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Towards automated cooking process

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Abstract

This paper presents a new approach towards the intelligent cooking process based on the correlation of the sound pressure in the cooking pan and the temperature of the pan's interior. When captured from the cover's handle the degree of correlation between the sound pressure and the interior's temperature is grater than the correlation between the temperature inside the cover's handle and the interior's temperature. With this new non-invasive approach (i.e. one that does not physically alter neither the pan nor the pan's contents), we achieved the automated cooking process. The main benefits are the minimization of the time spent behind the kitchen range and less power consumption.

Key words: Fuzzy control system, Sound based control, Automated cooking process, Intelligent cooking

1 Introduction

The cooking process itself usually requires a great amount of time and the person doing it has to be fully devoted to it, and during this time pay full attention. The more experienced they are the less time they spend for control, but nonetheless it cannot be overcome (Smrke & Prezelj, 2003). What we have in mind with control is the time sequence of output power corrections that are sent to the hot plate.

In the given article we analyze the possibility of automated food preparation (i.e. its automated control) (Smrke, 1999). This means that all the time we need for preparing food is merely the time spent for the preparation of the

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ingredients and set up the hot plate. There is no time spend for control of the cooking process. The cooking process can be split into two phases:

- heating (we have to heat the pan's contents as quickly as possible from room temperature to boiling point),
- status quo (the temperature should stay around boiling point, which is needed for the food to get prepared; this time depends on the type of dish.).

For the automated cooking process, first we have to get the input data, which has to be done non-invasively. Only then can we develop the appropriate control logic. There are several possibilities for the input data:

- the temperature of the hot plate,
- the temperature of the contents,
- the temperature acquired from inside the cover's handle or
- the sound pressure acquired from inside the cover's handle.

The first possibility (the temperature of the hot plate) is accurate and simple to acquire, but it does not give the data needed (i.e. the temperature of the pan's contents). In this case we have to calculate the correlation between the temperature of the hot plate and the temperature of the contents, which is mathematically very complicated. If we change the type of pan, this problem gets more serious because of the inertia law and the transmission of the heat from the hot plate to the pan.

The problem of the second possibility is that we put the sensor into the pan's contents, which is done invasively. This is not acceptable if we want to put this kind of product on the market. In the third case the temperature sensor is moved into the cover's handle. The invasiveness is solved. In addition there is also the problem of a time delay. The heat must travel from the hot plate to the pan and then also from the pan to the temperature sensor (this delay is typically longer than 1 minute). Thus this data cannot be used for control of the cooking process, especially in the status quo phase.

As a solution to all previously listed problems we suggest measuring the strength of sound (noise) made by bubble formation and bump which we called the sound pressure and it is expressed in dB (dB is an abbreviation for decibel). We actually captured the acoustic signal from the microphone. We assume that the sound pressure in the pan is the most representative data of all. There is no problem with invasiveness and also with complex correlation calculations. After a large number of tests we can say that the control logic, developed on one pan, can be used with other pans without changes.

The first goal of this paper is to present the analysis of the automated cooking process based on captured sound as an alternative indicator of the cooking process. The second goal is to present the comparison between cooking process

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led by a skilled cook and automated cooking process. The automation was achieved with a fuzzy controller with changing membership functions. Presented method is completely state-of-the-art and no previous literature with familiar contents was found.

2 Material & Methods

2.1 Testing environment

The non-invasive approach is shown as the means of mounting the cover's handle on different pans and in means of not altering the pan (Fig. 1).

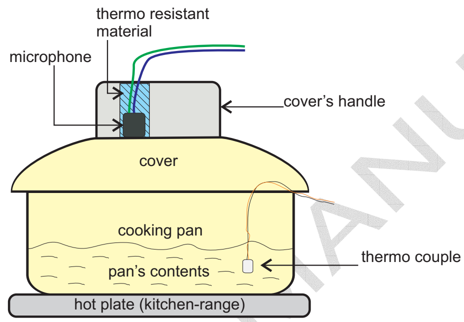

Fig. 1. The cooking pan with the microphone inside the cover's handle and the thermo couple in the pan's contents.

First a hole was drilled through the cover's handle but not through the cover. After that the microphone was put on the bottom of the drilled hole. The specifications of the microphone were:

- diameter: 6mm,
- frequency response: 20 - 13.000Hz,
- sensitivity: -60dB.

