British Journal of Anaesthesia 1996; **76**: 245–250

Fuzzy logic control of inspired isoflurane and oxygen concentrations using minimal flow anaesthesia

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Summary

In order to evaluate the performance of feedback fuzzy logic control of inspired oxygen and isoflurane concentrations, we studied 30 patients undergoing discectomy for lumbar ($n = 26$) or cervical ($n = 4$) disc herniation. Patients were allocated random to one of two groups: a standard group ($n = 15$) with low flow anaesthesia (1.2–1.3 litre min^{-1}) and manual control of gas concentrations and a fuzzy group ($n = 15$) with minimal flow (0.5 litre min^{-1}) and fuzzy logic feedback control of gas concentrations. Fuzzy logic control achieved and maintained very accurately the desired isoflurane concentration. Oxygen concentration was controlled more precisely than in the standard group. Delivery and costs of oxygen and nitrous oxide were significantly lower in the fuzzy group ($P < 0.01$). Accumulation of foreign gases was observed in one patient during low flow and in 11 patients during minimal flow anaesthesia. In conclusion, fuzzy logic control of inspired oxygen and isoflurane concentration during minimal flow anaesthesia was reliable and reduced anaesthetic gas delivery and costs. (*Br. J. Anaesth.* 1996; **76**: 245–250)

Key words

Anaesthetic techniques, low flow. Anaesthetics volatile, isoflurane. Computers. Model, computer simulation.

General anaesthesia is usually performed by delivering a fresh gas flow of 1.5–6 litre min^{-1}. As flow is increased, increasing amounts of anaesthetic gases are lost through the escape valve [1]. This increases costs [2] and results in a potential health hazard to personnel [3, 4] and destruction of the ozone layer [5]. Furthermore, a high fresh gas flow results in cold and dry inspired gases that may damage the tracheal epithelium [6].

Closed-circuit anaesthesia minimizes these untoward effects, but cannot be undertaken with many circle systems, mainly because of the high leakage rate, the presence of a hanging bellow which may cause negative pressures in the system and inaccuracy of flowmeters. These restrictions apply to a lesser extent to minimal flow anaesthesia, in which a fresh gas flow of 0.5 litre min^{-1} is delivered. Leakage rates of less than 50 ml min^{-1} can usually be tolerated. Therefore, unlike closed-circuit, minimal flow anaesthesia can be performed with many of the circle systems available. Moreover, it is not necessary to continuously adjust oxygen delivery to maintain the volume of the system.

However, when using this technique, the inspired gas concentrations do not correspond with those in the fresh gas because of mixing with exhaled alveolar gases.

The aim of this study was to evaluate the use of feedback control of inspired oxygen and isoflurane concentration during minimal flow anaesthesia performed by anaesthetists not trained in the minimal flow technique. The system was based on fuzzy logic [7, 8]. In order to compare the performance of the feedback system with a widely used anaesthetic technique, a group of patients undergoing low flow anaesthesia (1.2–1.3 litre min^{-1}) with manual control of inspired oxygen and isoflurane concentrations was also studied.

Patients and methods

We studied 30 ASA I–II patients, undergoing microsurgical fenestration and discectomy for lumbar disc herniation ($n = 26$) or cervical microdiscectomy with interbody fusion ($n = 4$). Patients with coronary artery disease and diabetes mellitus were excluded. The study was approved by the local Ethics Committee and written informed consent was obtained from all patients.

Two groups were studied. In the standard group, anaesthesia comprised the routine method of our department, that is a fresh gas flow of 1.2–1.3 litre min^{-1} and manual control of inspired oxygen and isoflurane concentrations. In the fuzzy group, minimal flow anaesthesia (0.5 litre min^{-1}) was undertaken with fuzzy logic feedback control of inspired oxygen and isoflurane concentrations. The anaesthetist set the desired inspired oxygen and isoflurane

