Automatic electropolishing of cobalt chromium dental cast alloys with a fuzzy logic controller *

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Abstract – Cavities and ageing leads to a higher demand for robust and durable dentures. Cobalt chromium dental cast alloys fulfill these requirements. After the casting, the alloys have to be thoroughly cleaned in an electrochemical dissolution bath. In the existing technology an expert has to control the polishing process. In this paper we present a fuzzy logic controller with 16 fuzzy rules, which completely automatize the polishing process of cobalt chromium cast alloys. The user has to only put the untreated cast alloys in the polishing machine and press the start button. Our experiments have shown, that the treated dentures have a consistent, very high quality during the service life of the electrolyte. Furthermore, the exchange point of the electrolyte is also automatically determined. The proposed strategy can be extended to other polishing processes with different cast alloys or electrolyte concentrations.

Keywords: fuzzy control, fuzzy rules, electrochemical polishing, electrochemical machining, electrolytic brightening, anodic dissolution, cobalt chromium dentures, electrolyte state.

Introduction

Electrochemical metal removal (ECMR) is the general name for a number of metalworking processes used for dissolving metal from workpiece surfaces in place of the conventional machining operations [Burk91]. A special field of application ECMR is the electrochemical dissolution of denture constructs. Such artificial teeth are used to bridge gaps which are caused by cavities or ageing. To allow food intake without difficulty, the dentures have to be very smooth and shiny. The first production step requires a perfect casted construct. These constructs (dentures) consist of a very rough cobalt chromium alloy that has to be thoroughly cleaned and polished. However, the dentures cannot be sufficiently polished mechanically because of their shape and roughness. So, electrochemical polishing using low concentrated sulphuric acid as an electrolyte is one adequate handling method [Sieg68] to polish the surface of the denture cast alloys. The main characteristics are defined in the German guiding rules VDI 3401, page 2 [VR72].

The state of the art requires manual control of these extremely nonlinear polishing processes. The user has to adjust specific parameters for each denture's shape, size and number, which vary with the environment, (*eg* the temperature or the state of the electrolyte. The variety of the marginal conditions and the nonlinear dependencies of the parameters is the reason for a missing mathematical model as well as the absences of an automatic polishing process. It was shown in a couple of experiments, that the polishing result varies for the same user. Nevertheless, the user has some vague and imprecise rules for the dependencies of the polishing parameters. The difficulty in compiling the control know-how is due to the nonlinear, time varying behaviour of the system and the poor quality of the available measurements. Fuzzy control seems to be a possibility to incorporate these rules and to im-

Figure 1: Cobalt chromium denture

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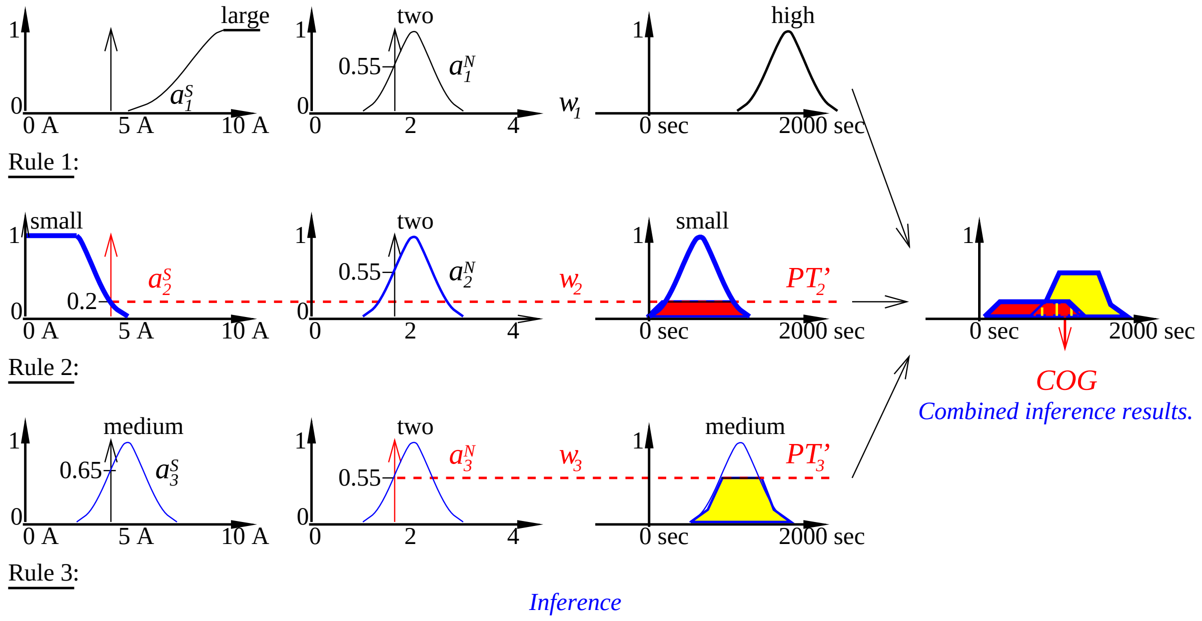

Figure 2: Fuzzy controller algorithm

plement them in an automatic control algorithm. Fuzzy rule-based systems (FRBS) or fuzzy logic controllers are important tools for modeling complex systems. To mirror natural language concepts, fuzzy logic replaces true and false with continuous membership values ranging from zero to one. This allows the processing of linguistic concepts (adjectives, adverbs) like “small”, “big”, “near”, or “approximately” in the control system. The main advantage is to control processes that are too complex to be mathematically modeled in real-time. So, the basic idea of this approach is to incorporate the know-how of a skilled human operator into fuzzy sets and fuzzy rules, which would then be combined by the fuzzy implication and the compositional rule of inference.

Before we describe the polishing process of dental cast alloys in section three and the design of the fuzzy logic controller in section four, a formal, brief overview of fuzzy control is given in the next section. An extended introduction to fuzzy control can be found in many good textbooks, *eg* [Kosk91, Dria93]. Furthermore, the properties of our new approach and the hardware implementation are described in section five and six.