The specifications of the cooking pan were:

- diameter: 220mm,
- exterior height: 110mm,
- thickness of the pan's bottom: 12mm.

The specifications of the hot plate were:

- diameter: 180mm,
- electrical power: 1500W,
- electrical voltage: 230V.

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The temperature sensor (thermo couple type K) needs to be in the pan's contents to measure the temperature. The hole was filled up with the thermo resistant material, which fixed both the sensor and the microphone to the cover's surface. The thermo resistant material also partly hindered the noise from the surroundings. The thermo resistant material was permanently elastic acetate silicone sealant with temperature stability range from -50℃ to +300℃ (more info: http://www.termo.si/en/tervol.htm). The cover's handle and the kitchen-range were connected with a PC. The sound pressure was captured directly through the sound blaster, which is usually installed in every computer as an integrated part of the motherboard or as a separated PCI card and used for capturing the sound (through the microphone input) and playing the sound (through the speaker output)(Fig. 2). The ND-6018 module (8 channel thermo couple input module) repeatedly captured the temperature as a certain electrical voltage on a thermo couple and transfered it into the text mode. To be more precise it has its own temperature sensor to measure the temperature of the surroundings. The ND-6520 module (RS-232 to RS-485 converter) transformed industrial standard RS-485 to the RS-232 standard used by a PC. The ND-6050 module (digital I/O module) turned the kitchen-range on or off. All modules are made by Adlink Technology Inc (more info: http://www.adlinktech.com/).

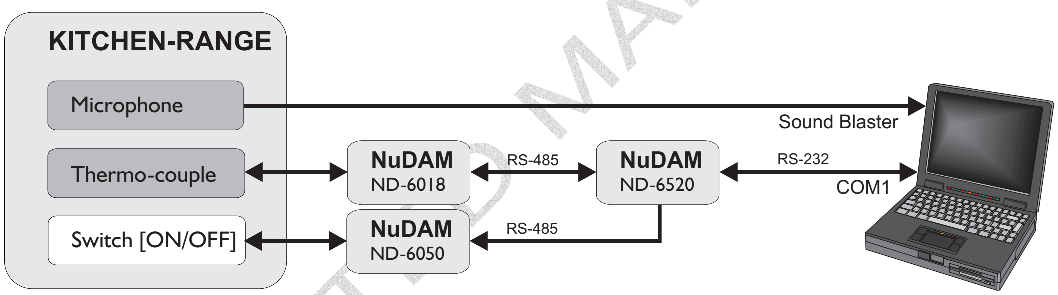

Fig. 2. Schematic view of testing environment.

The captured sound pressure (*Sound(n)*) and the output power (*Out(t)*) from the *KITCHEN-RANGE* are sent to the model build in the SIMULINK environment (MATLAB) (Matlab - Fuzzy Logic Toolbox, 2000) as shown in the (Fig. 3). The last N history samples of the *Sound(n)* are averaged in the *Buffer* and sent to the *Fuzzy Logic Controller*, which calculates the crisp correction ($\Delta Out(t{+}1)$) to the new output power ($Out(t{+}1)$).

Final system consists of an input segment and a control segment (Fig. 4). Embedded system from the input segment (S1) captures the sound pressure and sends it through the Bluetooth connection (BT) to the control segment, where the sound pressure is altered and used for the control of the hot plate. The fuzzy controller is placed in the embedded system inside the kitchen-range (S2). Besides the Bluetooth module there is also Digital/Analog output module used for output power control. The temperature sensor is not used in the final system, because it is not essential for the control, it was used just to

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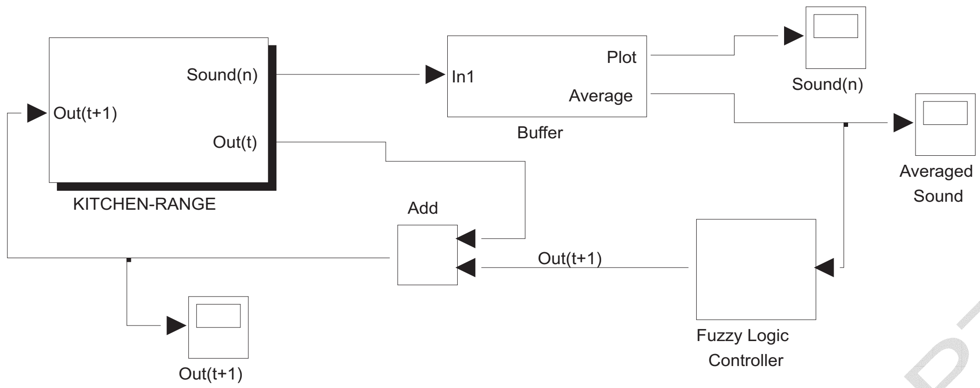

Fig. 3. Model in the SIMULINK (MATLAB) environment.

test the relationship between the sound pressure and the temperature.