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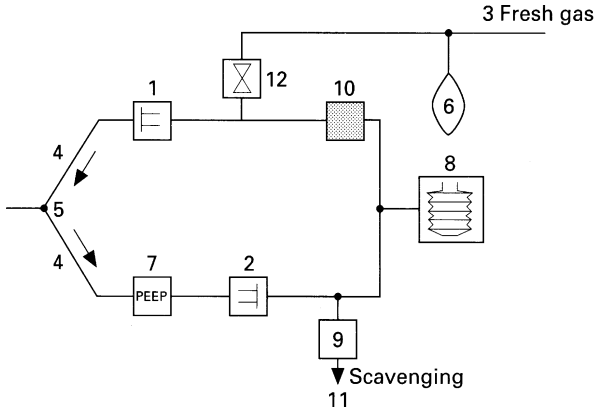

Figure 1 Simplified diagram of the anaesthetic system (Dräger Cicero IPPL). 1 = Inspiratory valve; 2 = expiratory valve; 3 = fresh gas inlet port; 4 = breathing tube; 5 = Y-piece; 6 = reservoir bag; 7 = PEEP valve; 8 = ventilator; 9 = overflow valve; 10 = carbon dioxide absorber; 11 = scavenging port; 12 = valve.

concentrations and the control system adjusted oxygen and isoflurane delivery to achieve and maintain the desired concentrations. The principles of fuzzy logic control are described in the appendix.

Patients were allocated randomly to each of the two groups on an alternate basis. They were premedicated with midazolam 7.5 mg orally, 30 min before induction of anaesthesia. Ringer's lactate 4 ml kg^{-1} was infused rapidly before induction of anaesthesia, followed by 2 ml kg^{-1} h^{-1} before surgery, 4 ml kg^{-1} h^{-1} during surgery and 2 ml kg^{-1} h^{-1} after skin closure. Anaesthesia was performed by staff members, residents or nurse anaesthetists with at least 1 yr experience in anaesthesia; they were not involved in the study but an anaesthetist involved in the study was always present.

After 3 min preoxygenation with 8 litre min^{-1} of 100 vol % oxygen via a face mask, anaesthesia was induced with fentanyl 1 μg kg^{-1} i.v. and thiopentone 5–7 mg kg^{-1}. The trachea was intubated after administration of vecuronium 0.1 mg kg^{-1}. After intubation, 30 vol % inspired oxygen and nitrous oxide, and isoflurane were delivered. The isoflurane concentration was set by the anaesthetist or nurse anaesthetist responsible for anaesthesia, without any influence from the anaesthetist involved in the study, to maintain systolic arterial pressure at 90–140 mm Hg. Vecuronium 1–2 mg was administered to maintain 0–2 responses to train-of-four stimulation of the ulnar nerve, evaluated visually. No other drug was administered until extubation.

After intubation, fresh gas flow was set to 4 litre min^{-1} for 15 min. Flow was then reduced to 1.2–1.3 litre min^{-1} in the standard group and 0.5 litre min^{-1} in the fuzzy group. To prevent accumulation of non-anaesthetic gases, when the cumulative inspired concentration of oxygen, nitrous oxide and isoflurane was lower than 85 vol %, fresh gas flow was increased manually to 10 litre min^{-1} until a total concentration of 97 vol % was achieved. After skin closure, flow was increased to 6 litre min^{-1} in both groups. Residual neuromuscular block was antagonized with neostigmine 2.5 mg i.v. and glycopyrronium 0.5 mg i.v. When four equal responses to train-of-four stimulation were observed, nitrous oxide was discontinued and 100 % oxygen was administered. The trachea was extubated as soon as the patient opened the eyes to verbal command.

The period of the study was divided into three parts: induction, from the beginning of preoxygenation to the end of high flow anaesthesia; maintenance, from the beginning of low-minimal flow anaesthesia to the end of surgery; recovery, from the end of surgery to extubation.

