Some Crisp Thoughts on Fuzzy Logic

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Talk Synopsis

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 proponents do not say *why* or *how* fuzzy logic control works.

4) This talk will try.

Key Points

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

2) Fuzzy logic control is most useful in "common sense" control situations, *i.e.* human replacement. Examples: "truck backer upper", car parking, train control, and model helicopter control problems.

3) Fuzzy set membership functions effectively quantize their input and output space. However, the quantization intervals are rarely uniform.

4) High sample rates are a key to most fuzzy logic control success stories. Fuzzy logic control papers never give the sample rates.

5) Many fuzzy logic success stories use more sensors than the controller that they improved on.

6) Most fuzzy logic controllers are compared to PID controllers.

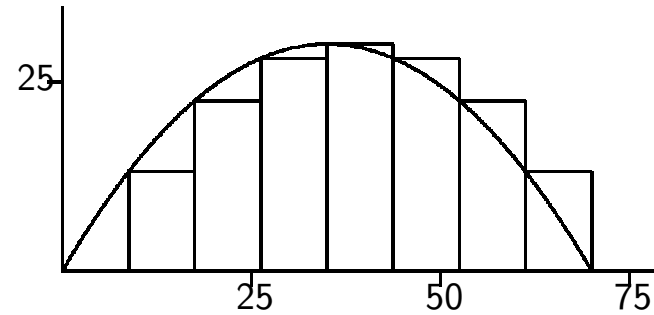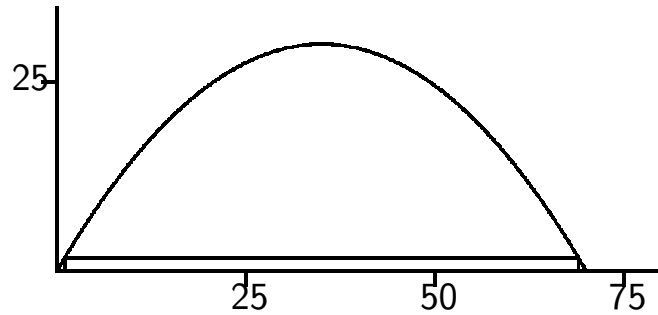7) It comes down to sample rate versus computational complexity.

Fuzzy logic control's most useful examples are when the human in the loop is being replaced.

- Train control (Sendai Subway)

- Model helicopter control

- Truck backer-upper demos

- Problems share the following features:

  - Train, truck, and model helicopter are designed for human control
    $\implies$ they are robust to imprecision.
  - Fuzzy rules come from the human operator rules.
  - Human operator rules come from an implicit input/output model of each of these systems.
  - Fuzzy logic control maps these into a computer program.
  - Human operator's bandwidth is very low.

Fuzzy logic as a rough quantizer

- Fuzzy set membership functions quantize their workspace.

- The quantization is coarse, but the functions can overlap.

- In control, this results in a feedback loop that has low precision measurements, but a fast sample rate.

- Low precision/high sample rate in feedback can lead to high precision output.

    - $\Sigma - \Delta$ converters
    - RISC versus CISC machines

  $\Longrightarrow$ It's a sample rate versus computational complexity isssue.

Sample Rate Issue As Numerical Integration

- Integrating with 1 interval, forward rectangular rule, fails miserably.

- How would we improve this? Either:

   1) have a more sophisticated model of the curve or

   2) add more sample points.

- How well you can do with low sample rate depends upon the accuracy of your model.

- With a high sample rate, the model becomes less critical so that even a forward rule integration works.

- The same is true in time with dynamic systems.

- Human sample rate is very low, e.g. television refreshes full screen at 30 Hz.

Fuzzy logic does not generate a control law, merely it maps it 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 "proven" that fuzzy logic can approximate any function to any accuracy.

- Root locus, frequency response design using Bode plots, and state space design do not *approximate* functions they *generate* functions.

What's new?

- Fuzzy logic does blur the borders of its membership functions. This concept could be useful for smoothly transitioning between different control regimes.

- Issue is a sample rate versus controller complexity.

- Fuzzy logic can be useful in the right place.

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.