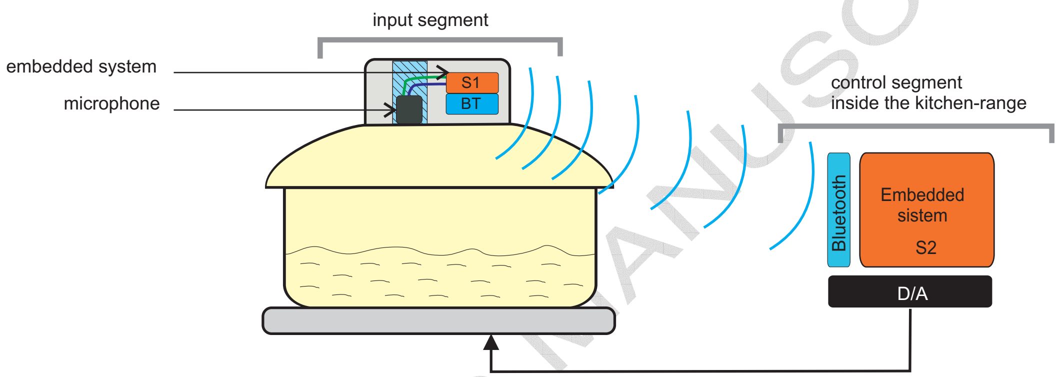

Fig. 4. Final system.

2.2 Sound pressure as an input

We captured the sound pressure from three different positions: from inside the contents, above the contents and in the cover's handle. In the first and in the second case we wrapped the microphone with a small polyvinyl bag and tighten it with a wire, which prevented the water and the steam to damage the microphone. We got similar results in all three cases, which confirm that cooking control can be based on non-invasively captured data (i.e. from inside the cover's handle) instead of the invasively captured data (from inside the pan).

The main problem of capturing the sound pressure is the noise from the surroundings. The cooking process is held in an environment with various sound sources (voices, rumbling on the desk, sound of kitchen appliances, etc.). This is why we have to transform the captured sound. The main goal of transformation the data is to get that part of the sound specter which is produced by the heating contents. Only the transformed sound presents representative

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Table 1
Contents of the experiments.

contents	water	salt	ingredient	repetitions
tap water	0.5l	-	-	16x
tap water	1l	-	-	5x
salted tap water	1l	5g	-	4x
salted tap water with rice	1l	5g	250g of rice	3x
salted tap water with pasta	1l	5g	500g of pasta	3x

input data for control.

In the first part of the analysis we focused on the frequency components and sound pressure with minimal impact from the surroundings sounds. We defined the parts of the frequency specter, which we captured later in the common kitchen environment (a lot of noise) and transformed them to get the input data for the control. In the second part of the analysis we made more sophisticated analysis of the chosen frequency specter. In the third part of the analysis we captured the sound once more, but this time in a regular kitchen environment. In the captured sound there were voices, sounds of kitchen appliances etc. Sounds like voices or rumbling on the kitchen desk were stressed out in the diagram of frequency analysis. Those sounds could disturb the control. That is why we used the transformation method described in next subsection, which eliminates the sounds that hinder our control. Results from the transformation of the sound captured in the regular kitchen environment confirm those from the kitchen environment with minimal impact of the surroundings sounds.

During the analysis of the captured sound pressure tap water was used for the material in the cooking pan. When the fuzzy controller was build we tested it also with salted tap water, salted tap water with rice and salted tap water with pasta. The number of repetitions and material used for each experiment is shown in Tab. 1.

2.3 Transformations of the sound pressure

We used filtering on captured samples of sound pressure to get the correct input variable to the controller. With this method only the decisive frequency components were used, other frequency components were eliminated. We have to realize that all natural sounds consist of different frequency components. That means that despite filtering, other sounds also influenced the chosen frequency component.