We used the Cicero workplace anaesthesia machine (Drägerwerke AG, Germany) (fig. 1). This allows monitoring of ECG, non-invasive arterial pressure (measured every 2.5 min), haemoglobin oxygen saturation using pulse oximetry, and inspired and end-tidal concentrations of oxygen, nitrous oxide and isoflurane sampled at the mouthpiece of the tracheal tube. For safety reasons the same gases were sampled at the mouthpiece of the tracheal tube with an additional monitor (Hewlett Packard M 1025B, Andover, USA). Gas sampled for analysis was returned by connecting the outlet port of both monitors with the expiratory limb of the breathing system.

In the fuzzy group, the anaesthetist or nurse responsible for anaesthesia set fresh gas flow, isoflurane and oxygen concentrations using three dialling buttons on an analogue control panel. The target for inspired oxygen concentration was 30 vol %. The values of inspired concentrations of oxygen and isoflurane set in the control panel represented the desired concentrations, that is the information that the anaesthetist fed into the fuzzy system, which in turn set the flowmeter and vaporizer to achieve and maintain the desired concentrations. The fuzzy logic system controlled a Dräger 19.3 vaporizer driven by an external servo-motor. The servo-motor itself was driven by a PID-controlled amplifier, which in turn was controlled by an electronic interface. The vaporizer driver was built in our laboratory and had been used in a previous investigation [9]. It has an immediate response time without overshooting. The vaporizer and PID control system had been calibrated by gas chromatography. The relation between setting and output was linear with flows of 0.5–5 litre min^{-1}. For safety reasons, the isoflurane concentration in the fresh gas was measured using a Hoyer PAAM gas analyser (Hoyer, Bremen, Germany). Two mass flow controllers (Bronkhorst Hi-Tec, Ruurlo, the Netherlands) were used to supply a precise flow of nitrous oxide and oxygen. They can deliver gas flows from 0.24 to 12 litre min^{-1} with an error of ± 0.2 % of maximum flow and ± 1 % of actual flow. Lower gas flows were obtained by intermittently switching off the flows. The Cicero vaporizer and flowmeters were bypassed. Whenever the anaesthetist desired a rapid change of inspired gas concentrations, a "turbo-mode" could be activated. This resulted in a temporary increase in fresh gas flow to 10 litre min^{-1} until the desired concentration was achieved. Whenever the inspired oxygen concentration was less than 26 vol %, the control system temporarily increased the oxygen fresh gas flow to 4 litre min^{-1} until the inspired oxygen concentration reached 26 vol %.

We used two separate static logic fuzzy controllers for oxygen and isoflurane. Both had fixed rules and a cycle time of 10 s. The fuzzy logic controller of inspired oxygen concentration determined the variables of a PID controller. The inputs were the error between desired and measured value, and fresh gas flow. That for inspired isoflurane concentration had three inputs: error between desired and measured values, its integral and fresh gas flow.

In the standard group the anaesthetist or nurse changed the fresh gas flow, and isoflurane and oxygen concentrations using the control panel. The mass flow controllers and vaporizer described above were used. The set values of isoflurane and oxygen concentrations, however, represented the fresh gas concentration as during a normal anaesthetic procedure, the only difference being that the anaesthetist used the panel instead of the vaporizer and flowmeters directly. The target for inspired oxygen concentration during the maintenance period was 30 vol %. In the standard group the "turbo-mode" and the automatic increase in fresh gas flow, when the inspired oxygen concentration was lower than 26 vol %, were not available.

Desired and measured inspired concentrations of oxygen and isoflurane, fresh gas flows, fresh gas concentration of isoflurane and arterial pressure were sampled using the Cicero every 10 s and stored on a IBM compatible computer. The resolution of the measurement of isoflurane concentration was 0.1 vol %.

DATA ANALYSIS

Control of inspired oxygen concentration in the two groups was compared by computing the duration of episodes during which oxygen concentration was between 28 and 32 vol %.

The ability of the fuzzy control to achieve rapidly the desired isoflurane concentration is described as the time needed to change the isoflurane concentration, calculated as follows: time from change of isoflurane concentration to achievement of desired concentration, divided by the difference between previous and desired inspired concentration. Changes of 0.1 vol % were not analysed. Increasing and decreasing concentration of isoflurane were calculated separately. Overshoot was analysed by averaging the maximum difference between measured and desired isoflurane concentration observed during the first 2 min after achieving the desired concentration. The ability of fuzzy logic to maintain the desired isoflurane concentration was described by the frequency distribution of the deviation (*measured–desired*) *isoflurane concentration*, beginning 2 min after achieving the desired concentration, until the concentration was changed again.