Basic terms of Fuzzy Controllers

The fuzzy control algorithm is based on the generalized modus ponens inference rule [Wata90]:

Premise:	A is true
Implication:	If A then B
Conclusion:	B is true

Fuzzy functions replace “crisp” propositions A and B. These functions characterize and define fuzzy sets through $\mu_i : U \to [0,1]$ with $x \mapsto \mu_i(x)$, so $i = \{(x, \mu_i(x)) | x \in U, \mu_i(x)\}$. Zadeh [Zade65] defines fuzzy sets in three important fuzzy operations:

Intersection C = A ∩ B,

$$\mu_C(x) = \min(\mu_A(x), \mu_B(x))$$

Union C = A ∪ B,

$$\mu_C(x) = \max(\mu_A(x), \mu_B(x))$$

Complement $\bar{A}$,

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x)$$

A, B and C are fuzzy sets and U is the universe of discourse for x. These fundamental operations together with the set [0,1] forms a fuzzy algebra, so that any logic function can be built. After Zadeh’s basic work a lot of other fuzzy operations have been defined [Yage80, Zimm90]. The important operations fulfill the triangular norm (t-norm, *eg* minimum) or t-co-norm, *eg* maximum conditions. Instead of $\mu_A(x)$ we only write A to denote the fuzzy set A. Replacing continuous functions with unit pulses implements the Boolean algebra, a subset of the fuzzy algebra. In contrast to a conventional knowledge based system, the premise of the rule is a value in [0,1] instead of $\{0,1\}$. The example in Figure 2 introduces the basic fuzzy algorithm. It shows three simple rules for a polishing device with two inputs ($n = 2$) “size” (in Ampères) and “number” (of dentures) and one output ($m = 1$) “polishing-time” (in seconds). The “size” (surface) is measured by the current between the two dentures (Figure 3).

R1: IF size is large AND number is two
THEN polishing-time is high
R2: IF size is small AND number is two
THEN polishing-time is small
R3: IF size is medium AND number is two
THEN polishing-time is medium

The input values of the variables “size” and “number” are simultaneously switched to all the rules to be compared with the stored premises (IF parts). Now the truth values α_i^{size}, α_i^{number} for every sub-premise are calculated by:

$$\begin{aligned} \alpha_i^{size} &= \mu_{A_i}(size) && ,\ for\ A_i \in \{small, med.\} \\ \alpha_i^{number} &= \mu_{B_i}(number) && ,\ for\ B_i \in \{one, two\} \\ & && ,\ for\ i = 1 \ldots 3 \end{aligned} \tag{1}$$

$\alpha_2^{size} = 0.2$ and $\alpha_2^{number} = 0.55$ in rule 2 generates a rule matching or truth value of $\omega_2 = 0.2$, because the fuzzy logic conjunction “AND” is interpreted as the minimum of α_i^{size} and α_i^{number} ($\omega_i = \min(\alpha_i^{size}, \alpha_i^{number})$). $\alpha_1^{size} = 0.0$ indicates that the input does not match with the stored sub-premise at all, which leads to a complete non-contribution of rule 1 to the output. The conclusion of each rule is

$$PT_i' = \{\min(\omega_i, PT_i(x)) \mid x \in PT_i\}, \text{ for } i = 1 \ldots 3 \tag{2}$$

and represents the conclusion (THEN part) of each rule. The fuzzy result function PT' is the unification of all sub-results PT_i' and is calculated by:

$$PT' = \bigcup PT_i', \text{ for } i = 1 \ldots 3^1. \tag{3}$$

In most applications the output values are “crisp” numbers (unit pulses), which are accomplished by calculating the center of gravity (COG) of the resulting fuzzy function PT':

$$COG_{PT} = \frac{\int x \times PT'(x)dx}{\int PT'(x)dx} \tag{4}$$

The described FRBS with binary input and output values is called BIOFAM (Binary Input-Output Fuzzy Associative Memory) [Kosk91] or the MIN-MAX algorithm [Mamd74] with the COG used as defuzzification method.

The calculation of the fuzzy result function PT' and the center of gravity is the bottleneck during the computation of the fuzzy algorithm. Therefore, a modified result function calculation (FCOG) [Infr90, Surm95b] is suggested, in which the center of area M_i and the area A_i of a membership function are calculated before run time (l = number of output membership functions):

$$A_i = \int PT'(x)\ dx, \quad M_i = \int x \times PT'(x) dx$$

$$COG_{PT} = \frac{\sum_{i=1}^{l} \omega_i \times M_i}{\sum_{i=1}^{l} \omega_i \times A_i} \tag{5}$$

A fuzzy controller with multiple inputs and one output is called a MISO fuzzy controller. Each multiple input/multiple output (MIMO) fuzzy controller with *m* output variables is a unification of several MISO controllers. MIMO describes a partial, n-dimensional, nonlinear and dynamic free function $f : U \subseteq \boldsymbol{R}^n \rightarrow \boldsymbol{R}^m$ because the I/O behaviour of the FRBS depends only on the current input vector and the algorithm has no storing or delaying elements.

More mathematically the 6-tuple FRB = $(\mu_{ab}, R, T, I, T-CO, DEF)$ is a family of fuzzy controllers (FC) with the membership functions μ, the fuzzy rule base R, the t-norm fuzzy conjunction T, the implication I verifying $I(a,0) = 0\ if\ a \neq 0$ (*eg* a R-implication or t-norm), the t-co-norm T-CO and the defuzzification method DEF (*eg* center of gravity, maximum or FCOG). The main parameters for the FRBS are the number of fuzzy rules *k* and the position (*a*) and widths (*b*) of the input and output membership functions. Of prime importance is that FC $\in$ FRB is a universal approximator.

THEOREM 1 (Universal approximator) *Let FRB be the set of all FC and* $f : U \subseteq \boldsymbol{R}^n \rightarrow \boldsymbol{R}$ *be a continuous function defined on a compact U. For each* $\varepsilon > 0$ *there exists a* $FC_\varepsilon \in FRB$ *such that*
$sup\{\mid f(\vec{x}) - FC_\varepsilon(\vec{x}) \mid \ \mid \vec{x} \in U\} \leq \varepsilon.$

Castro [Cast93] provides the proof. Clearly, from a theoretical viewpoint a fuzzy controller performs the same actions as other universal approaches. The important part is, that the fuzzy rule-based approach is a high level, symbolic modeling technique. Since the fuzzy rules resemble much more closely the way humans explain general rules, the fuzzy controller algorithm easily defines the function f.

Electropolishing of cobalt chromium dental plate cast alloys

During electropolishing, a power supply unit forces an electric charge and material exchange (ions) between the dental plate (anode) and metanium sheet (cathode). The ions migrate towards conducting electrodes through an electrolyte (low concentrated sulphuric acid). The reaction environment is shown in Figure 3. In what follows, a simplified description of this electrochemical procedure is given.

Applying a voltage results in a charge exchange between the cathode and the anode in which the workpiece gets oxidized [VR72]. Furthermore, molecular oxygen arises on the positive electrode. The oxygen recombination is exothermal, that means a part of the supplied energy is converted into heat and the electrolyte heats up during polishing.

