DOMESTIC APPLIANCES

Home appliances of the future will automatically adjust to several house-related factors, such as the number of people present, temperature and light levels, and even the cleanliness of the floor. The appliances will even operate by themselves.

Fuzzy logic has helped bring about the realization of these dreams and has entered many aspects of life in general, especially in Japan and increasingly in the United States: automotive (1–7), air and spacecraft (8), and even the stock exchange (1,4,9,10). The concept of the fuzzy-controlled future home has already appeared in Japanese trade shows and households. Numerous domestic appliance applications use fuzzy logic to achieve design goals. One goal is that the appliance should be simple to operate. A second is that the appliance should have a short development time. A third goal is that the appliance should be cost effective compared to its standard logic counterparts. Finally, the designs should be dynamic and adjust to new inputs and different users.

In this article, an overview of fuzzy logic and neural network technology in domestic appliances is presented. A literature review has been compiled at the end of the article. The use of microprocessors in designing classical appliance controllers and an overview of classical appliances using microprocessors is also presented. Finally, intelligent sensors used in domestic appliances are included.

APPLIANCE TECHNOLOGY

Streamlining housework to provide consumers with more free time has always been a design target (11). The following paragraphs in this section provide an overview of the microprocessor-based appliance sensors and controllers in general and fuzzy and neuro-fuzzy controllers in particular.

Microprocessor-Based Appliance Controllers

The computer revolution made it possible to fabricate the entire brain of a computer as a single chip integrated circuit called a microprocessor. The rapid increase in the number and variety of computer applications has made microprocessors a significant part of our lives. One of the main applications of microprocessors is in low-cost, general-purpose computer-based applications. Microprocessor-based household appliances have been available in consumer markets for some time. These appliances have proven to be more safe, convenient, easy to use and program, reliable, and energy-efficient than conventional controlled home appliances. Domestic appliances that use microprocessors are reviewed in the following section.

Microprocessor applications span the entire range of industrial, commercial, and consumer tasks. One of the main applications of microprocessors is in low-cost general-purpose computers. Technology has been used to help people in most household activities since the 1950s and before (e.g., telephones, record players). More recent technological achievements offer great ways of making household activities more convenient and fun. Microprocessors are used in industry in such applications as educational games and toys, programmable timing and control systems for appliances, or for building heating and cooling systems, word processing systems, and information and record storage.

A microcomputer can perform certain routine household functions, such as menu planning and cooking. Range ovens for household cooking feature digital controls, displays, timers, and microprocessor control. Here a stored program in read only memory (ROM) is used to provide information on the cooking time for various types of food. The program turns burners or ovens on and off. Touch-control panels and displays for such digitally controlled ranges have been developed. Large volume and low cost characterize many of these consumer applications. This is the area of a single-chip microprocessor. These microprocessors are sufficient for simple control functions, such as those required by a microwave oven controller. Microprocessors react much faster and switch with greater precision to variations in measured process parameters. The microprocessor eliminates elector-mechanical or hard-wired logic. It also provides more functions and it can provide reasonable tests. If the user makes an error in selecting controls, a microprocessor flashes a warning and does not execute the command. It can also prevent some problems by detecting them before they occur using continuous records of parameter variations saved in the microprocessor memory (12–15).

Refrigerators, clothes dryers, and televisions are more domestic appliances currently controlled by microprocessors. A refrigerator by Whirlpool adjusts its inside temperature when food is added or the kitchen warms up, and the GE 24E refrigerator beeps if the door is left open. Dryers have moisture sensors that end the cycle when the clothes are dry and dishwashers that alert the users when the drain is clogged and when other mechanical failures occur. The F8 microprocessor has been used in color television to provide tuning and programming up to a year ahead, and it is easy to provide a digital clock and built in games (16). New technologies, such as fuzzy and neural network technology, are making home appliances smarter and more efficient.