Fresh gas delivery of oxygen and nitrous oxide was recorded using the set point signals of the mass flow controllers, and expressed as the mean of all values of fresh gas flow during each phase (induction, maintenance and recovery) in each patient. Isoflurane delivery was computed by calculating the mean of the product (total fresh gas flow × fresh gas concentration of isoflurane) during each phase in each patient. The fresh gas concentration of isoflurane represented the fraction of gas set at the vaporizer (e.g. 2 vol % = 0.02). Costs of oxygen, nitrous oxide and isoflurane were calculated by multiplying the delivery by the price of each agent.

The stability of anaesthesia was evaluated by computing the duration of episodes during which systolic arterial pressure was between 90 and 140 mm Hg.

Numerical variables in the two groups were compared by Student's *t*-test when data were distributed normally, otherwise the Mann–Whitney *U* test was used. Normality was checked by the Wilk–Shapiro test [10]. Categorical variables were analysed by Fisher's exact test. $P < 0.05$ was considered significant. The statistical package used was RS/1, version 4.3.3 (Bolt Beranek and Newman Inc., Cambridge, MA, USA).

Results

Patient characteristics, and duration of surgery and recovery phase are presented in table 1.

During maintenance, the inspired oxygen concentration remained at 28–32 vol % for a longer period in the fuzzy than in the standard group (table 2). In one patient in the fuzzy group and in five in the standard group, the inspired oxygen concentration reached a value of 26 vol %, once in each patient. The minimal value was 24 vol %, which occurred once in both groups. No particular event (e.g. disconnection, airways obstruction, etc.) preceded these decreases in the inspired oxygen concentration. When the critical value of 26 vol % was reached in the fuzzy group, the inspired oxygen concentration was increased automatically by the control system by increasing the oxygen fresh gas flow to 4 litre min^{-1}.

The performance of fuzzy logic control of inspired isoflurane concentration is described in table 3. Inspired isoflurane concentration was changed 125 times during the maintenance period. In 13 instances (nine patients) the desired concentration was achieved by activating the "turbo-mode", in nine instances isoflurane concentration was changed by 0.1 % and in 52 the set point was changed again before the desired concentration had been achieved. In eight instances in which the desired concentration was reached, the set point had been increased (decreased) while isoflurane concentration was still decreasing (increasing), and before the previous desired concentration had been achieved. All of these 82 changes in isoflurane concentrations were not analysed. Thus, 26 increases and 17 decreases in inspired isoflurane concentration are shown in table 3. The ability of the system to maintain isoflurane concentration was expressed by the frequency distribution of the deviation (measured–desired) isoflurane concentration, measured 2 min after achieving the desired concentration, until the concentration was changed again. This phase lasted 30 s or less in seven instances, which were therefore excluded from analysis. Thus the ability of the system to maintain isoflurane concentration was analysed in 36 instances (table 3).

Table 1 Patient characteristics, and duration of surgery and recovery phase (median (25–75 percentiles))

	Standard group	Fuzzy group	*P*
Sex (M/F)	7/8	8/7	ns
Age (yr)	41 (35–51)	43 (37–49)	ns
Weight (kg)	72 (60–77)	77 (67–86)	ns
Preop. systolic arterial pressure (mm Hg)	120 (110–130)	130 (120–140)	<0.05
Duration of surgery (min)	75 (58–109)	85 (52–117)	ns
Recovery phase (min)	17 (14–24)	16 (13–22)	ns

Table 2 Control of inspired oxygen (O_2) concentration in the two groups during the maintenance phase. The duration of episodes during which the concentration was between 28 and 32 vol % below 28 and above 32 vol % are expressed as percentage of duration of the maintenance period. Median (25–75 percentiles) values are presented