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[1] compositional rule of inference [Mamd74]

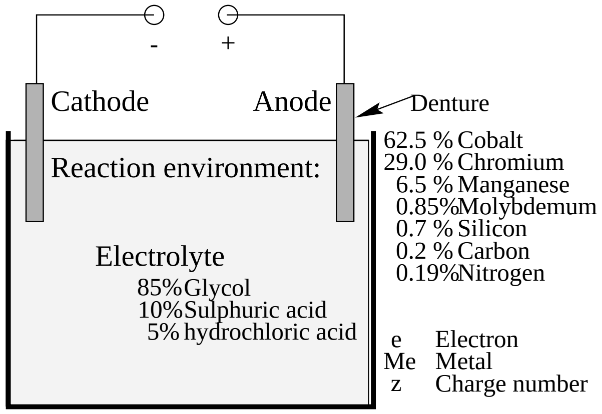

Figure 3: Polishing process. Reaction equation: $2e^- + 2H^+ \rightarrow H_2 \uparrow$, $Me \rightarrow Me^{2+} + 2e^-$, $Me^{2+} + 2OH^- \rightarrow Me(OH)_2 \downarrow$

On the cathode, hydrogen is reduced on the whole. The oxidized part of the atoms changes into ions in the electrolyte and forms soluble and insoluble chemical mixtures (Figure 3). The insoluble part can be recognized as a dark sediment in the electrolyte.

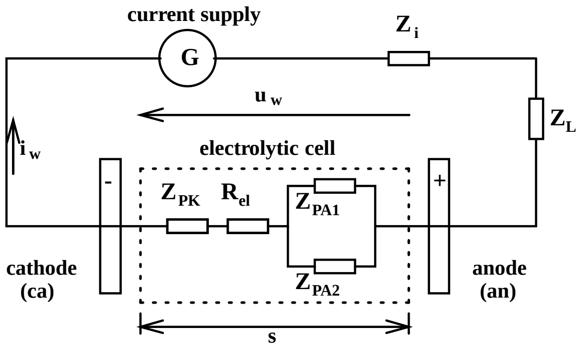

Figure 4: Circuit diagram of the polishing process with an external current supply

Figure 4 shows the electrical circuit diagram. The electrolytic cell contains the current supply G with its complex impedance Z_i and the wire and contact resistance Z_L. Z_L includes the current feeding the electrodes to the effective electrode area. Z_i consists of inductive and capacitive components of the current supply. The impedance Z_W of the cell consists of the polarisation resistance of the cathode (titanium) Z_{PK} and the anode Z_{PA} (dental plates) as well as the Ohmic electrolytic resistance between the cell R_{el}. R_{el} depends on the specific circuit capacity κ, the average distance s between the electrodes and the size of the effective electrode area of the anode (A) and the cathode (K) [VR72].

$$R_{el} = \frac{1}{\kappa} \frac{s}{A(K)} \tag{6}$$

Furthermore, the specific circuit capacity κ depends on the composition of the electrolyte solution as well as its concentration and temperature T_a. In particular, the circuit capacity κ changes on the border between the electrodes and the electrolyte during the operation. The effectiveness of the electrolyte mainly depends on the specific weight γ, the metal concentration G_m, the electrolyte concentration, the water concentration, the temperature, the viscosity and the specific circuit capacity κ. The durability L_d of the electrolyte and the momentum state E_z of the electrolyte are calculated by the number of Ampère hours taken.

Polishing parameters

The important parameters during the polishing process and their principle dependencies from each other are analysed with sheet steel in experimental studies ("Hull-Cell-Studies") [Venk91]. Some of the results of these studies can be adopted to cobalt chromium cast alloys. According to that, we find the following dependencies, which are supplemented with our own experiments [Huse94] [Surm95a]:

- The polishing result improves exponentially with the time t.

- A relative motion between the dental cast alloy and the electrolyte improves the brightening result during the polishing process. The motion of the workpiece causes the discharge of gas bubbles from it besides causing the removal of heat from the anode and electrolyte exchange on the denture surface.

- There is a nonlinear relationship between the polishing result and the temperature of the electrolyte. The higher the temperature the higher is the specific circuit capacity κ and the lower is the resistance R_{el}. However, temperatures over 55^{o}C lead to a condensation of the electrolyte and can burn the user if he touches the pan. So, temperatures over 55^{o}C have to be excluded because of injury to the user. Consequently, a working temperature of 48^o, ± 4^{o}C is chosen based on the restrictions in [Poll93].

- Furthermore, the current density S is important for the polishing result. The average current density S_a results from the applied current and the surface of the dentures. The current density S is the effective current i_w over each surface area unit. The density is different on the anode and the cathode. A current density S_a, which is too high "burns" the top of the dentures and sometimes big metal molecules burst out of the metal.

- The increasing service life L_d of the electrolyte deteriorates the polishing result (L_d is measured in

Ampère hours). The metal molecules, which are dissolved in the electrolyte change the circuit capacity, and with that the Ohmic resistance R_{el} of the electrolyte also changes. On the one hand, this shifts the current density and on the other, the polishing time needed to get satisfying results is extended. Furthermore, the optimum temperature is shifted higher. The change in the current density depending on the electrolyte state is a modeling uncertainty and is hence not considered. A new electrolyte contains only a few ions. So, the polishing time has to be increased during the initial polishing processes. The maximum material turnover on the work piece / electrolyte phase border is reached after a few polishing experiments. Figure 5 shows the activity depending on the bath concentration.

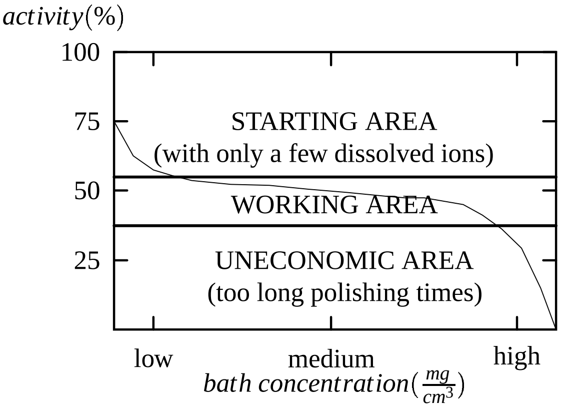

Figure 5: Activity line (in %) of chemical polishing processes depending on the electrolyte concentration

- The polishing result depends in a nonlinear way on the number of dentures in the electrolyte bath, i.e., the optimum current of a large denture is not equal to the optimum current of its half. That's why on the one hand, the distance s between the electrodes is different (eq. 6) because of the different two-dimensional arrangement of the dentures in the electrolyte, while on the other, the polishing process parameter κ changes on the border between the electrodes and the electrolyte during the operation.

