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A Fuzzy-Logic Thermostat

It's easy to think that the old way is good enough, especially for everyday controls. But, Constantin shows us otherwise. A fuzzy-logic AC controller uses several variables to bring greater comfort at less cost.

The constantly increasing performance/price ratio of microcontrollers means electronic systems can replace more and more electromechanical ones. In design, the goal is not to just replace the solution, but also to improve it by adding new functionality.

One product where this goal has been achieved is the fuzzy-logic thermostat developed by Microchip Technology and Inform Software for an air-conditioning (AC) systems manufacturer. The design uses fuzzy logic to implement a radically new and efficient concept of a thermostat on a low-cost microcontroller.

The heating and cooling of homes and commercial buildings consume a significant portion of the total energy produced in the world. Increased efficiency in these systems can yield big energy savings.

These savings can be found in construction improvements (e.g., better insulation) or more intelligent building control strategies. Here, I'll focus on the latter—applying fuzzy-logic control techniques for AC systems.

Fuzzy logic offers a technical control strategy that uses elements of everyday language. In this application, it was used to design a control strategy that adapts to the individual user's needs. It achieves a higher comfort level and reduces energy consumption.

With a fuzzy-logic software development system, the entire system, which includes conventional code for signal preprocessing and the fuzzy-logic system, can be implemented on an industry-standard 8-bit microcontroller. Using fuzzy logic on such a low-cost platform makes this a possible solution with most AC systems.

AC CONTROL

Quite a few AC systems already use fuzzy-logic control. In 1990, Mitsubishi introduced their first line of fuzzy-logic-controlled home ACs. Industrial AC systems in Japan have been using fuzzy logic ever since. Now, most Korean, Taiwanese, and European AC systems use fuzzy logic.

There are different incentives to use fuzzy logic. For industrial AC systems, it minimizes energy consumption. The controller optimizes the set values for the heater, cooler, and humidifier depending on the current load state.

Car AC systems use fuzzy logic to estimate the temperatures at the driver's head from multiple indirect sensors.

Home ACs are much simpler. They

don't contain a humidifier and only cool or heat at one time. Fuzzy logic gives them robust temperature control.

Each home AC has a thermostat that measures room temperature and compares it with the temperature set on the dial. The thermostat uses a bimetallic switch and compares the set temperature with room temperature. It minimizes the number of AC starts by using a hysteresis.

Figure 1 shows the control diagram of a straightforward microcontroller implementation of this principle. The difference between the set and actual room temperatures turns the AC on and off using a hysteresis stage.

Since most home AC systems don't provide continuous power control and the number of on/off switches is minimized, there's no real room for improvement in this design.

FUNCTIONAL ANALYSIS

The question is: how do you improve the design and add functionality. A thermostat's sole purpose is to keep the room temperature constant. If the AC can only be turned on or off, not many design alternatives are obvious.

But, isn't this a major error in thinking? The original objective for a thermostat is not to keep temperature constant but to maintain maximum comfort.

Room temperature doesn't always correspond to the subjective temperature felt by people. During the day, a higher temperature is considered more comfortable than at night. The same room temperature is perceived as warmer if the room is sunlit.

Empirical analysis of how people adjust the temperature dial on their ACs tells even more. If the set temperature is turned down significantly at once, it's pretty obvious that a large cooling effect is desired.

To expedite the cooling, most people turn the dial down lower than what typically corresponds to a comfortable room temperature. Usually, they forget to put the temperature dial up again when a comfortable room temperature is reached. Before this error is corrected, the increased cooling wastes energy.

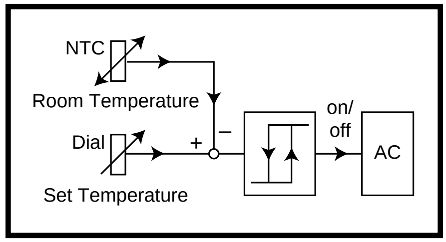

Figure 1—*A conventional thermostat compares room temperature with set temperature to turn the AC on and off.*

Another example is when the set temperature is changed only by a small amount. This indicates that the user wants the room temperature to be kept exactly at a desired point.

If the air conditioner overreacts, the user corrects the temperature again, seeking the desired room temperature. This both wastes energy and annoys the user.

INTELLIGENT THERMOSTAT

Obviously, a thermostat that understands and interprets these conditions and interdependencies can do a much better job than the simple on/off-type controllers shown in Figure 1.

However, putting such intelligence into a microcontroller's assembly program is anything but easy. The algorithm is based on empirical knowledge, and it involves many different factors and conditions. The design of a mathematical model is thus intractable.

Figure 2 shows the structure of the intelligent fuzzy-logic thermostat. The underlying design is the same as with Figure 1, but the fuzzy-logic controller intervenes at two points.

One output of the fuzzy-logic system corrects the set temperature, and another output adapts the hysteresis interval.