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The frequency component that has been used for the input of controller was changing rapidly through the time, which was our next problem to solve. Fig. 5 presents a typical rapid changing of chosen frequency component (marked as sound). We have to consider if that kind of function is suitable for controlling, because controlling is based on a set of time based commands. Those commands determine the output power of the hot plate. We also have to consider the length of the control decision period. If we choose a long control decision period and curve from Fig. 5, we can easily capture only values that deviates the most from the average value. Large deviations of captured sound pressure are the result of the nature of sound.

Rapid changes of the sound pressure in the Fig. 5 were first around -95dB, after that they moved up to around -55dB, this change was due to the onset of boiling.

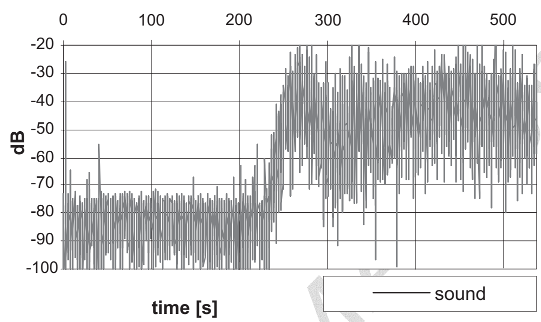

Fig. 5. The sound pressure through time (frequency component of 1 KHz).

We found the solution to this problem in another transformation of the captured sound pressure. We calculated an average of the last N history samples of the captured sound pressure. This method is called sliding window. The effect of mentioned method is presented in Fig. 6 and Fig. 7 (marked as average sound). A larger sliding window gives a smoother curve of the captured sound pressure. The disadvantage of this solution is that smoothing artificially generates time delay, which should not be too long.

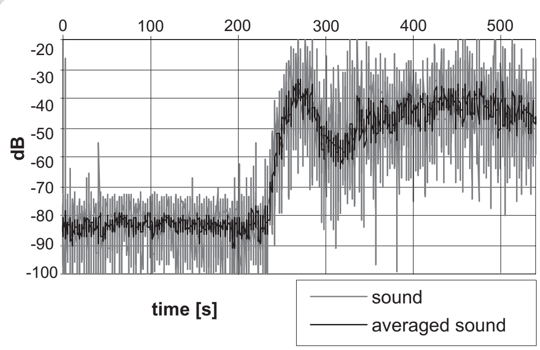

Fig. 6. The effect of the sliding window on the captured sound pressure ($N=10$).

If we take a look at the figures 6,7 and 8 we can see that first the sound pressure is low (below -80dB until 200 seconds), then there is a quick jump

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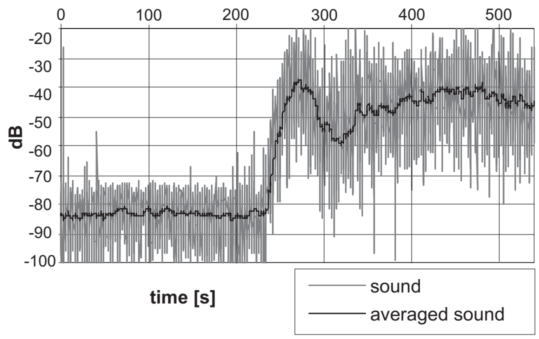

Fig. 7. The effect of the sliding window on the captured sound pressure (*N=50*).

which indicates the start of boiling (between 200 and 300 seconds). After boiling the sound pressure is high with slight oscillations (from 350 seconds on).

2.4 Correlation between the sound pressure and the temperature of the contents

We assumed that for the most critical point of the cooking process (point of boiling) equation (1) holds

$$T(t + \Delta t) = f(sound(t)). \tag{1}$$

The time difference Δt shows that with the sound pressure at this moment we can predict the temperature in the future. Fig. 8 presents the graph of the captured sound pressure and the graph of the temperature of the contents. We can determine that there is a correlation between the sound pressure and the temperature.

Sliding window of last 200 history samples was used in the Fig. 8, because smoother curve is more appropriate for presenting in the graph. The time difference (Δt) in this case is approximately 20 seconds. The smaller sliding window is used the larger time difference is generated at the same sampling rate. For the control we used smaller values than 200. Throughout several experiments and different values of history samples (less than 200) we determined that time difference (Δt) in the most critical stage is always longer than 20 seconds.