State-of-the-art polishing machines[2] are **user**-controlled with a heating and cooling device to control the temperature of the electrolyte, a motor for the motion of the denture cast alloys and a power supply for the manual adjustment of the current [Frie90, Lind91]. Now, the goal is to automatize the polishing process with a rule-based fuzzy logic controller, so that the user has to only put in the dental plates and press the start button without any other adjustments. The fuzzy logic controller guarantees a consistent high quality polishing result independent of the denture size and the electrolyte state.

Design of the fuzzy logic controller

During polishing, the behaviour of the electrolytic cell is extremely nonlinear because of the parameter variations. Hence, the cell is considered as an uncertain system in general, without any closed analytical model. A skilled human operator also has some difficulties in consistently polishing the denture cast alloys optimally. On the one hand, estimating the size of the dentures is imprecise and so is estimating the basic polishing time. On the other hand, the operator estimates the state of the electrolyte manually. Particularly if different users operate the same polishing machine, there is high uncertainty about the electrolyte quality. So, the user cannot increase the basic polishing time in an optimal way.

The fuzzy rules and the membership functions for the linguistic variables were developed with our own fuzzy case-tools FunnyLab [Surm92] based on the subjective human experience described above. The 16 fuzzy rules presented in Figure 7 control the polishing process.

The rules 1-3 control the power of the motor – the power supply depends on the temperature of the electrolyte. The polishing process starts only if the temperature has reached the working point, (around 48^{o}C). The fuzzy rules 4-6 control the temperature of the electrolyte through the heating and cooling system. They monitor and control the system and keep it in the working point, around 48^{o}C. Depending on the number and size of the dental cast alloys, the fuzzy rules 7-12 determine the basic polishing time, the control voltage for the power supply and according to that, the current density. Depending on the electrolyte state, the basic polishing time increases (rules 13-16). Figure 8 shows the polishing process flowchart.

Figures 9 and 10 show the membership functions of the four linguistic input variables and the six linguistic output variables.

The universe of discourse of the membership functions is defined through our own experiments. It is worth mentioning, how the two linguistic variables "size" and "number" of the dental cast alloys are defined. For the calculation of the input values of these variables, a predefined control voltage is applied in the working temperature range. Then, the size of the denture (effective area of the anode) adjusts a determined resistance and a determined current, corresponding to equation 6. It is also necessary to consider the electrolyte state, because the specific circuit capacity κ determines the electrical resistance R_{el} (eq. 6), and κ depends on the electrolyte state. The size of a dental cast alloy is indicated through the current in ampères at the highest control voltage of the power supply to save computation time (Figure 9).

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[2] *ie* Dentalux 2 from Krupp Medicine Technic GmbH, Essen, Germany

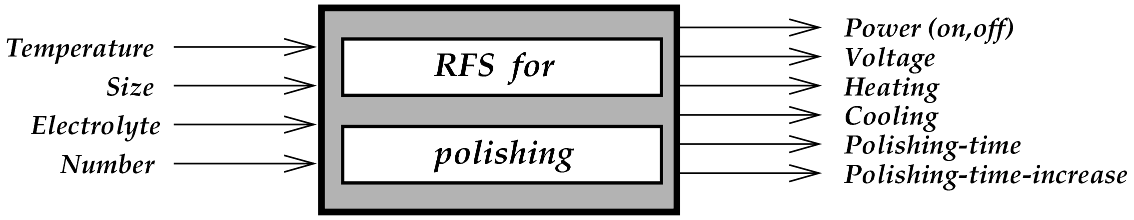

Figure 6: Linguistic variables of the fuzzy logic controller

1: IF Temperature is low THEN Power is off
2: IF Temperature is normal THEN Power is on
3: IF Temperature is high THEN Power is off

4: IF Temperature is too low THEN Heating is on AND Cooling is off
5: IF Temperature is medium THEN Heating is off AND Cooling is off
6: IF Temperature is too high THEN Heating is off AND Cooling is on

7: IF Number is one AND Size is very small THEN Polishing-time is very small AND Voltage is very small
8: IF Number is one AND Size is small THEN Polishing-time is small AND Voltage is small
9: IF Number is one AND Size is medium high THEN Polishing-time is high AND Voltage is medium high
10: IF Number is two AND Size is medium high THEN Polishing-time is medium AND Voltage is medium
11: IF Number is two AND Size is high THEN Polishing-time is medium high AND Voltage is high
12: IF Number is two AND Size is very high THEN Polishing-time is very high AND Voltage is very high

13: IF Electrolyt-state is new THEN Polishing-time-increase is very high
14: IF Electrolyt-state is good THEN Polishing-time-increase is zero
15: IF Electrolyt-state is medium THEN Polishing-time-increase is medium
16: IF Electrolyt-state is bad THEN Polishing-time-increase is high

Figure 7: The fuzzy rules

Simultaneous polishing of two dentures on the one hand reduces the average distance s between the anode and the cathode, and on the other increases the specific circuit capacity κ. Therefore, the electrical resistance decreases and the current increases. The resulting transition gap can be used to detect the number of dental cast alloys. With the bath dimensions of 25 cm × 10 cm × 10 cm, the large dental cast alloys require a current of $\approx 6A$ for one denture and $\approx 10A$ for two dentures. The values vary around $0.5A$ depending on the electrolyte state.

The authors of the “Hull-Cell-Studies” [Venk91] do precise reflection and weight loss measurements for the judgment of polishing results. Other verifying methods are: profile analysis, interference measurements and microscopic pictures of the polished surface [Burk91]. In our case, we used some reference dentures and classified them with a raster electron microscope. Figure 11 shows three reference dentures and their raster electron microscope pictures.

Properties of the fuzzy controlled polishing machine

Since our work is the first in the field of automatic polishing of cobalt chromium dental cast alloys [Surm94], it was not possible to compare the given rule base with other approaches. Nevertheless, an impression of the input/output behaviour of the fuzzy controller is presented by showing the dependencies defined through the fuzzy rules. Figure 12 shows the influence of the temperature on the heating and cooling system as well as on the voltage. The relays switch on if the output value $Defuzz(x) > 0.6$ and they switch off if the output value $Defuzz(x) < 0.4$. A relay