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Reexamining the Evidence

- In the 1950s, adaptive control was big hype with "a lot of enthusiasm, bad hardware, and nonexisting theory."(Åström, 1983)

- Previous technologies that were hyped to save the world:

  - adaptive control

  - AI/expert systems

  - neural networks

- The hype eventually always gets to, "You don't have to know anything about the problem. X will take care of it."

Bogus Claims

- The fuzzy logic is "model free".

- One can ignore sample rates and the Nyquist Criterion.

- Pay no attention to those extra sensors we are using!

- Fuzzy logic works much better than conventional control with nonlinear systems.

- Fuzzy logic control systems are inherently more flexible and adaptible than conventional control.

"Model Free" Control

- Fuzzy logic proponents claim that fuzzy logic is "model free".

- Bogus. No intelligent action is possible without a model of what we are dealing with.

    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?' (James Burke, *The Day the Universe Changed*,1985)

- The model is implicit in the rules, which were generated from the designers knowledge (i.e. model) of the system behavior.

Sample Rates and Nyquist Criterion

- "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.*](C. Vibet, 1993)

- I have yet to see a fuzzy logic control paper where they give the sample rates.

- I have yet to see a direct comparison between a fuzzy logic controller and a conventional controller with the exact same sample rate (never listed), sensors, actuators, and computation power.

- *For virtually any sampled data control system 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.*

Ignore those extra sensors we are using!

- In a 1993 *Scientific American* article Kosko and Isaka describe some fuzzy logic success stories:

  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.

- Later, they 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.

- Did I mention they were using extra sensors?

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.

- The conventional controller they are comparing it to is a PID controller based on a linear system model.

- It may be that fuzzy logic rules encompass a better model (implicit but there) of the system than an *inappropriately applied* linear model.

- No comparison 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.

Sensors, Actuators, Sample Rates, Models

- Car parking problem is wonderful example. Cars and parking spaces are designed for human control (human sensors, human sample rate, human rules).

- For control problems, sensors/converter/actuator/timing/modeling issues are not just *implementation issues*.

- Analogous to saying that running Windows on a VT100 is merely an implementation issue.

Flexibility and Adaptation

- Fuzzy logic proponents often deride conventional controllers for being rigidly programmed and therefore unable to adapt.

- Example, Earl Cox's article in the February 1993 issue of *Spectrum*:

  > 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.

- Cox does not note 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 so that they can learn.

- No mention of universal problems that adaptive systems face:

  - convergence issues,

  - having a rich enough input to identify the system behavior,

  - signal to noise problems, etc.

Whirlpool Refridgerator

- Jan. 13, 1994, Stanford University: Prof. Zadeh mentions that Whirlpool wins $30 million for refridgerator that uses fuzzy logic and is 29% more efficient than 1993 government standards.

- Jan. 12, 1994, Mt. View, CA: Bob Pease mentions that Whirlpool wins $30 million for refridgerator that uses fuzzy logic and is 29% more efficient than 1993 government standards.

  – Bob then quotes article (*Popular Science, January 1994*) that says they chose a particular model "as the starting point because it was already only 20 percent below the 1993 standards; they needed just another 10 percent..."

  – Fuzzy logic is responsible for 3-4% energy improvement.

    "We're ekeing out a little more efficiency with fuzzy logic, in some cases 3.5% savings," says Blankenship. (One of the Whirlpool engineers.)*(Design News, 12-6-93)*

  – They added a microprocessor and sensors.

  – $30 million is not a cash prize: it is paid over time by energy utilities, based on future refridgerator sales.