Table 1. Sensors Used in Domestic Appliances

Sensor Type	Domestic Appliance
Optical sensor	Washing machine, dishwasher, dryer
Load sensor	Washing machine, rice cooker
Moisture sensor	Dryer
Heat sensor	Dryer, toaster
Ultrasonic sensor	Vacuum Cleaner, TV
Humidity sensor	Microwave oven, air conditioner, rice cooker
Infrared sensor	Microwave oven, air conditioner, vacuum cleaner, TV
Temperature sensor	Microwave oven, washing machine, refrigerator, air conditioner, rice cooker, shower, carpet
Turbidity sensor	Dishwasher
Conductivity sensor	Dishwasher
Position sensor	Washing machine, TV
Pyro sensor	Vacuum cleaner
Tuning-fork sensor	Vacuum cleaner

Sensors

A sensor is a device that produces a measurable response to a change in a physical condition, such as temperature or thermal conductivity, or a change in chemical concentration (17,18). Sensors are particularly useful for making in situ measurements, such as in domestic appliances. A sensor is usually packaged as a complete unit that supplies a control unit with data inputs.

The availability of low-cost, reliable sensors is probably the most critical factor in the realization of electronic control systems. For this reason, integration is a solution that allows sharing the sensors among different systems, with a reduced number of required sensors and consequently reduced cost. In these devices, the specific conditioning and self-diagnosis electronics are integrated into the sensors (smart sensors). Table 1 shows some of the sensor types used in domestic appliances.

All sensors, whether they have digital or analog outputs, measure real-world phenomena that are then interpreted by another system to indicate a value or a warning, or even to close a control loop. It is very important that the integrity of the data is maintained by the proper choice of interface. Cost, user-friendliness, and reliability in domestic appliances are primary drivers in the choice of interface. For given performance, the sensor that requires the fewer connections is always selected.

The use of semiconductor technology applied to sensing applications is producing sensors with inherently more decision and diagnostic capability that communicate bidirectionally with the host microcomputer in complex systems. Furthermore, recently developed fuzzy logic and neural network approaches to control systems and the multiplexing of sensor outputs for use in several systems made previously cost-prohibitive sensing applications a reality.

Fuzzy controllers have contributed in designing smart and efficient sensors. For example, in domestic appliances, temperature with dynamic variations in time requires a quick response by measuring and controlling devices. The speed of the measuring system is dictated by the temporal behavior of the sensor. A fuzzy control concept has been realized for improving the dynamic behavior of a temperature sensor (19). The final temperature is reached within a considerably shorter time with the fuzzy controller sensor than with the temperature sensor without a fuzzy controller.

The Fuzzy Appliance Controller

Appliances with fuzzy logic controllers provide the consumer with optimum settings that more closely approximate human perceptions and reactions than standard control systems. Products with fuzzy logic monitor user-dictated settings automatically set the equipment to function at the user's generally preferred level for a given task (20). This technology is well suited to adjustments in temperature, speed, and other control conditions found in a variety of consumer products (21). The following paragraphs briefly outline the design steps for a fuzzy appliance controller.

The first step in designing a fuzzy controller is to subdivide the input and output variables into their descriptive linguistic terms and then to establish membership functions for each range (22). A membership function represents each of the fuzzy sets and transforms the crisp real work into the fuzzy view of the real world (23). These functions provide the appliance with the machine equivalent of perception and judgment (24). For example, the input Room_Temp may be divided into classes such as Cold, Cool, Warm, Very_Warm, and Hot. Usually, however, a seven-label gradation for controllers' (25) linguistic hedges, such as Very, About, or Slightly, can be used to narrow or broaden the adjective's definition (26).

Each membership function identifies the range of input values that correspond to an adjective. Each fuzzy adjective has a region whose input values gradually change from being full members to nonmembers (27,28). This transition corresponds to a change from a one to zero state.

Second, the control system is defined in terms of input and output rules. Generally, a control system rule consists of two input variables that combine to direct the output variable (4,29). These rules are described in everyday language. For example, a rule for an appliance could be, "If the wash load is average (cloth quantity) and the fabrics being washed are soft (cloth quality), then the washing time is short" (30).

Finally, the sensor inputs are compared to membership functions, the rules are processed and then combined into a single composite action for each output (9,25). The output of all of the rules is reduced to a single output by taking the logic sum. Next, the defuzzification process takes place. This process changes the fuzzy inferencing results into output understood by the control system hardware. Although there are several defuzzification methods, the most common is the center-of-gravity (COG). COG takes the weighted average of all fuzzy outputs for each system output (9).