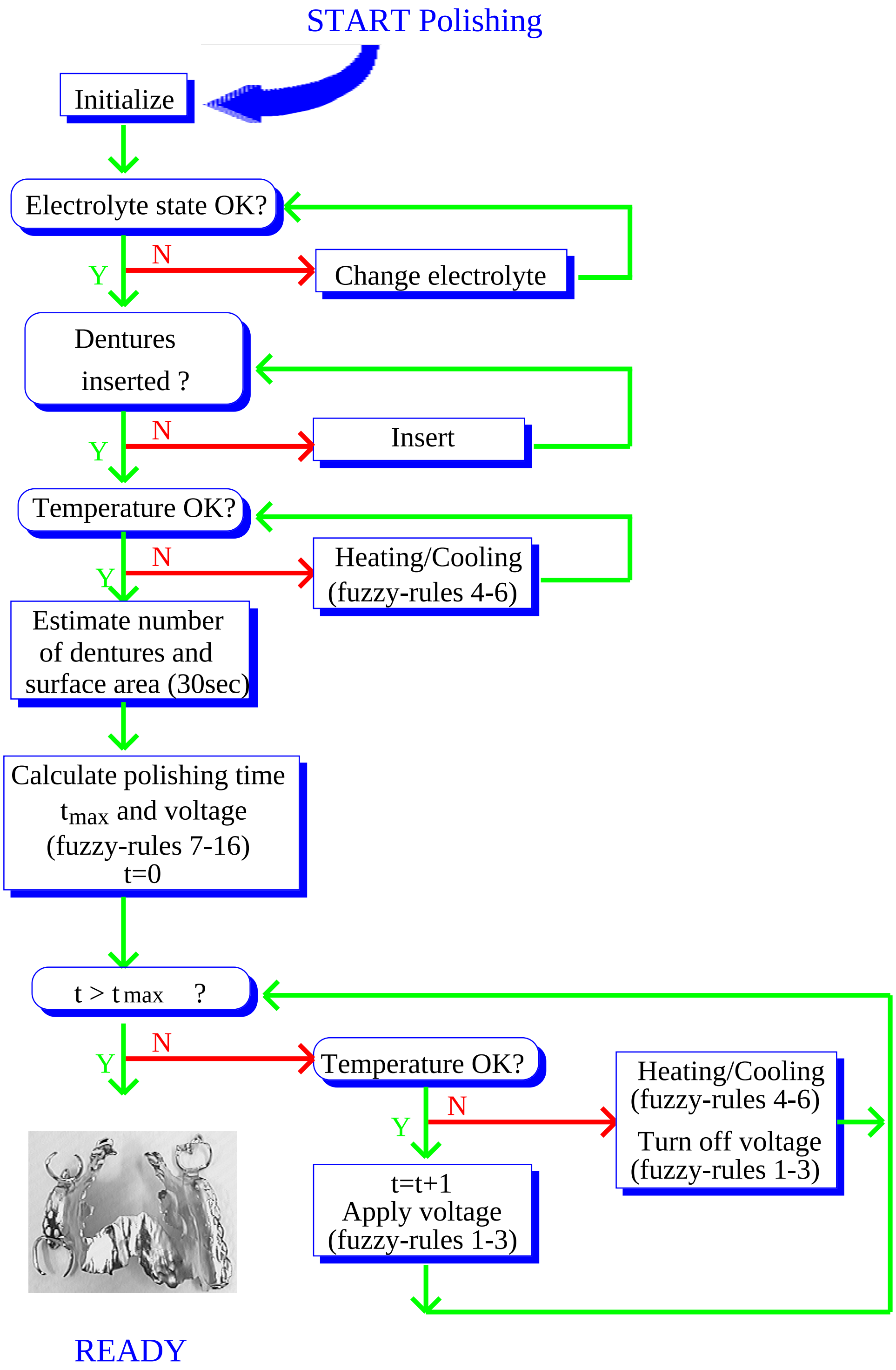

Figure 8: Polishing process flowchart

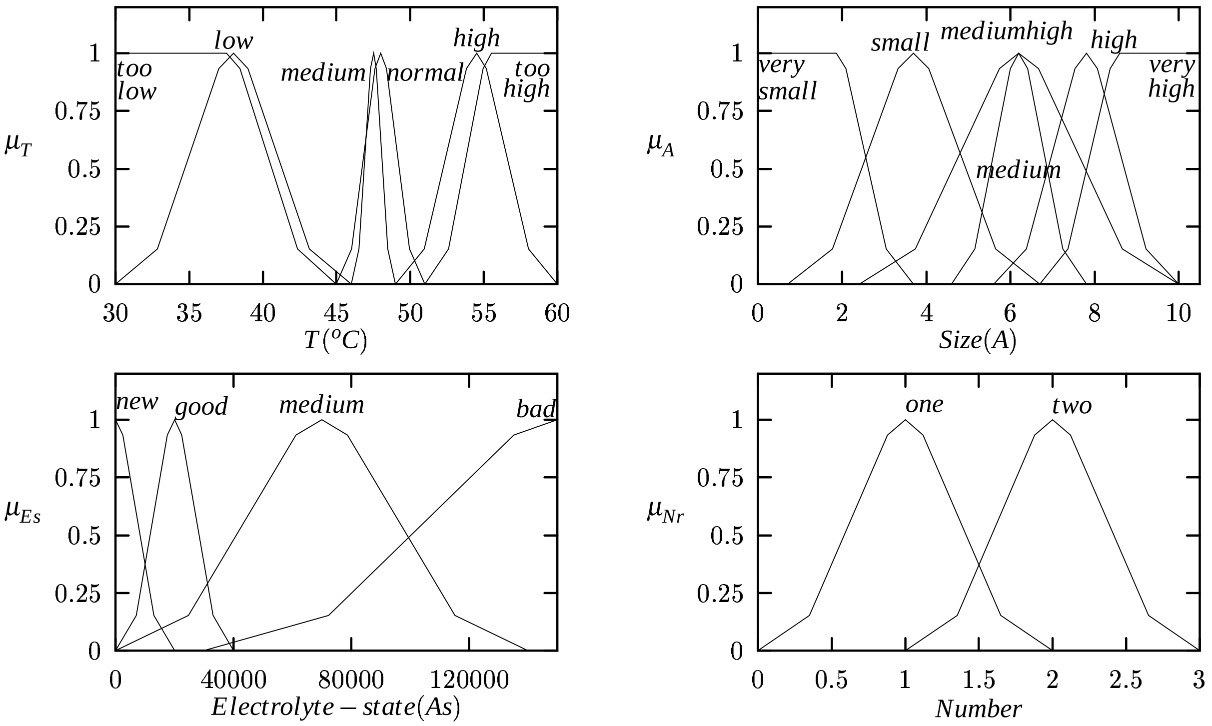

Figure 9: Membership functions of the four input variables

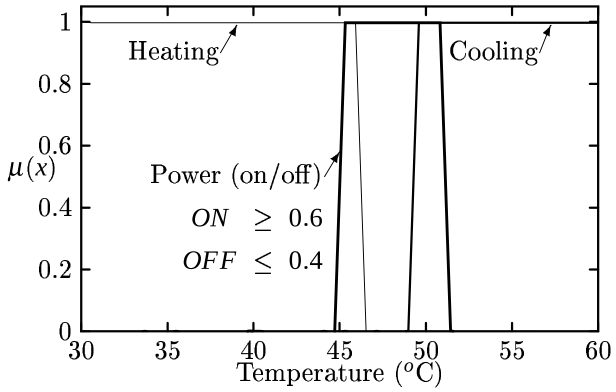

Figure 12: Behaviour of the power depending on the electrolyte temperature. The system is switched on if the output value $\mu(T) > 0.6$ and is switched off if $\mu(T) < 0.4$.

can only switch on/off if there was no change during the previous 5 seconds. A temperature of more than 45^{o}C turns on the voltage and starts the polishing process. An increase in temperature over 46^{o}C switches the heating system off and a further increase over 49^{o}C switches the cooling system on. If a further increase in the temperature takes it above 51^{o}C, then it is too great to be cooled by the cooling system and the process is turned off until the temperature decreases.