2.5 Automation of the cooking process

We decided to use fuzzy logic (Davidson, 1996; Zimmermann, 2001; Mraz, 2001; Klir & Yuan, 1995), because it is easy to build the fuzzy controller

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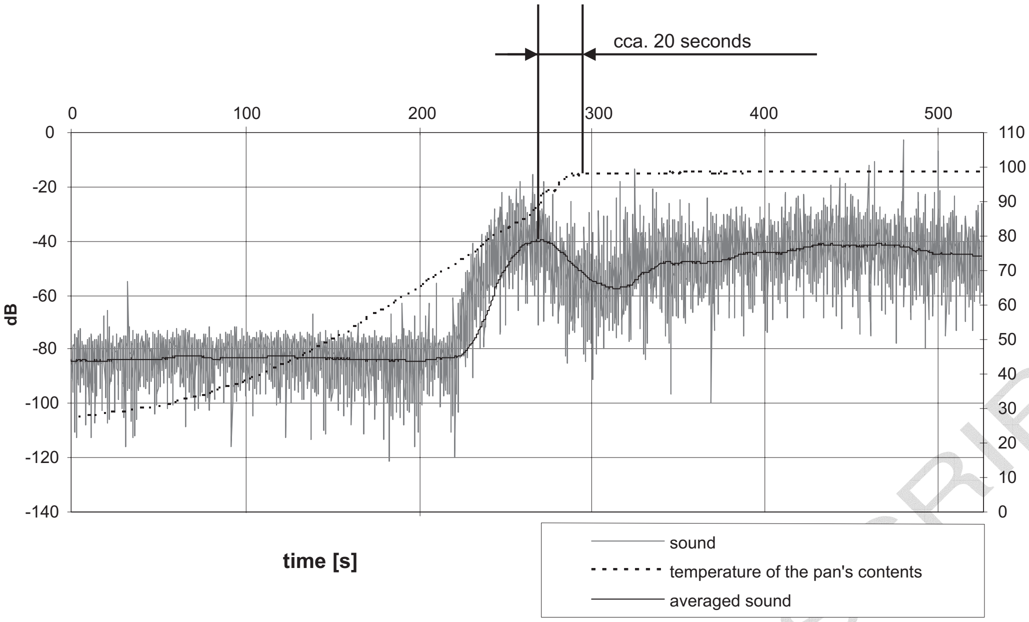

Fig. 8. The sound pressure and the pan's contents temperature through time (*N=200*).

based on fuzzy rules, especially when dealing with the cooking process. We took into the consideration the possibility of using the linguistic control, which is based on fuzzy (uncertain, imprecise and approximate) knowledge and input data. The cooking process is more easily described with linguistic terms than with exact mathematical equations.

We assumed that we can set a list of linguistic rules that are based on the sound pressure. The fuzzy logic controller (O' Connor et al., 2002; Ioannou I. et al., 2004; Ioannou II. et al., 2004; Davidson et al., 1999; Castellano et al., 2003; Xiang & Zheng-Jin, 2005; Zimic et al., 1996) will be based on those rules. We can describe the decision process as:

$$\Delta Out(t+1) = f(sound(t)), \tag{2}$$

$$Out(t+1) = Out(t) + \Delta Out(t+1). \tag{3}$$

Where *Out(t)* is the output power of the hot plate in present period of time, *Out(t+1)* is the output power in the next period of time, Δ*Out(t+1)* is the desired change of the output power in the next period of time, *sound(t)* is the sound pressure and f is the controller's translation function. The sound pressure presented in Fig. 8 was captured during the cooking process led by a skilled cook. The material in that case was 1 litre of tap water with 5g of salt. The curve can be split into three segments:

- constant low sound pressure,
- rapidly increasing sound pressure,

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- and constant high pressure with slight oscillations.

According to the aforementioned segments we defined an input linguistic variable sound, with three membership functions. We can see in Fig. 8 that at normal cooking process the sound pressure never returns to the first segment. Because of that, we decided that at the beginning the controller has to be more robust. The main point of the fuzzy controller were not the rules but the limits of the membership function. The correct limits at the right time of the cooking process had to be determined. After a lot of experiments we set the first segment limit at -80dB and the following membership functions were used (Fig. 9). We used Zimmerman's notation (Zimmermann, 2001):

- **low** (the first segment, [-90, -90, -90, -60] dB),
- **medium** (the second segment, [-80, -45, -45, -20] dB),
- **high** (the third segment, [-60, -20, -20, -20] dB).