The Baked Potato Analogy

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*!
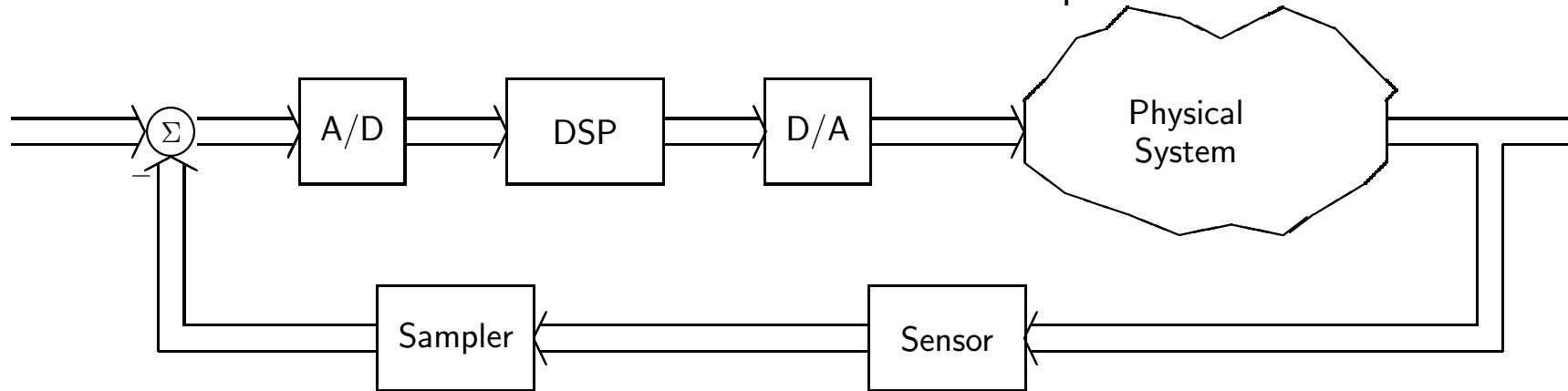
Conclusions

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

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

3) Most fuzzy logic control papers are loaded with hype, unsubstantiated claims, and inappropriate comparisons.

4) The framework for why fuzzy logic control works when it works can help debunk a lot of the hype.

Why it Works

- Many improvements can be attributed to effects of feedback

    - "The goal of feedback control is to use the principle of feedback to cause the output of a dynamic process to follow a desired reference variable accurately in spite of the path the reference variable may take, the external disturbances, and any changes in the dynamics of the process." (*Franklin, Powell and Emami, 1991*)

    - Who ever thought of putting a feedback loop on a rice cooker, an electric shaver, a washing machine, a toaster, a . . .

- Sensors used to be expensive, now they are cheap. $\implies$ It is easier to add lots of extra sensors to systems.

- Better actuators allow for intermediate levels of setpoints.

- Cheap microprocessors.

- High sample rates relative to system dynamics.

- Interpolation between different control regimes.

- ⋆ Lots of sensors, high sample rates, simple control algorithms on cheap microprocessors, applied to stable devices that never had a feedback loop but for which a human rule set exists means lots of improvement.

- ⋆ Except for the interpolation, none of this is inherently due to fuzzy logic.

Fair FL versus "Standard" Control Comparison

1) Pick physical system for which a "standard" servo can be done.

    a) Fix: # of sensors, sample rate, A/D, D/A, DSP architecture.

    b) Only allow code in DSP to be changed.

    c) Which method works better? (RMS error, bandwidth.) How simple is it? (Lines of DSP code.)

2) Allow sample rate to change as well.

    a) This allows for sample-rate/algorithm complexity tradeoff to be made.

    b) If FL has inherent superiority, it should either match performance with smaller code or improve on performance with same size code.

3) Allow for multiple regions of operation that require domain switching.

4) Same architecture in human replacement problem.

The Top 10 List of Things Prof. Zadeh and I Agree On
(with respect to Fuzzy Logic)

10) Fuzzy Logic is more useful than its detractors claim.

9) Lots of extra sensors help control systems.

8) Bart Kosko writes better science fiction than William Shatner. (Three words: *Star Trek V.*)

7) Fuzzy rules incorporate an implicit model of the system.

6) Fuzzy logic does not generate a control law: it maps a pre-existing control law into a logic set.

5) Fuzzy logic control has been most useful in human operator replacement applications.

4) Sample rate issue has not been addressed by the field.

3) Most fuzzy logic control problems could have been solved by "conventional" methods.

2) Fuzzy logic control is better than conventional control in places where conventional control cannot be used.

And the top thing that Prof. Zadeh and I agree on:

1) Who is this Bob Pease guy, anyhow?