Figure 13 and 14 show the basic polishing time and the control voltage of the power supply for one and two dentures depending on their effective size. The figures show the differences in the region of the transition gap between two small and one big denture. While for two dental cast alloys, the basic polishing time increases considerably, the control voltage for the power supply changes only a little because of the altered average distance s and the specific circuit capacity κ. The basic polishing time increases as a percentage with the electrolyte state as shown in figure 15. A new electrolyte bath contains only a few dissolved ions, so the basic polishing time has to be increased in the beginning, but the maximum material volume on the material / electrolyte phase border is reached after a few polishing trials. At the end of the service life, the polishing time increases again and the electrolyte has to be changed at a lifespan of 250.000 As because of the long and uneconomical polishing times. Figure 16 shows the increasing polishing time depending on the state of the electrolyte and the size of the dental cast alloys.

Hardware implementation

The polishing machine is 27 cm high, 30 cm wide, 31 cm long and consists of a primary clocked power pack, which is controlled by a microcontroller[3] [Pasc94]. The microcontroller selects the required current from $0-10A$ over a pulse-duration-modulation (PDM) interface. A PDM current has the advantages of smoother surfaces, higher

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[3] Intel 80535

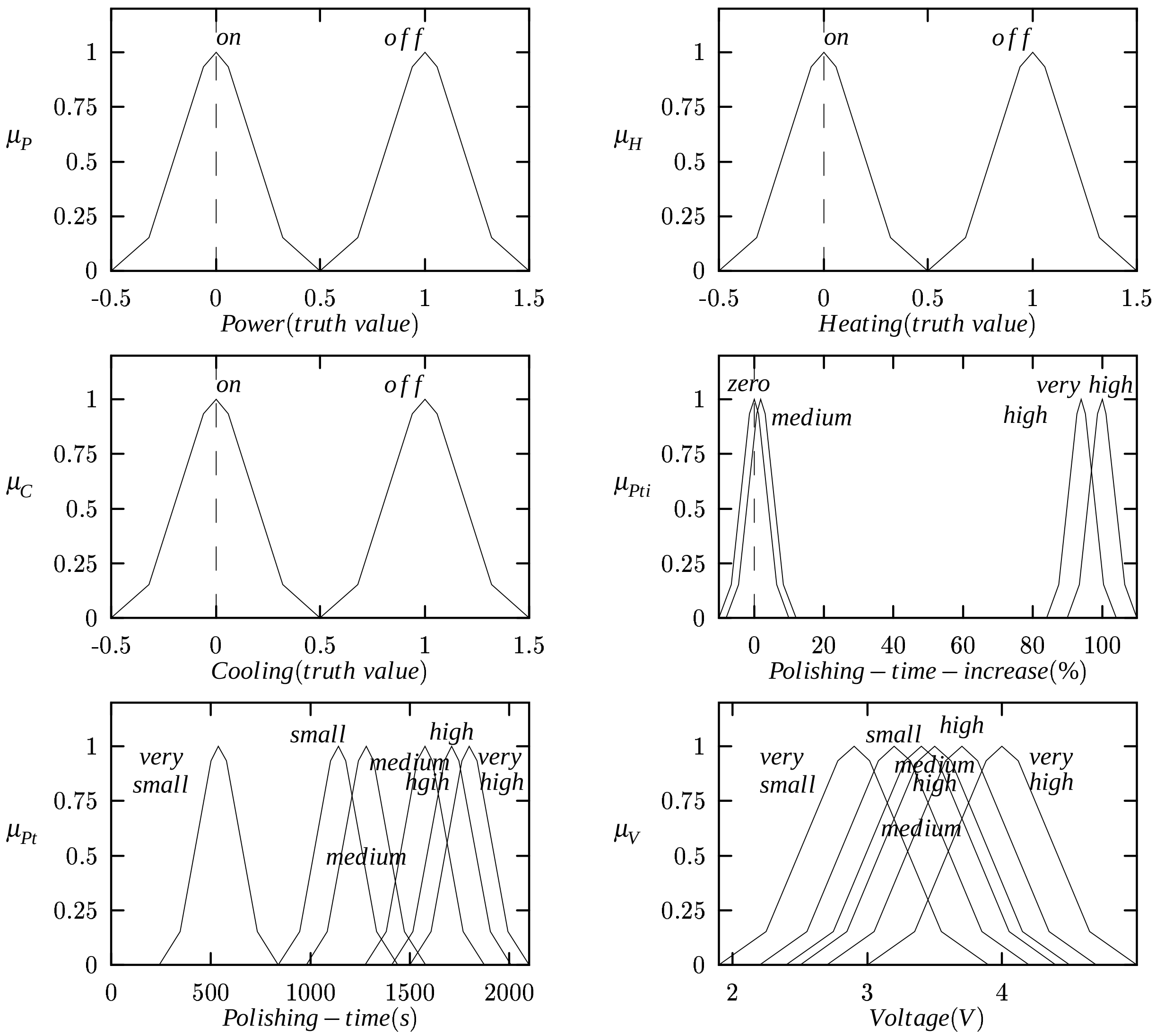

Figure 10: Membership functions of the six output variables

severity and lower abrasion of the dentures. Also, additives for the electrolyte can be saved and improvements in the current gain and dispersion capability can be reached through pulse-plating [Leis92]. Figure 17 shows the block diagram of the polishing device with the control unit. Linked by the polishing electrodes, the dental cast alloys in the electrolyte are directly connected with the output signal of the current control.

On the other side, the polishing electrodes are linked with a motor to move the dentures in the bath. The motor is connected with the microcontroller over relays, so that it can control the movement of a denture. For the calculation of the current flow in the polishing bath, the voltage is measured over a resistor and transferred to the microcontroller.