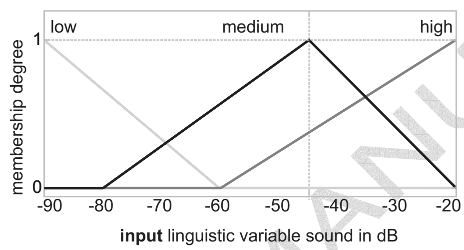

Fig. 9. Definition of the membership functions of the input linguistic variable *sound*.

When the averaged sound (*sound(t)*) was between -80dB and -55dB membership functions limits were determined linearly between those two values. To reach this goal the controller changed the membership functions (Fig. 10, Fig. 11 and Fig. 12) according to the strength of the averaged sound (*sound(t)*) as follows (MATLAB code):

```
if (sound(t) > -80) and (sound(t) < -55)
   l1=-90+min(max((sound(t)+90)/40,0),1)*(-60-(-90));
   l2=-90+min(max((sound(t)+90)/40,0),1)*(-60-(-90));
   l3=-90+min(max((sound(t)+90)/40,0),1)*(-60-(-90));
   l4=-60+min(max((sound(t)+90)/40,0),1)*(-50-(-60));
   m1=-80+min(max((sound(t)+90)/40,0),1)*(-60-(-80));
   m2=-45;
   m3=-45;
   m4=-20+min(max((sound(t)+90)/40,0),1)*(-20-(-30));
   h1=-60+min(max((sound(t)+90)/40,0),1)*(-40-(-60));
   h2=-20;
   h3=-20;
   h4=-20;
   low ([l1, l2, l3, l4]);
   medium ([m1, m2, m3, m4]]);
```

