSP then I too can do much better than the conventional controller that their fuzzy logic replaced.

Farther down, the authors mention fuzzy logic control of washing machines which adjust the wash cycle giving a

> finer wash than a 'dumb' machine with fixed commands. In the simplest of these, an optical sensor measures the murk or clarity of the wash water, and the controller estimates how long it would take a stain to dissolve or saturate in the wash water. Some machines use a load sensor to trigger changes in the agitation rate or water temperature.[4]

The *simplest* of these fuzzy logic controlled washing machines uses at least 1 extra sensor (the optical sensor) and a microcontroller. No comparison is made to what would happen were the microcontroller programmed to use a conventional controller that made use of the optical and/or load sensors.

Their claims are analogous to the following. Cook a baked potato in a conventional oven with a conventional controller. It takes 1 hour. Now we put a similar potato in a microwave oven with a fuzzy logic controller. The microwave oven cooks the potato in 10 minutes. This *clearly* illustrates the *superiority* of the *fuzzy logic controller*! It not only cooked the potato much faster; it saved energy, thus preserving the ozone layer. And it even beeped to tell me that the potato was ready! The claims of Kosko and Isaka are not much different. Much of what they are attributing to fuzzy logic *could be* that they had added extra sensors and a microcontroller/DSP chip. The earlier "conventional" methods did not have access to this.[7]

In his next article[10], Bob Pease will make a point that fuzzy logic controllers are assuming many sensors: one on position, one on velocity. My point is that for a rigid body, this is full state feedback. It is common knowledge in conventional control that if one has full state feedback, one can design a controller that works amazingly well.[8] I have yet to see a fuzzy logic paper that does a comparison between a conventional controller that has access to all these sensors.

3.4 Fuzzy Logic and Nonlinear Systems

Many proponents of fuzzy logic control argue that fuzzy logic works much better than conventional control when the system is nonlinear. However, the conventional controller they are comparing it to is a PID controller based on a linear system model.

In the sense that the fuzzy logic rules encompass a better model (implicit but there) of the system than an *inappropriately applied* linear model, the fuzzy logic rules will work better. Recall that the linear model has its faults as well. If a control system is designed using a linear model that doesn't characterize the system behavior well, then the control system will probably fail to work well. However, a fair comparison would be one made between a fuzzy logic controller and a nonlinear state feedback controller that measures all the same variables at the same sampling rate as the fuzzy logic controller. If such a comparison is made there is no guarantee that the fuzzy logic controller will work better.

The car parking problem is often held up as a problem that is difficult for a conventional controller to solve. Humans can park cars, but if you tried to describe this in terms of a typical dynamic model, no human would be able to do this. I believe the car parking problem hides what is going on. Of course it is difficult for a standard controller to park the car. Why? Because the sensors and actuators on humans do not work that way. Thus, cars are designed to work with human control and thus probably will respond well to fuzzy logic control. Humans

[6] You cannot fool mother nature.

[7] Technically a microwave oven is a different *actuator* than the conventional oven. However, I believe the analogy still holds.

[8] Full state feedback is an 800 pound control gorilla that can do whatever it wants – modulo the standard requirement of controllability.

lack the sensors and actuators to put a car exactly 6.0 ± 0.01 inches from the curb. Put sensors in appropriate places (say one on each fender) that can sense the distance to the curb and surrounding cars and you might have a different situation. We have our eyes (slow sampling stereo vision), our force feedback from the steering wheel, our acceleration sensors (stomach on roller coasters, pressure variations against our nerve cells for most everything else), and our model for how the car behaves. Going from parking a VW to parking a Winnebago is hard because even though the sensors and actuators are the same, the *model* is *way off*.

If it is true that many of the fuzzy logic proponents are software jocks, then the notion of ignoring the sensors and data formats is a typical "That's an implementation problem!" argument. To someone whose mind is closed to the real world, inelegant sensor/converter/actuator/timing issues cloud the beautiful theory.

3.5 Flexibility and Adaptation

As noted in the above quotation from Kosko and Isaka[4], fuzzy logic proponents often deride conventional controllers for being rigidly programmed and therefore unable to adapt. Perhaps the worst example of this came from Earl Cox's article in *Spectrum* where he states:

> Static systems of this kind are fine for applications in which the environment is known and predictable. But they can lead to disaster when the assumptions upon which they are built are violated – as they did during the Carter administration's ill-fated Iranian hostage rescue attempt. At that time, helicopter crashed in the desert because their navigation and engine controls failed when environmental conditions moved outside their expected operating range.[15]

This spawned a wrath of replies in the *IEEE Control Systems Magazine* by a large number of control system researchers[16].

It is important to note (and Cox does not do so) that most fuzzy logic control systems in the literature are *not* adaptive. Thus, they cannot learn. Claims are being made that fuzzy logic control systems can easily be combined with adaptive schemes (e.g. Neural Networks, adaptive control) so that they can learn. However, these will have the same problems that all adaptive schemes have: convergence issues, having a rich enough input to identify the system behavior, signal to noise problems, etc.

4. Conclusions: Why and When Does It Work

The best real justification I can believe on the cost savings is the notion that sample rate and controller/algorithm complexity, while being inversely *related* to each other, are not inversely *proportional* to each other. Thus in some cases, it is much cheaper to do fast sampling with simpler logic (e.g. RISC computers versus CISC computer, $\Sigma - \Delta$ converters). This varies dramatically from problem to problem. I find it very easy to believe that there are problems for which it is much cheaper to design fast, simple silicon than slow, complex silicon. In this case you probably win with a fuzzy logic controller. However, I have never seen such a tradeoff explained by any fuzzy logic proponent.

As has been noted above, there are many cases where the "new and improved" fuzzy logic control system makes use of extra sensors. The fuzzy logic proponents give all the credit to the fuzzy logic and none to the fact that they are using extra sensors on the system. I believe that the advent of inexpensive sensors is what is behind much of the recent success of fuzzy logic control applications. Nevertheless, the fuzzy logic control systems do make use of the extra sensor information, and there is a significant question as to how easy it is to incorporate this information into a standard control algorithm. (Of course it can be done. However, multivariable/multirate control is a much more difficult problem to analyze. Fuzzy logic might win by using the extra sensor information in a less precise but still effective way allowing a simpler implementation and therefore a higher sample rate.)

Finally, there are many problems where the system has been *designed* to work under the control of a human operator. By using extra sensors and faster sampling rates than the human could ever do a fuzzy logic control system might easily outperform a human operator. In fact, if the system is nonlinear and if there is a more complete implicit model of the system's behavior incorporated in the fuzzy rules than in a linear model, the fuzzy logic control system should outperform a conventional controller. This does not mean that there is not a nonlinear dynamic model for the system from which one can achieve better control with a nonlinear state space controller. This nonlinear controller may be more complicated than the fuzzy logic controller. If this is the case, it might affect what sample rate at which the system can be measured. This in turn affects the quality of the control.

The point of all of the above is that there is no magic here. Fundamental rules of system behavior still apply. When one does realistic comparisons of fuzzy logic control versus conventional control, one must include such unelegant issues as system modeling, sensors, actuators, and sample rates. Such fair comparisons have yet to show up in the literature.

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