Furthermore, the polishing machine contains a heating and cooling system. The cooling system consists of a spiral pipe, which has to be connected to an external water supply. The microcontroller controls the temperature by switching the heating and cooling system on and off with further relays. By measuring the voltage drop over a temperature resistor in the electrolyte bath, the microcontroller calculates the electrolyte temperature. The user can start the polishing process or he can give simple inputs to the microcontroller by the use of buttons. A small display shows messages or the internal states of the polishing machine. Storing the electrolyte state E is possible because the microcontroller is battery buffered. Even if the external power of the polishing machine is switched off, the rest current supply of the microcontroller is guaranteed. The whole control algorithm including the fuzzy system is stored in an EPROM. All experiments during the development process of the control algorithms were done on a PC with a digital I/O card and the fuzzy case

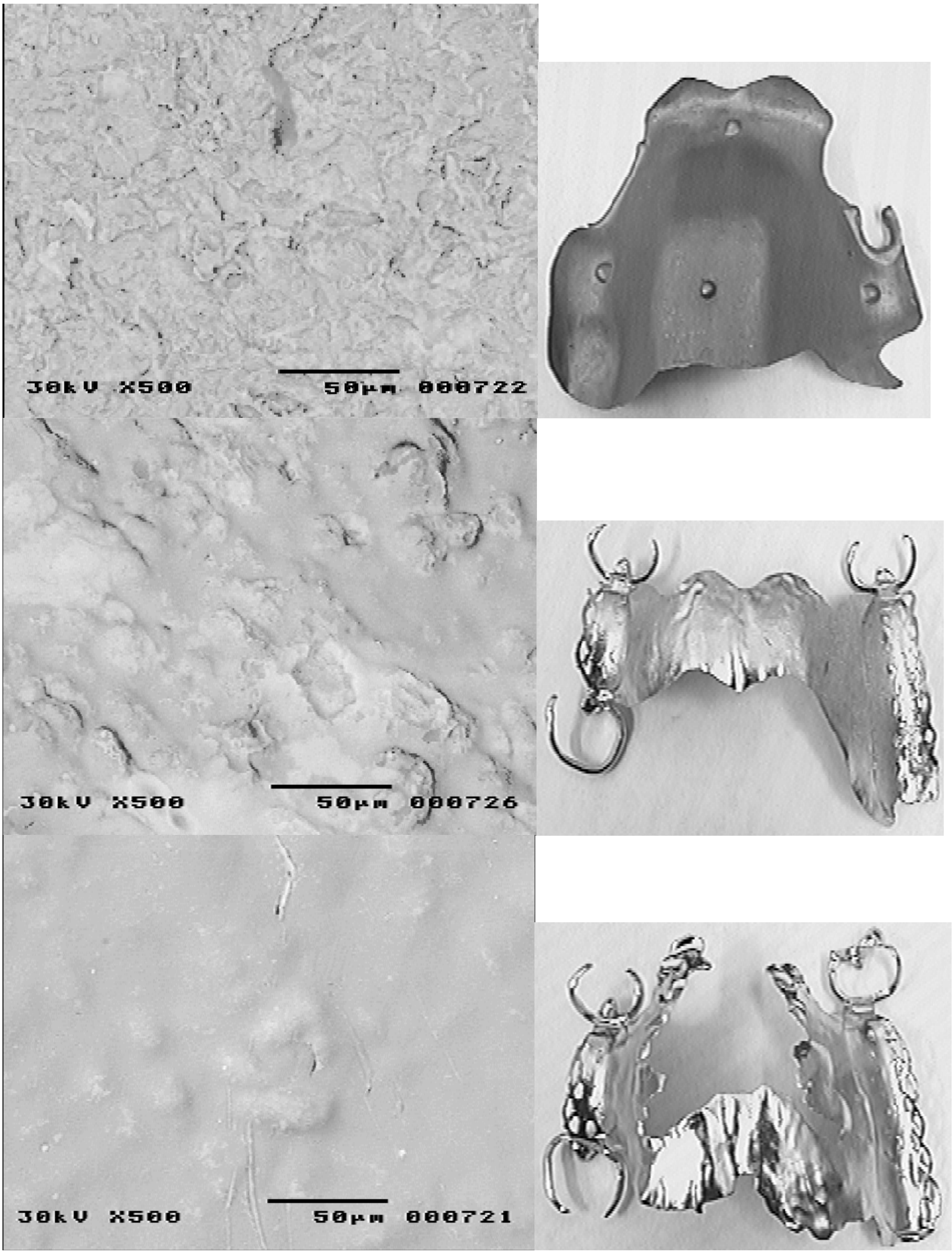

Figure 11: Comparison of a non-polished (above) with an inadequately-polished (middle) and a well-polished denture (right) and the raster electron microscope pictures (left) of the respective denture surfaces

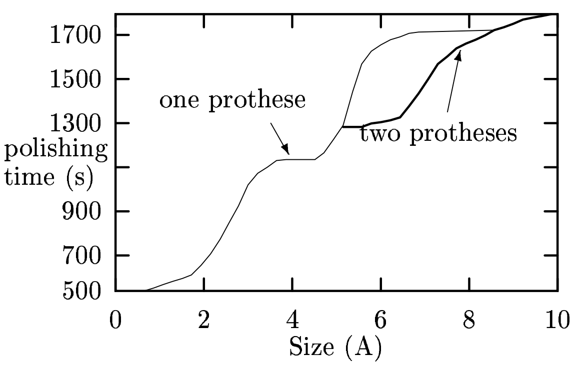

Figure 13: Basic polishing time depending on the number and effective area of the denture

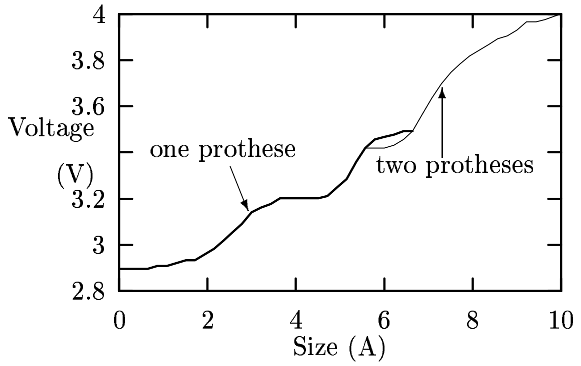

Figure 14: Voltage for the current supply depending on the number and the area of the dentures

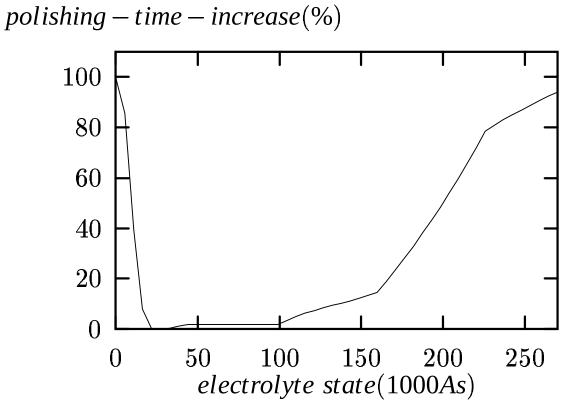

Figure 15: Increase of the basic polishing time depending on the electrolyte state (in %)