The input variables of the fuzzy-logic controller stem mostly from the set-temperature dial and the room-temperature sensor. An inexpensive LDR photo sensor measures the brightness in the room.

FUZZY -CONTROLLER DESIGN

Design, debugging, test, and implementation of the fuzzy-logic controller was supported by the development software *fuzzy*TECH [3]. The fuzzy-logic controller uses five input variables (computed from the sensory values) to analyze and interpret the conditions in the room:

- Number of set-temperature changes (`ChangeNr`)

This input signal identifies a user who tries to set the room temperature very precisely (rule 4 in the lower window in Photo 1). To satisfy such a user, the hysteresis is set to `small`.

This variable counts each time the user moves the dial. Every 6 h, this variable is counted down until zero is reached.

- Difference between the set and room temperatures (`TempError`)

When the difference between the set and room temperatures is very large, the fuzzy-logic system increases the temperature error (rules 5 and 6).

At the same time, the hysteresis is set to `large`, so disturbances do not interrupt the cooling process. This strategy ensures the desired temperature is reached as quickly as possible.

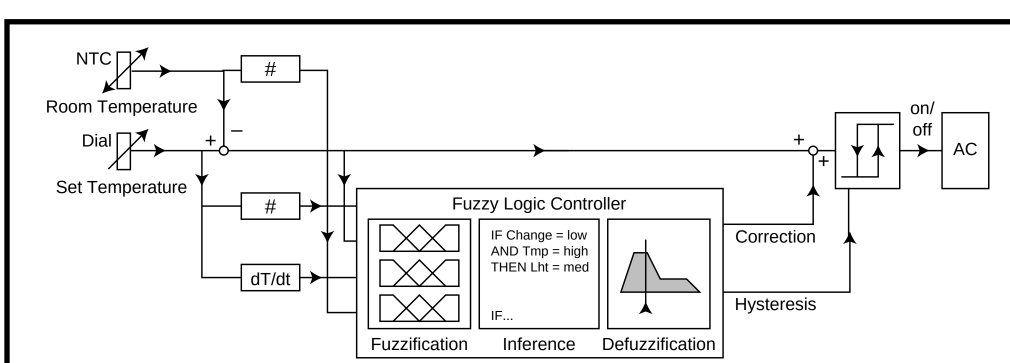

Figure 2—*The fuzzy-logic controller corrects both set temperature and hysteresis depending on the room usage and condition, which is why a fuzzy-logic approach was selected for the implementation of the empirical knowledge on the microcontroller.*

Attempting to alter temperature quickly is compromised by the fact that overshoot and undershoot are likely. However, with strong temperature errors, overshoot can be beneficial.

For example, if you come into a previously unused room where the AC was turned off and set the dial to a much lower temperature, the short undershoot of the room temperature gets rid of excessive heat stored in the walls and furniture of the room.

• Last set-temperature change (`dTemp_by_dt`)

The amplitude of the last set-temperature change indicates whether you want to have a strong cooling effect or to fine-tune the room temperature.

For example, rule 3 of the fuzzy-logic controller uses this input variable to detect fine-tuning. Because this signal is a differentiated signal, it disappears after 30 min. if the dial is unmodified.

• Number of room temperature changes > 3°F within past 2 h (`RoomFluct`)

This input variable indicates how heavily the room is used. Room temperature changes larger than 3°F are typically caused by open windows or by conferences involving an overhead projector and a large audience.

• Brightness in the room (`Brightness`)

If direct sunlight hits the room, the set temperature automatically reduces (rule 2) to increase comfort. During the day or when room lights are on, the set temperature increases slightly (rule 1) and the hysteresis is set to `small` to conserve energy.

CONTROL STRATEGY

Photo 1 shows the main window of the development software *fuzzy*TECH during design. The Project Editor window displays the structure of fuzzy-logic inference.

The fuzzy-logic thermostat's structure is straightforward. All input variables are fuzzified and fed into one rule block. The two outputs of the rule block become the outputs of the fuzzy-logic system and are then defuzzified.

The Correction window exemplifies a membership-function set definition for the linguistic output-variable definition. The grayed areas visualize the process of defuzzification.

Some of the fuzzy-logic controller rules are listed in the Spreadsheet Rule Editor window. Each row represents a fuzzy-logic rule, expressing part of the empirical knowledge implemented in the system.

The five left columns under the If button are input variables. Each field shows the value of the linguistic variable. The two double columns on the right represent the two output variables. The numbers between 0 and 1 in the smaller columns denote the relative weight of the rules that can be tuned during controller optimization.

All input variables have three terms with piecewise linear membership functions. The output variable `Correction` has five terms and uses center-of-area defuzzification. The output variable `Hysteresis` has three terms and uses center-of-maximum defuzzification.

In total, 34 rules describe the complete fuzzy-logic control strategy.

CHOOSING MICROS

*fuzzy*TECH generates the fuzzy-logic controller as complete program code from the graphical representation. The output is portable C source code, specialized-function blocks for PLCs, or assembly code for microcontrollers.