	Standard group	Fuzzy group	*P*
O_2 concn 28–32 vol % (% of duration of period)	64 % (47–94 %)	82 % (76–91 %)	<0.01
O_2 concn <28 vol % (% of duration of period)	2 % (0–10 %)	1 % (0–4 %)	ns
O_2 concn >32 vol % (% of duration of period)	23 % (5–42 %)	17 % (9–20 %)	<0.05

Table 4 Stability of anaesthesia in the two groups during the maintenance period, evaluated by stability of systolic arterial pressure (SAP). The duration of episodes during which SAP was between 90 and 140 mm Hg, less than 90 and greater than 140 mm Hg are expressed as percentage of duration of the maintenance period. Median (25–75 percentiles) values are shown. No statistically significant difference between the two groups

	Standard group	Fuzzy group
SAP 90–140 mm Hg (% of duration of period)	97 % (91–100 %)	96 % (91–100 %)
SAP <90 mm Hg (% of duration of period)	0 % (0–0 %)	0 % (0–0 %)
SAP >140 mm Hg (% of duration of period)	1 % (0–7 %)	2 % (0–9 %)

The duration of episodes during which systolic arterial pressure was less than 90 or greater than 140 mm Hg is presented in table 4. Table 5 shows the inspired concentrations, delivery and costs of gases.

In four patients in the fuzzy group, 4–29 min after the beginning of minimal flow, low volume of gas in the circuit was detected by the alarm system. The volume was restored by briefly pressing the oxygen flush button. Median body weight of these patients was higher than that of the other 11 patients (87.5 and 73 kg, range 65–100 and 61–90, respectively), but the difference was not statistically significant.

In 11 patients in the fuzzy group and in one in the standard group, fresh gas flow had to be set at 10 litre min^{-1} for 45–60 s, because of high concentration of non-anaesthetic gases. This occurred in the fuzzy group for the first time 18–41 min after the beginning of minimal flow (median 22 min) and a total of 1–5 times in different patients. Within the fuzzy group, median body weight of the 11 patients who required high flow was higher than that of the other four patients (79 and 70 kg, range 62–100 and 61–77, respectively), but the difference was not statistically significant.

Discussion

We have assessed the performance of fuzzy logic control of inspired oxygen and isoflurane concentrations during minimal flow anaesthesia. As only the research anaesthetists involved in the study (and not those performing clinical anaesthesia) were familiar with the minimal flow technique, we could not study a control group of patients undergoing minimal flow anaesthesia with manual control of

Table 3 Description of the performance of fuzzy logic feedback control of inspired isoflurane concentration during the phase of minimal flow. n = Number of increases (n_1) and decreases (n_2) of isoflurane concentrations and of phases during which isoflurane concentration was not changed (n_3), which were included in the analysis. The first two variables describe the ability of the feedback system to achieve the desired isoflurane concentration, whereas the last one describes the ability to maintain the desired concentration, beginning 2 min after achieving the desired concentration, until the concentration was changed again. The 13 occasions when the "turbo-mode" was manually activated are not included. Median (25–75 percentiles) values are presented

Time to increase inspired isoflurane concn (s vol $\%^{-1}$) ($n_1 = 26$)		700 (540–850)
Overshoot after increasing isoflurane concn (vol %) ($n_1 = 26$)		0.1 (0.1–0.2)
Time to decrease inspired isoflurane concn (s vol $\%^{-1}$) ($n_2 = 17$)		660 (360–1130)
Overshoot after decreasing isoflurane concn (vol %) ($n_2 = 17$)		0.1 (0.1–0.2)
Frequency distribution of the deviation (measured − desired isoflurane concentration when isoflurane concentration was not changed ($n_3 = 36$)	$\leqslant -0.3$ vol %	0 %
	−0.2 vol %	3 %
	±0.1 vol %	94 %
	+0.2 vol %	3 %
	$\geqslant 0.3$ vol %	0 %