As this defuzzified result applies to an appliance control system, it gives the intake fan speed, the washing time for a laundry load, or the cooking time for a frozen dinner in a microwave oven. Figure 1 shows a structure of a fuzzy controller system which consists of three parts: a fuzzification which translates a crisp input to a fuzzy function using the membership functions (labels); a fuzzy inference engine which induces the fuzzy outputs from the fuzzy inputs; and a defuzzification that translates a fuzzy output to a crisp value which then is used to control the domestic appliance (31).

Fuzzy technology is used in domestic product design to satisfy the following requirements (32):

1. developing control systems with nonlinear characteristics and decision making systems for controllers
2. coping with an increasing number of sensors and exploiting the larger quantity of information available
3. reducing the product development time
4. reducing the cost of incorporating technology into the product

Fuzzy systems do not directly control the actuators in most applications to consumer products but determine the parameters used for control. For example, fuzzy controllers may determine washing time in a washing machine, or if the hand or the image is shaking in a camcorder, determine the optimal contrast for watching television.

The more intelligent the consumer domestic product is, the more sensors and information need to be available to the product. Fuzzy technology is a natural choice for accommodat-

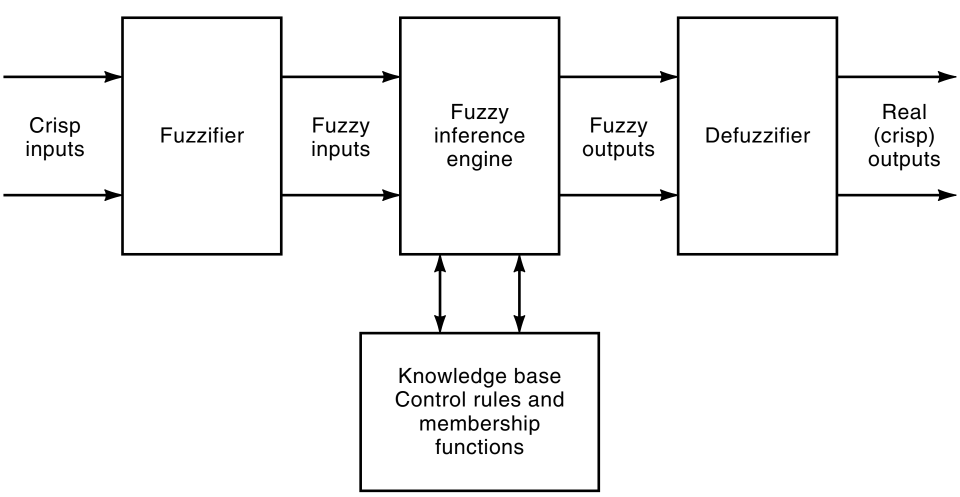

Figure 1. Structure of a fuzzy controller.

ing the increasing number of sensors and the large amount of information available to the product. However, this increase in information leads to higher complexity of design that cannot be fully tackled by fuzzy reasoning alone. Neural networks are being used to speed up the development of this fuzzy complex rule-based system.

Neuro-Fuzzy Logic

Neural networks and fuzzy logic are complementary rather than competing technologies (8). Neural networks assign relative weights to data that is represented, along with their decision structures, like biological neural systems (33). A fuzzy set is an extension of the traditional set theory that allows grades of membership other than 1 or 0. Fuzzy logic is a digital control methodology that simulates human thinking by incorporating the imprecision inherent in all physical systems (4). In more general terms, fuzzy logic is a way that electronic devices react to vague inputs (34). Fuzziness takes into account the nuances of language and eliminates unnecessary precision (35).

Many similarities exist that enhance the relationship between fuzzy logic and neural networks. For example, neural networks learn ideas in ways that are similar in form to fuzzy logic's membership functions. This learning capability is used to master the relative importance between rules and the values of each element in a rule. Another commonality is that fuzzy logic takes a weighted sum of the If-Then rules which is analogous to neural network action (36,37).

Neural networks help fuzzy programmers determine membership functions and logic rules. One method of interaction works by letting the neural net monitor the human expert's reaction to a situation. Then models are built that reflect the relationship between the stimuli and response. Rule structures and membership functions are automatically generated from these models. Now the neuro-fuzzy controller matches the knowledge of the human expert using the best qualities of both systems (8,38). Another method, called adaptive fuzzy systems, uses neural networks to learn fuzzy rules (36).