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```
   high ([h1, h2, h3, h4]);
end;
```

When the sound pressure comes to the third segment it has to be more precise, which will result in minimal oscillations of the sound pressure. We set a third segment limit at -55dB and the following membership functions were used:

- **low** (the first segment, [-60, -60, -60, -50] dB),
- **medium** (the second segment, [-60, -45, -45, -30] dB),
- **high** (the third segment, [-40, -20, -20, -20] dB).

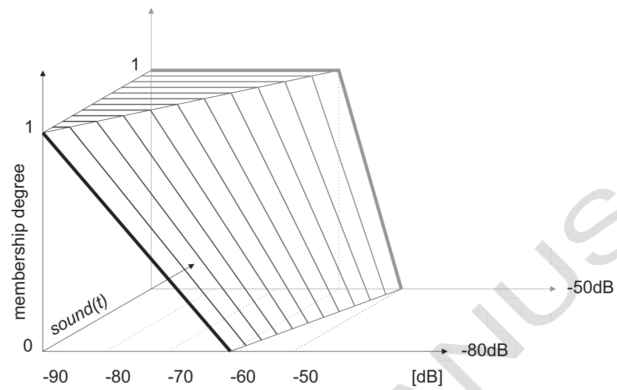

Fig. 10. Membership function low is changing according to the strength of the averaged sound.

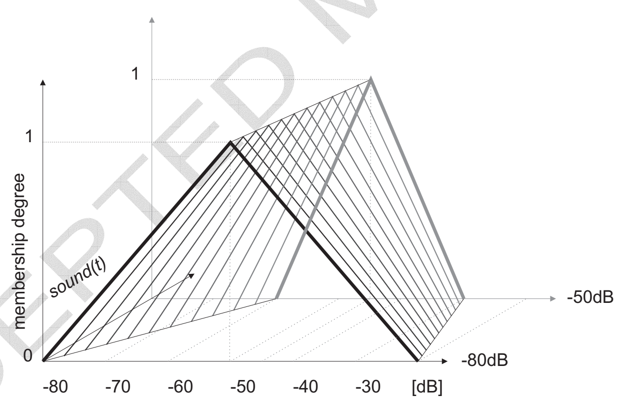

Fig. 11. Membership function medium is changing according to the strength of the averaged sound.

The fuzzy inference was based on the following list of rules:

p1: **if** (*sound* **is** *low*) **then** (Δ*Out(t+1)* **is** *increase*),

p2: **if** (*sound* **is** *medium*) **then** (Δ*Out(t+1)* **is** *hold*),

p3: **if** (*sound* **is** *high*) **then** (Δ*Out(t+1)* **is** *decrease*).

When the sound pressure was low the fuzzy controller increased the output

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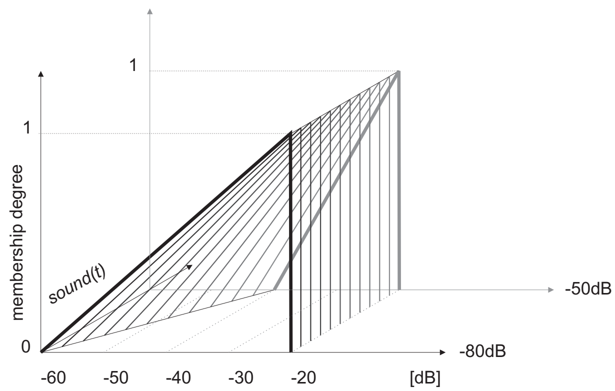

Fig. 12. Membership function high is changing according to the strength of the averaged sound.

power, when it was high the controller decreased the output power and when it was medium the controller hold the output power at the same level as it was before. As an output we defined a linguistic variable Δ*Out(t+1)*, again with three membership functions:

- **decrease** ([-0.3, -0.3, -0.3, 0]),
- **hold** ([-0.3, 0, 0, 0.3]),
- **increase** ([0, 0.3, 0.3, 0.3]).

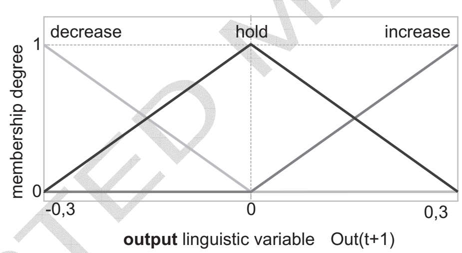

Fig. 13. Definition of the membership functions of the output linguistic variable Δ*Out(t+1)*.

According to that maximum change of the output of the fuzzy controller (Δ*Out(t+1)*) was 0.3. At the beginning we determined the maximum of the output power (*Out(0) = 1*), because we want the contents to boil as soon as possible. We used the COG (center of gravity) method for the defuzzification, which returns crisp value. This value was used in equation (3) to calculate the output power *Out(t+1)*. It has to be noted that the mathematical operation (addition) in equation (3) is defined as:

$$a + b = max(min(a + b, 1), 0). \tag{4}$$

This means that the output power *Out(t+1)* is a real number from the interval [0,1]. When it is more than 0.5 it means turn on the hot plate and vice versa.

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3 Results and Discussions

In the first part of the analysis we captured the whole frequency specter several times (from 0Hz to 22000Hz). Nyquist-Shannon sampling theorem states that the sampling frequency must be at least twice the maximum frequency component of the signal. Otherwise, the original signal cannot be recovered from the sampled signal. Our maximum frequency was 22000Hz, so according to the Nyquist theorem we used sampling frequency of 44100Hz. We examined the captured data and determined the area of frequency specter where the frequency components with the larger amplitudes are. Fig. 14 shows amplitudes of particular frequency components of the captured sound during the cooking process. We can see that the highest values are more at the lower frequency components. We chose the area [500Hz, 1500Hz], which is shown with an arrow in Fig. 14.