Table 5 Median (25–75 percentiles) values of inspired concentration, delivery and costs of inhaled agents in the two groups during the maintenance period. Inspired concentrations were recorded every 10 s, and the values shown represent medians and 25–75 percentiles of the mean values calculated for each patient

	Standard group	Fuzzy group	*P*
Inspired concentrations			
Oxygen (vol %)	30 (29–31)	30 (30–31)	ns
Isoflurane (vol %)	0.9 (0.8–1.2)	0.9 (0.7–1.1)	ns
Delivery			
Oxygen (litre min^{-1})	0.59 (0.52–0.64)	0.34 (0.31–0.40)	<0.01
Nitrous oxide (litre min^{-1})	0.94 (0.80–1.07)	0.32 (0.25–0.39)	<0.01
Isoflurane (ml gas min^{-1})	18.2 (13.3–25.7)	16.2 (9.4–18.5)	ns
Costs			
Oxygen (Swiss Francs h^{-1})	0.05 (0.05–0.06)	0.03 (0.03–0.04)	<0.01
Nitrous oxide (Swiss Francs h^{-1})	1.02 (0.86–1.15)	0.35 (0.27–0.42)	<0.01
Isoflurane (Swiss Francs h^{-1})	6.40 (4.67–9.04)	5.68 (3.30–6.49)	ns
Total (Swiss Francs h^{-1})	7.36 (5.59–10.17)	6.02 (3.65–6.98)	<0.05

inspired gas concentrations. However, although the standard group does not represent a true control group because of the different fresh gas flow used, it allows comparison of fuzzy controlled anaesthesia with a widely used anaesthetic technique. However, control of inspired oxygen and isoflurane concentrations is easier during low flow than during minimal flow anaesthesia and therefore, the experimental design was biased *against* the fuzzy logic system.

One may wonder why we developed a system controlling inspired isoflurane concentration, as most anaesthetists think in terms of end-tidal concentration and previous studies have shown good control of end-tidal concentration with other feedback algorithms [11, 12]. One reason is that end-tidal feedback control may not be feasible or reliable in some situations, such as during spontaneous ventilation or anaesthesia in children with a face mask. Furthermore, unlike the aforementioned studies [11], we used minimal flow anaesthesia, and the desired concentration was not fixed during operation [12] but changed according to anaesthetic requirements. During minimal flow anaesthesia there is usually a large difference between end-tidal and fresh gas concentrations and the response of end-tidal concentration to changes in the fresh gas concentration is very slow. Because of these features it is difficult to develop an automatic system controlling end-tidal concentration by directly adjusting fresh gas concentration. We therefore developed a system to control inspired concentration, which can be used later in the control of end-tidal concentration in a cascade feedback system.

The control of inspired oxygen concentration in the fuzzy group was more precise than in the standard group, in spite of the lower fresh gas flow delivered (table 2).

Fuzzy logic control achieved and maintained the desired inspired concentration of isoflurane during minimal flow anaesthesia very accurately: overshoot was not observed and the desired concentration ($\pm$ 0.1 vol %) was maintained for 94 % of the time (table 3). The long time needed to achieve the desired concentration (table 3, which does not include the occasions when the "turbo-mode" was activated) was the result of the very low fresh gas flow delivered. The anaesthesia machine, Physiophlex (Physio BV, Hoofddrops, The Netherlands), allows feedback control of gas concentrations during closed-circuit anaesthesia. The presence of a turbine hastens gas mixing. This allows rapid achievement of inspired concentration when the fresh gas concentration is changed, thereby facilitating development of a feedback system. Such a technical feature is not available in conventional anaesthetic systems, such as that used in our study.

It was not possible to compare the two groups in terms of control of inspired isoflurane concentration, as in the standard group the anaesthetist controlled the fresh gas concentration and was not requested to specify a desired inspired concentration. This was avoided because the anaesthetists were used to adjusting the vaporizer to reach a desired end-tidal concentration or a pharmacological effect, but not a specific inspired concentration.