A fuzzy input variable is partitioned into several one-dimensional input spaces (fuzzy linguistic values). Performance of a fuzzy system depends on how this partitioning is done. Neural networks are used as optimized methods to determine the parameters of the partition. Figure 2 shows a block diagram of the neuro-fuzzy system.

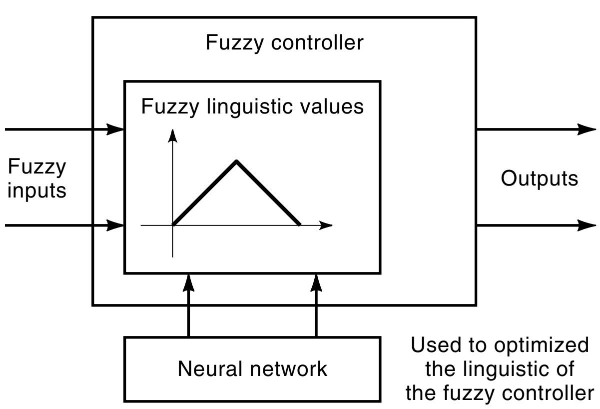

Figure 2. A neural network optimizes the membership functions.

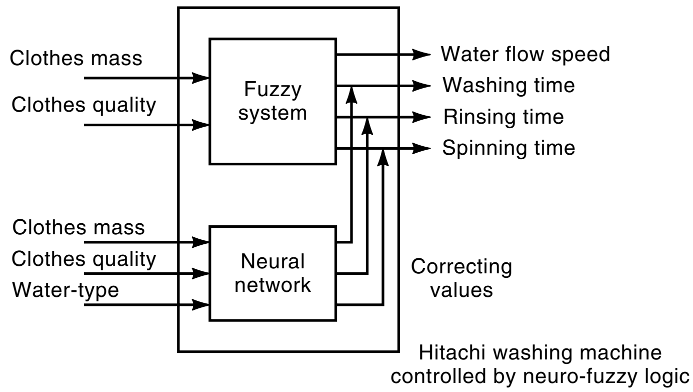

Figure 3. A neural network corrects the output of a fuzzy logic.

Another approach to using neural networks (NN) in designing fuzzy systems is that of using NN as a correcting co-system. Thus completely redesigning the fuzzy system is avoided. Figure 3 shows the schematic underlying the Hitachi washing machine (32).

Taken separately, both neural networks and fuzzy logic have drawbacks. Neural networks learn but do not have an easily discernible structure (39). To make optimal decisions, fuzzy logic needs a growing amount of data from sensors which require time to collect and process (40). Used together, the programmer combines the decision making capabilities of one with the learning capabilities of the other. The result is a more easily understood rule structure and approximately 45 times faster processing speed compared with completely fuzzy systems (38,40,41).

In the context of consumer products, neural networks and fuzzy logic have been put to use in the following approaches (32):

1. neural nets (NN) as development tools for fuzzy systems
2. independent use of NN and fuzzy logic
3. cascade combinations of NN and fuzzy logic
4. learning user preferences

The last approach is a recent trend that uses neural networks to customize a standard system according to each user's preferences and individual needs. For example, a domestic product, known as a kerosene fan heater, that is used extensively in Japan (32) to heat houses, uses a NN-based learning user preferences approach. The burner burns vaporized oil and this requires preheating the burner before it starts heating its surroundings. This preheating phase takes a considerable amount of time. Sanyo (19) uses a neural network to learn the usage pattern of the heater. Then the heater predicts when it is going to be turned on, so that it starts preheating accordingly. This predictive ability reduces the energy consumption by half.

Many Asian companies have manufactured domestic products that use neural networks and fuzzy logic. Table 2 shows some of these products and their manufacturers.