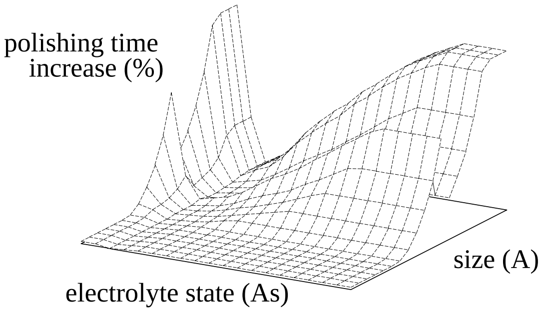

Figure 16: 3D plot of the dependencies between the electrolyte state, the size of the dental cast alloys and the increasing polishing time

tool FUNNYLAB [Surm92].

Conclusions

Starting from a purely user-controlled polishing machine for cobalt chromium dental plate cast alloys, we have developed an automatic polishing machine based on a fuzzy logic controller. The depicted fuzzy rules are based on physical equations, experimental studies in the literature and our own experiments. The results of the preliminary experiments are implemented in a fuzzy knowledge-base with fuzzy case tools. Thus, it was possible to build the first automatic polishing machine for cobalt chromium dentures [Surm94].

With the fuzzy rules it is possible to consider the plausibility of all the input values simultaneously while calculating and storing the electrolyte state within a microcontroller, together with the simultaneous evaluation of the electrolyte ageing and the size and number of dentures. We note that in particular, the size of the denture (effective surface of the anode) and the electrolyte state cannot be precisely calculated. So, the several hypotheses are weighted and combined with the compositional rule of inference in the fuzzy logic controller.

While operating previous polishing machines, the user had to estimate and adjust individual parameters like the size and contour of the dental cast alloy as well as the electrolyte state. Now, everything is adjusted automatically. Furthermore, the calculation and storage of the electrolyte state in the microcontroller enables to determine the exchange point of the electrolyte when it is used up through ageing. The new polishing machine shows a consistent very high quality of the dentures during its service life.

The fuzzy system is easy to understand and maintain because the fuzzy rules correspond directly to the user's experience. Therefore, different automatic polishing processes with other alloys or varying electrolyte solutions can be developed by only shifting the membership functions. Also, bigger and more complex polishing processes can be automatically controlled by implementing the user's experiences in fuzzy rules, provided that appropriate fuzzy case tools are available.

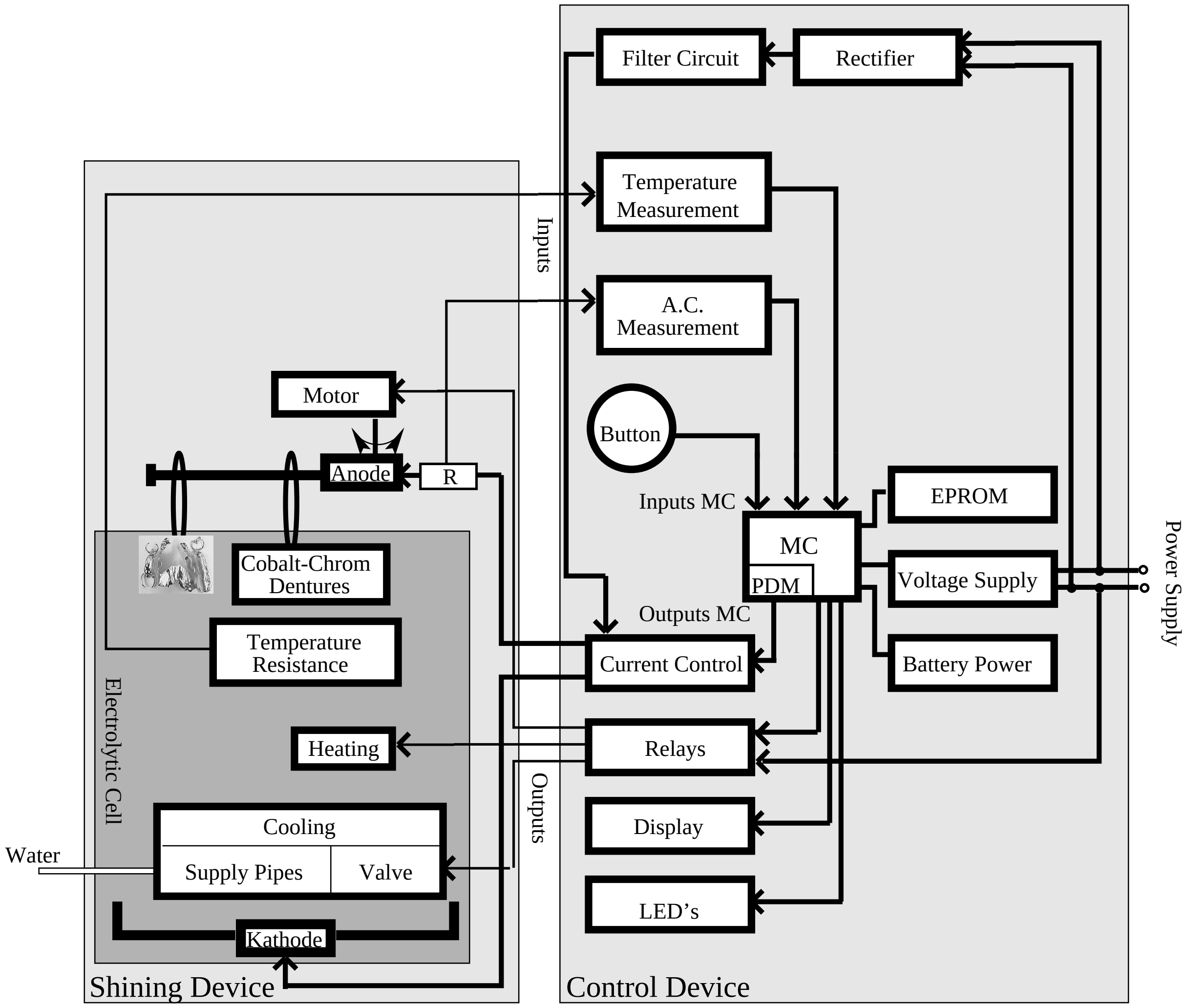

Figure 17: Schematic representation of the polishing machine hardware

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