Fifth IFSA World Congress (1993), 937 - 940

Balancing Speed, Precision, and Flexibility

Accelerating Complex Rule Bases in Hardware

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Abstract: A new hardware architecture achieves high speed, high precision fuzzy inference capabilities while maintaining flexibility on par with software approaches. This flexibility allows unmodified, uncompromised porting of fuzzy system designs into hardware. The architecture is also scalable and offers data resolutions from 8 bits to 32 bits.

Trade-off's

There are three counteracting factors which need to be balanced when implementing fuzzy inference capabilities in hardware.

The first is "speed" which is dependent not only on the actual architecture but also the process technology. The second is "precision" as represented by the data resolution of the input/output values and the belief values. The third, and perhaps the most important, is "flexibility", or the ability to process complex rule bases.

Most fuzzy hardware implementation efforts to date have emphasized "speed" at the expense of "precision" and "flexibility". However, many applications which require the high speeds offered by hardware approaches tend to also require higher precision and increased flexibility.

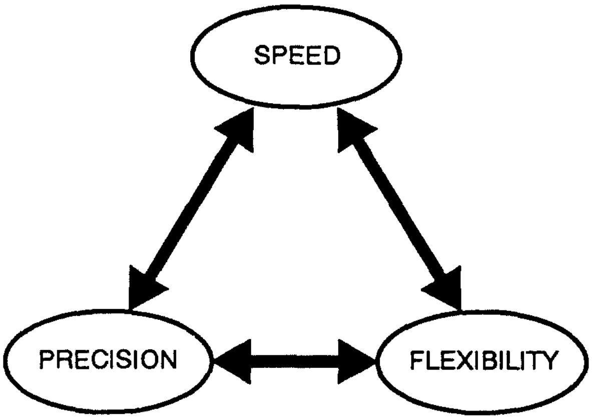

Figure 1. Counteracting factors for hardware implementations of fuzzy logic

All of the above factors were taken into consideration during the development of the FCA (Fuzzy Computational Acceleration) technology resulting in an architecture which offers:

- high speed inferencing capabilities

- scalability from 8 to 32-bit data resolution
- flexibility to process complex rule bases

In determining how much flexibility needed to be designed into hardware, numerous high-end applications were studied and the following list of desirable features was created. The FCA incorporate all of these capabilities.

1. Remove upper limit from the number of membership functions per input or output.
2. Support three fuzzy operators: AND, OR, NOT.
3. Remove restrictions on the number of antecedents per input variable in the premise.
4. Allow nesting of clauses in the premise.
5. Allow rule weighting.
6. Provide centroid defuzzification.
7. Allow for external fuzzification of inputs.
8. Allow for external defuzzification from rule alpha values.
9. Remove upper limit on the number of rules allowed.
10. Incorporate quadratic smoothing of triangular and trapezoidal membership functions.
11. Support hierarchical rule bases.
12. Support multiple rule bases.
13. Allow for resolution beyond 8-bits.

Precision

Higher precision (item 13) was achieved by incorporating a slice architecture design. This method allows for relatively easy scaling from 8 to 32 bits of data resolution with minimal speed degradation.

Flexibility

The new architecture can evaluate hierarchical rule bases (item 11) like the one shown below without modifications to the fuzzy system design.

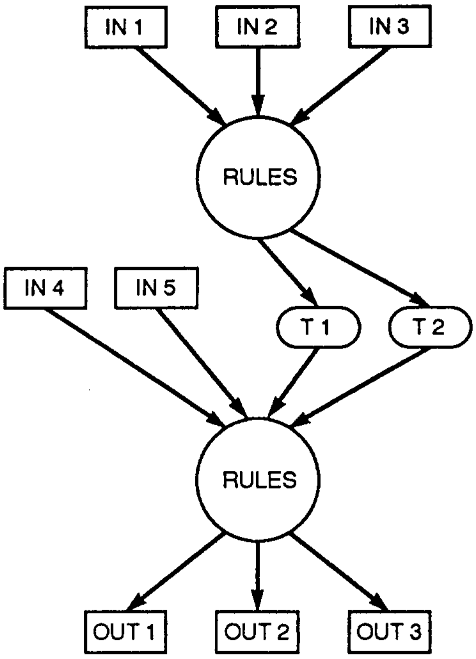

Figure 2. Hierarchical rule base

Rules of the following form can also be accepted due to compliance with items 2, 3, and 4 from the preceding list.

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If (x is blue OR x is green) AND
(y is maroon OR y is orange) AND
z is large,

then A is dark, B is negative.
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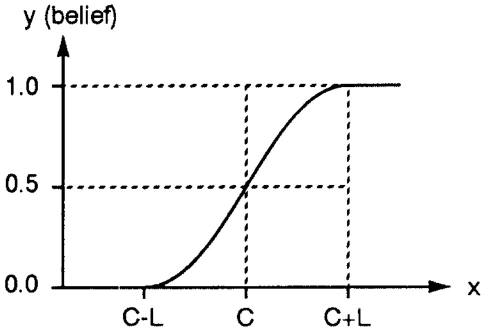
Rule weighting (item 5) was found to be useful during the system tuning process. By changing the weight of a rule instead of the rule's output membership function size, the effect of that rule on the outputs can be adjusted individually without affecting other rules which may share the same output membership function.

The external fuzzification and defuzzification capabilities (items 7 and 8) permit customizing of fuzzy operators and defuzzification methods.

Furthermore, the new architecture supports quadratic S-function formats (item 10).



$$\text{For } C-L \le x \le C, \quad y = \frac{(x-(C-L))^2}{2 \cdot L^2}$$

$$\text{For } C < x \le C+L, \quad y = 1 - \frac{((C+L)-x)^2}{2 \cdot L^2}$$

Figure 3. Quadratic S-function equations

The S-function format can be used on its own for defining membership functions or as a tool in "smoothing" triangular and trapezoidal membership functions. The effect on the output values of such "smoothing" can be best observed using control surface plots.

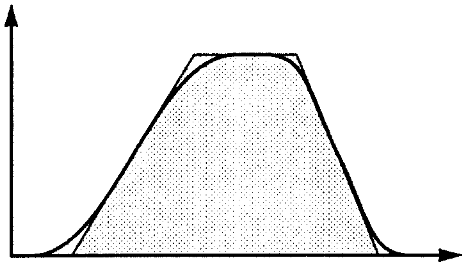


Figure 4. Quadratic smoothing of a trapezoidal membership function

Speed

The aforementioned precision and flexibility have been designed into the FCA architecture without sacrificing computation speed. Inference speeds for some sample rule bases are shown in the table below.

TABLE 1. Inference speed and required memory

Rule base[1]	Inference speed[2] (micro-sec)	Knowledge base memory size (words)
4 in, 2 out, 25 rules	64	1.0 K
4 in, 2 out, 50 rules	96	1.2 K
8 in, 4 out 50 rules	176	2.4 K
8 in, 4 out 500 rules	1240	10.0 K

1. All rule bases have 16-bit data resolution, 7 membership functions per input, 9 membership functions per output. Sum-product inference with centroid defuzzification is performed.

2. Inference speed is based on a 20 MHz clock rate on a 1.0 micron CMOS device.

Summary

High speed, high precision fuzzy inference capabilities were realized while maintaining enough flexibility to meet the stringent requirements of most complex rule bases. This circumvents the problem of modifying or compromising a fuzzy system design during implementation into hardware. With this new architecture, system designers are at liberty to design and tune their systems optimally without being restricted by the final implementation platform.