FUZZY APPLIANCES

Currently, the fuzzy boom has spread everywhere in Japan. Almost all electronics products manufactured in Japan are

Table 2. Some Domestic Neuro-Fuzzy Products

Domestic Neuro-Fuzzy Appliance	Manufacturing Companies
Air conditioner	Matsushita Electric, Goldstar
Washing machine	Matsushita Electric, Sanyo, Hitachi, Sharp, Toshiba, Goldstar, Samsun, Daewoo
Vacuum cleaner	Matsushita Electric, Hitachi
Rice cooker	Matsushita Electric, Sanyo, Sharp
Kerosene fan heater	Matsushita Electric, Sanyo, Sharp, Mitsubishi, Toshiba, Fujitsu General, Corona, Toyotomi, Samsun
Electric thermo pot	Matsushita Electric
Microwave oven	Matsushita Electric, Sanyo, Goldstar
Induction heating cooker	Matsushita Electric
Clothes dryer	Sanyo
Desk-type electric heater	Sanyo
Electric carpet	Sanyo
Electric fan	Sanyo
Refrigerator	Sharp

based on fuzzy technology (42). A spokesperson for Goldstar, a Korean company, who is aware of the potential benefits to his company stated: "In Japan, electronics goods with fuzzy logic are already so popular that it seems to me that those that do not offer fuzzy applications within a few years will not be able to survive" (43). This is a majority opinion echoed through the literature of fuzzy consumer electronics. Domestic appliances do not sell unless they have "that warm fuzziness about them" (44).

The importance of fuzzy logic in today's appliances is already demonstrated in Japan. The following paragraphs in this section discuss fuzzy logic as applied to various appliances.

Washing Machine and Dryer

Models are equipped with two optical sensors that sense the quality and quantity of dirt in the wash (33,45–48). The sensors work by detecting light passing through a water sample which is altered by the particles suspended in the solution (49). The pair of sensors determines the degree of soiling from the wash water's turbidity or soiling speed and whether oil or mud caused the stain. They determine soiling types by the stain's dissolving rates—mud disperses faster than oil in water. They also discriminate between liquid or powder detergents and meter the amount of detergent required (11,35,50–52). A load sensor determines the volume of clothes to be washed (51).

The fuzzy controller analyzes the accumulated data and then selects the most efficient cleaning method from approximately 600 possible variations of water volume, flow strength, and washing time (28,33,51,53). These models are very popular with consumers. The initial production run sold out within weeks (53).

The basic neuro-fuzzy washing machine uses sensors for water temperature, laundry volume (load size), and water level. From these sensors the AI unit gathers data on laundry conditions, such as fabric type, and then automatically selects one of 250 washing modes (54). These washing modes optimize water temperature, water level, washing and cycle time, and spin-drying time (1,29,43,55). Some models also have a feature that schedules unattended washing during the lower power rates that may be charged at night (56). Other neuro-fuzzy models account for detergent type, cloth quality, and water hardness. Then the machine chooses from 3800 different operating parameters (51).

Sharp makes a variation on the basic machine that shoots bubbles into the wash to dissolve detergent completely. Bubble action is "a combination of air bubbles and swirling water action" (57). The cleaning power of this machine is increased by 20% over nonfuzzy machines (57,58). The machine also claims 30% savings in fill and drain times and 70% water savings over conventional dual-tub systems (47).

The results from any of the models are an output tailored to the required task. The machine automatically washes durable, highly soiled clothing more thoroughly (59). For most of the machines, the only user input necessary after loading the laundry is to press the start button (51,53,60,61).

The companion dryer uses three heat sensors that monitor load size, fabric type, and hot-air flow. The fuzzy controller determines the optimum drying time and shuts itself off when the contents are dry (52,62) thus saving on time and energy costs.

Vacuum Cleaner

The basic fuzzy logic vacuum cleaner uses a single sensor to judge the amount of dust and the floor type (29,63). By monitoring the change in dust quantity, the controller decides whether the floor is bare, where the dust comes up at once, or whether it is thick-pile carpeting from which dust is gradually released. The four-bit microprocessor detects the dust by pulsing an infrared light-emitting diode (LED) and monitoring the output of a phototransistor. Dust passing between the two components blocks light and changes the output signal (49,51). Based on that data, the fuzzy controller correlates the best suction power and beater-bar speed for each specific job. For example when a hard floor is detected, the motor and beater-bar are slowed because not much suction is needed (64,65).

In addition to analyzing the floor type and amount of dust, the neuro-fuzzy version also analyzes the type of dirt. This information is used to adjust both the suction power and brush rotation speed for a 45% increase in processing speed (41,62). Another variation of the basic fuzzy model is the Toshiba vacuum cleaner that advertises power steering along with all of its fuzzy features (66).