Because the fuzzy-logic thermostat is a low-cost, mass-market product, the PIC16C71, a standard 8-bit microcontroller, was used for the thermostat's prototype.

Since this microcontroller only provides 1024 words of program ROM and 36 bytes of RAM, it greatly limits the complexity of conventional assembly programs that can be implemented.

Using *fuzzy*TECH's PIC assembly-language generation, the fuzzy-logic controller requires only 550 words of ROM and needs only temporary RAM storage. This arrangement enables you to implement your program on a low-cost microcontroller along with other periphery control code.

SIMULATION RESULTS

The fuzzy-logic system was tested using data recorded in rooms of different buildings under various conditions. The test data was preprocessed using an Excel spreadsheet.

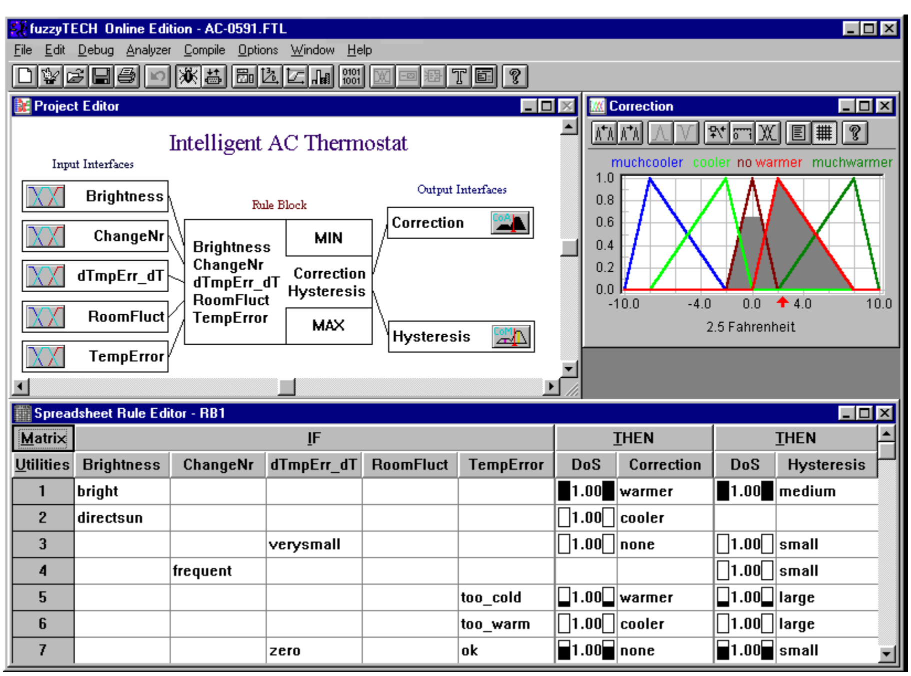

Photo 1—*The fuzzy-logic controller was designed in the* fuzzy*TECH software system. The upper left window shows the structure of the system, involving five input interfaces, one rule block, and two output interfaces. The window in the upper right corner shows the defuzzification of one output variable. The lower window shows part of the fuzzy rule base in spreadsheet form.*

To test the performance of the fuzzy-logic solution, *fuzzy*TECH's Excel Assistant was used. Spreadsheet cells link directly to the inputs and outputs of a fuzzy-logic system. Since this link is dynamic, the fuzzy-logic system can be monitored and modified using *fuzzy*TECH's analyzers and editors while browsing through the data sets.

Analysis of the controller performance shows that the fuzzy-logic thermostat detects situations where less cooling sufficed. In a standard residential house, average energy consumption was reduced by 3.5%. As well, comfort level increased, since depending on the situation, the fuzzy-logic thermostat reduced the room temperature by up to 5°F more than the conventional thermostat.

The fuzzy-logic thermostat doesn't require any modification of the AC itself. By replacing existing temperature controllers, even old ACs can be upgraded. If ventilation is also controlled, even better performance can be reached in a more sophisticated design.

RAISING MIQ

This case study exemplifies how the application of fuzzy logic enables embedded intelligence in existing products. Even with products considered too mature for radical enhancement, integrating human experience and implementing experimental results can deliver significant improvements [4].

Professor Zadeh, the founder of fuzzy logic, calls this "raising the Machine Intelligence Quotient (MIQ)." Rethinking what systems and appliances should and could do for the user can create radically new products.

Because making machines respond to conditions in our lifestyle and usage patterns mostly involves human intuition and expertise rather than mathematical relations, fuzzy logic is an empowering technique for such designs.

Constantin von Altrock began research on fuzzy logic with Hewlett-Packard in 1984. In 1989, he founded and still manages the Fuzzy Technologies Division of Inform Software, a market leader in fuzzy-logic development tools and turn-key applications. You may reach Constantin at cva@inform-ac.com.

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SOURCES

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