During minimal flow anaesthesia a decrease in the volume of gas in the anaesthetic system was observed in four patients, probably because of persisting nitrous oxide uptake of the patient. Accumulation of foreign gases in the circuit, a well-known disadvantage of closed-circuit anaesthesia [13], occurred frequently. Accumulation of nitrogen causes dilution of oxygen and anaesthetic agents. High blood concentrations of acetone after long-term closed-circuit anaesthesia increase the incidence of postoperative nausea and vomiting [14]. Methane accumulation can disturb infrared analysis of volatile anaesthetics [15]. Frequent flushing of the system with high fresh gas flows to remove foreign gases partially offsets the advantages of the minimal flow technique. Flushing of the anaesthesia circuit rapidly removes nitrogen and methane from the system [13], but does not decrease blood concentrations of acetone during long-term closed-circuit anaesthesia [14]. At present it is not known if blood concentrations of acetone increase during minimal flow anaesthesia.

Unlike oxygen and nitrous oxide delivery, isoflurane delivery in the fuzzy group was not significantly lower than in the standard group ($P = 0.06$). This was in part the result of frequently flushing the system with high flows because of accumulation of foreign gases. This factor would have had a lower

impact if we had studied longer operations, as nitrogen elimination from the body decreases with time. Furthermore, as a result of different individual requirements, inspired isoflurane concentration and delivery varied greatly (table 5). Therefore, the expected small difference in isoflurane delivery between low flow and minimal flow anaesthesia might only be detected by studying a large patient population.

Appendix

INTRODUCTION TO FUZZY LOGIC CONTROL

Fuzzy logic

By *crisp objects* we imply that something is of a yes-or-no-type rather than a more-or-less-type. For instance, in a set of individuals we may say "John is a boy". But if we wish to define body height and decide that a person of 170 cm or more is tall and the rest are short, we have to classify Peter, who is 169.9 cm, as "short", and John, who at 170 cm is only 1 mm taller, as "tall". In order to avoid this dilemma fuzzy logic is introduced, that is the boundaries of a set are *fuzzy* instead of *crisp*. This makes it possible to classify an element as being *to a certain degree* a member of a set, by introducing membership function values between 0 and 1 [16]. It should be noted that fuzzy sets and continuous membership functions are closer to human thinking.

Fuzzy logic and probability theory are different. Probability theory deals with questions such as: "there are 30 white balls and 70 black balls in a bag. I draw a ball without looking. Is this ball black?" Answer: "with a 70 % probability it is." Fuzzy logic deals with questions such as: "I have a grey ball. Is this ball black?" Answer: "we assign the value 0 for absolute white and 1 for absolute black. The statement "the ball is black" has a truth value of, say, 0.2 (the ball is light grey)". Thus fuzziness does not imply randomness [17].

Knowledge-based control

The classical controller calculates the input signal of the plant to be controlled based on the difference between a reference signal and the actual output of the plant. For instance, a so-called PID controller considers the error, its integral and its range of change in computing the input signal for the "plant" according to a mathematical formula. It is also possible to design a controller which uses a knowledge base to perform the controller function. For instance, it is possible to control the speed of a car so that it is constant with the following set of rules:

IF (speed is very low) THEN (accelerate sharply)
IF (speed is low) THEN (accelerate slightly)
IF (speed is high) THEN (decelerate)
IF (speed is very high) THEN (brake)
IF (speed is low AND road is uphill) THEN (accelerate sharply)

The values for "very low", "low", etc., have to be defined crisply.

Fuzzy control

A fuzzy controller is a knowledge-based controller where the variables have fuzzy instead of crisp values. It consists of: a *fuzzification module* which performs linguistic classification of variables; a *fuzzy knowledge-base* similar to a regular knowledge-base as in the car example containing rules of the type IF (error is slightly negative) THEN (fresh gas concentration is small); an *inference engine* which uses the fuzzy rules in the knowledge-base to produce a fuzzy control output based on control inputs; and a *defuzzification module* which determines a crisp control value from a fuzzy control value.

Acknowledgement

We thank Pasquale Scaramozzino, PhD, lecturer in the Department of Economics at SOAS University of London, UK, for his comments on the statistical methods.

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