Although the efficiency and power saving of these cleaners are greatly increased over conventional vacuums, the user must still press the power button and run the vacuum across the floor. In the more advanced unit, however, the user is not even required to be present. This robot vacuum, which is quiet enough to run at night, navigates a room and cleans as it travels. It operates approximately 20 min per battery charge and when it runs low on power, it returns to its charging port. After recharging itself, it continues vacuuming where it stopped before recharging once again. This robot cleaner is actually a cordless vacuum equipped with several sensors including a gyro and tuning-fork structure to control its movements. The gyro and fuzzy logic control the sweeping movements and an ultrasonic sensor detects obstacles, enabling the robot to dodge them. The unit automatically adjusts to a transition from bare floor to carpet and can even be set to clean daily while the owner is on vacation (67). This time and labor saving unit, tentatively called the Home Cleaning Robot, has not yet been released by Matsushita (49,52,64,68).

Microwave Oven

The basic fuzzy-logic microwave oven uses three sensors: infrared, humidity, and ambient temperature. The sensors monitor the temperature of the food and oven cavity and the amount of steam emanating from the food (52). Based on this data, the controller calculates the type, size, and weight of the food; whether it is frozen or thawed; whether the oven had been used immediately beforehand; and the degree of "doneness." This system results in the most efficient cooking time and usage of cooking conditions (roasting or hot air blower) (41,52,69). All of the microwaves advertise one-touch operation and use fuzzy logic to simulate a cook's best judgment (49).

A more advanced model employs eight sensors that monitor aroma and change in food shape in addition to the previously mentioned attributes. This unit also has a ceramic grill to emulate a barbecue and, using special attachments, kneads bread dough and mashes potatoes (49,60).

Refrigerator

Kenmore and Whirlpool models use fuzzy logic to determine the most energy-efficient time to defrost (60). The fuzzy controller senses temperature changes and defrosts when necessary rather than at regular intervals (48). However, Sharp has taken this application of fuzzy logic much further. This model uses a neuro-fuzzy logic control system that learns the consumers' usage patterns for optimum performance (70).

The Sharp refrigerator memorizes the time and frequency of door and freezer drawer openings. When the usage pattern is learned for each compartment, the control system automatically begins a cooling cycle before heavy traffic periods. This feature minimizes temperature fluctuations in the compartments (70).

Based on the memorized data, the unit also chooses the most appropriate time of day to defrost (71). An additional feature tells the unit not to make ice at night which may disturb light sleepers. The consumer pushes a button on the unit before retiring. The system memorizes this time and repeats this pattern every night (70).

Air Conditioner

Mitsubishi Heavy Industries began producing of the first fuzzy air conditioning system in October 1989. The system was based on 50 fuzzy rules, used max-product inferencing, and centroid defuzzification methods. A thermistor was used to detect room temperature and to control the inverter, compressor valve, fan motor, and heat exchanger. The results from both the simulation and production show (compared to standard systems) a 20% reduction in heating and cooling times, a two-fold increase in temperature stability, and an overall power saving of 76% for the simulation and production savings of 24% for cooling and 17% for heating cycles. A contributing factor to the increase in power saving was a reduced number of on/off cycles (39,51).

New models have sensors that evaluate the shape/size of a room and the inside/outside temperatures and humidity levels (3,65). By using an infrared sensor, the unit also determines the number of people present and cools the room accordingly (1,42,51,60). These inputs are used by the fuzzy controller to balance the temperature with the power needs of the house resulting in the greatest possible efficiency (29,65). Air velocity and direction are adjusted automatically for maximum comfort (72). Mitsubishi's "CS-XG Series" uses neuro-fuzzy logic to generate 4608 control patterns based on environmental data (73).

Fuzzy logic also improves the unit's defrosting control. When a room is being kept warm and the temperature outside is low, frost forms on the unit's outside evaporator. Conventional systems defrost at regular intervals regardless of air conditioner demand. A fuzzy system on the other hand evaluates the outdoor and evaporator temperatures and chooses the most efficient interval for defrosting (1).

A future improvement on this system will encompass all household environmental controls. This system, already called HVAC, will be a unified programmable command system integrated into the smart house (71). The HVAC system will automatically recognize a user and adjust the comfort levels accordingly. For example, if the user enjoys a dry environment, the system will respond to this preference when the smart house detects the user's presence. As with all fuzzy appliances, the changes are made without user intervention (74).

Miscellaneous Fuzzy Appliances

Dishwasher. This fuzzy appliance uses two sensors to detect the number of dishes loaded and the amount and general type of food encrusted on the dishes. Based on these inputs, the fuzzy controller efficiently varies the soap, water, and cycle time (65,75). The Maytag model also adjusts for dried food on dishes by tracking the time between loads. Turbidity, optical, and conductivity sensors are used to optimize cycle time and detergent usage (76). Conventional dishwashers assume the worst case when washing dishes. Since the fuzzy system does not have to make these assumptions, the fuzzy controller should provide 10% to 40% water and energy savings (77).

Rice Cooker. Although this application may never find a large market in the United States, it is still a viable fuzzy-logic application. This rice cooker uses three sensors to monitor the steam, ambient temperature, and the volume of rice. The sensors are checked once every minute, and the remaining cooking time is calculated (52,62,72). The unit has four preprogrammed settings for different styles of rice: white, porridge, glutinous (sticky), and mixed. Other features are available that make cooking perfect rice quick and easy (62).

The use of fuzzy logic allows the user to fill the pot with the same amount of water each time. The controller changes the steaming method based on the type of rice desired. Without fuzzy logic, the user would be required to change water levels depending on the type of rice desired and volume of rice in the cooker (51).

A variation on the rice cooker is in development. It not only cooks rice, but seeks a larger market by cooking foods indigenous to many countries. This cooker is said to consume 9% less power than conventional design (56).

Toaster. A "smart" toaster adjusts the heat and toasting time depending on the type of bread it senses in the toaster. The user's preferences are also learned and memorized (65).

Television. This high-priced product is targeted in Japan to wealthy and middle-aged people who love gadgets (75). Regardless of the market, this TV uses fuzzy logic to react to changing conditions. The television automatically increases brightness, as the room grows darker, and increases volume as the user moves farther away from the set (62,65). Fuzzy TVs show sharper pictures than traditional sets and automatically adjust contrast, brightness, and color. The TV also maintains stability across channels, keeping settings constant even when the stations themselves vary the settings (51).

Carpet. A "smart" carpet's quick-heating function adjusts to low room temperatures and warms hard to heat floors instantly. The carpet also uses fuzzy logic to adjust to changes in room temperature (52).

Shower. Fuzzy logic is used in this shower system to keep the water temperature stable even if the water pressure changes (3,29,60,72).

THE BENEFITS OF FUZZY LOGIC IN APPLIANCES

The commercial importance of fuzzy logic is growing, especially in Japan where consumers have enthusiastically accepted this technology (53). In the 1980s, the Japanese embraced fuzzy logic as the technology of choice for control systems (38). The first commercial fuzzy boom was in 1990 and now the Japanese are preparing for the fifth round and beyond (46,78). Reportedly, eight out of every ten fuzzy applications have been successful (1). The twelve examples of fuzzy logic presented in this paper illustrate some of the benefits gained by using this technology. In general, these benefits are simplicity, rapid prototyping, cost efficiency, and flexibility.

Simplicity

Fuzzy logic uses preprocessing to turn a large range of values into a small number of membership grades. This action reduces the number of values that must be evaluated by the controller and also reduces the number of rules. The fewer the rules, the faster the fuzzy logic system generates output. Most consumer products use less than 20 rules. Typically, a fuzzy system results in a 10 : 1 rule reduction that requires less software and memory to implement the same decision making capability as conventional methods (4,79).

Rapid Prototyping

This benefit helps the designer react more quickly to market needs. The similarity between human thinking and fuzzy logic facilitates understanding and trouble shooting which reduces a product's time to market. In a comparison between fuzzy and standard logic, engineers at Rockwell found that the fuzzy system results in simpler rules, less math, and a more accurate representation of the process. Omron engineers found that fuzzy logic slashes development time by 75% (61).

Cost Efficiency

Fuzzy logic exhibits cost efficiency through the reduction in circuitry and in energy savings. With fuzzy implementation, the potential exists to reduce circuitry by a factor of 1000 thereby making simple learning controllers possible (62). Designers can add advanced features to low-cost microcontrollers. Features that would normally require a 32-bit processor can be implemented in fuzzy logic with a low-cost controller (80). The consumer experiences these savings in price competition between companies. Energy savings are realized through cycles tailored to the specific condition (81). For example, the Mitsubishi air conditioner features a 24% power saving (39).

Flexibility

Flexibility in the appliance could be defined as adaptation to new inputs and users. The appliances detailed in this paper definitely illustrate this benefit. Each unit adjusts its output based on constantly changing conditions, such as going from a carpeted to bare floor. New users are also considered in the fuzzy control system, such as the air conditioner that senses the number of people in the room and then cools the room accordingly (1,42,60).

THE NEGATIVE SIDE

With fuzzy logic appliances experiencing immense sales in Japan, why aren't they experiencing more widespread popularity. Reasons vary from the philosophical (the acceptance of imprecision) to the practical (the appliances are structurally different). Physically, Japanese appliances are smaller than their US counterparts and the added cost of shipping a large washing machine overseas would not be profitable. One solution is to release the appliances in the United States, which is exactly what General Electric is considering. General Electric is currently developing a fuzzy logic dishwasher for release in the United States although the dishwasher will probably be marketed as "smart" or "intelligent," not fuzzy (51).

Critics claim that improved sensor technology is the real hero in these appliance applications. Although it is true that better sensors have helped fuzzy logic, they are not the centerpieces of this control technique. All controllers need sensor information to make decisions and have benefited from better and more inexpensive sensors. Fuzzy logic takes advantage of the low degree of precision required for appliance control and turns it into an efficient design. For example, room temperature does not need to be controlled to 0.1 degrees. Therefore, an inexpensive, lower precision sensor is used with fewer overheads (e.g., design time, testing time, man-hour and manpower, prototype time, and so on) required than with conventional controllers. Examples, such as a washing machine application that uses 1000 to 2000 rules with a standard PID controller and is implemented in fuzzy logic using only 200 rules, are not uncommon (51).

Fuzzy logic appliances have also been accused of being nothing more than conventional logic using look-up tables and percentages (51). If some applications have adopted this method and labeled the product as fuzzy logic, then they are clearly abusing the name recognition "fuzzy," as in some countries. However, this misuse of the term should not detract from this control methodology. Countless real applications of fuzzy logic have been used in household appliances.

THE FUTURE

It took two decades for fuzzy logic to transfer from theorists' hands into production. Now engineers worldwide are dreaming up new applications for fuzzy control systems that greatly enhance consumer products (68). Currently, Japanese companies are leading in developing fuzzy-logic based hardware and software, and they have been particularly successful in pushing this technology into consumer products (21). However, the Europeans are joining the Japanese at the forefront of fuzzy-logic development, and major projects are underway in France, Germany, and Spain (37).

Fuzzy logic has been a laboratory toy in the United States since the early 1970s, but the technology has not been widely seen in consumer markets (44). However, recently US businesses have taken an interest in this field. One example is Motorola's Semiconductor Products Sector that has developed microcontroller technology that makes use of fuzzy logic for automotive applications.

According to some forecasts, the worldwide market for fuzzy logic semiconductors may total $10 billion to $13 billion by the year 2000 (82). Matsushita planned to introduce 200 fuzzy logic-based products by 1995 (38). A Goldstar spokesperson approximated that "70 to 80% of all electric home appliances will use either fuzzy logic or AI by 1995" (43). But Zadeh, the founder of the theory of fuzzy logic, is not surprised. "In the US, there's a tradition for what is precise, for Cartesian logic. In Japan, there is more appreciation of the imprecise, of ambiguity. I've always been confident that people will come around to my way of thinking" (60).

CONCLUSION

As an introduction to smart domestic appliances, this article presented an overview of the fuzzy appliance controller. Neuro-fuzzy logic was also discussed as an improvement to standard fuzzy-logic theory. The main portion of the article was dedicated to fuzzy logic in domestic appliances. The functions for the many appliances and the sensors they use are summarized in Table 1. In each case, fuzzy logic saves energy by shutting off the appliance when the task is completed, optimizes results, and simplifies the operation to a single on/off button. The use of microprocessors in designing home appliance controllers was also presented. Finally, a forecast for the future of fuzzy logic was summarized.

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DOPING, SEMICONDUCTOR. See SEMICONDUCTOR DOPING.

DOPPLER BEAM-SHARPENING. See RADAR ALTIMETRY.

DOPPLER FLOWMETERS. See FLOW TECHNIQUES, INDUSTRIAL.