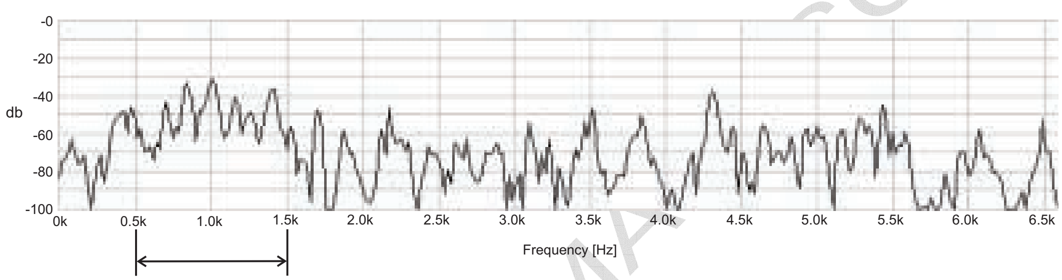

Fig. 14. Amplitudes of the particular frequency components of the sound pressure captured during the cooking process in the cover's handle.

In the second part of the analysis we filtered each frequency component from the captured sound and made an average of amplitudes for each frequency component. On the chosen area there was the largest average of amplitudes at frequency component of 1 KHz. This frequency component was used for the control of the cooking process.

During the cooking process the sounds from the pan consisted mainly from the aforementioned frequency component, which is why we can conclude that influence of the other sounds is minimal at the mentioned frequency component.

According to the Fig. 8 now we can confirm our assumption. Based on the prediction of the temperature we can also conclude that the captured sound pressure is a very good basis for control of the cooking process (also at a less critical stage).

We compared cooking process led by the fuzzy controller with changing membership functions with the cooking process led by the skilled cook. When the skilled cook controlled the cooking process, we just captured the data (sound, temperature and the state of the hot plate switch). He turned the power off when the contents started to boil, because normally, when we want to cook something, first we boil the contents and then we cook for a certain period of time at slight boiling of the contents. After the cooking process was finished we looked up into the saved data and determined that he turned the power off when the time was 325s. At that point saved data showed that the temperature of the pan's contents was 95.38℃. The graph in Fig. 15 shows sound, averaged sound and temperature for the cooking process led by a skilled cook.

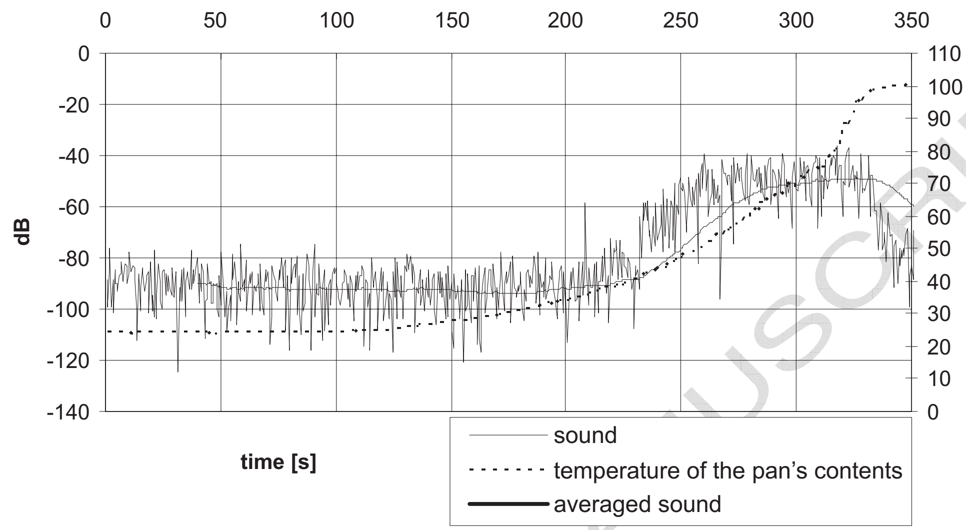

Fig. 15. Sound, averaged sound and temperature at the cooking process led by the skilled cook.

The graph in Fig. 16 also shows the same three curves but for the fuzzy control. We can see the difference in comparison with Fig. 15. The data in this case (fuzzy control) showed that the output power fell below 0.5 when the time was 318.6s, this means when the fuzzy controller with the changing membership functions turned the power off. At that point the temperature of the pan's contents was 75.38℃, but afterwards the contents still boiled (dashes line in Fig. 16 reached temperature 100℃, when the time was 357s).

More time the power is turned on more energy is used, based on that we defined power consumption. Our controller turned the power off before the skilled cook did, which means fuzzy control spent less power. As the means of power consumption we can conclude that fuzzy temporal controller is better.

We have to stress out that if we compare the curves in Fig. 15 and Fig. 16 the boiling point is not at the same index. The reason is that the processing of the inference takes time. When the cooking process was led by a skilled cook there was no processing just capturing and saving the data, which means less time per cycle (more frequent capturing). As a consequence there were fewer samples captured in the same period of time when the cooking process was led by the fuzzy controller. The sampling rate of 2 Hz and the sliding window of the last 20 history samples were used for capturing the sound pressure in

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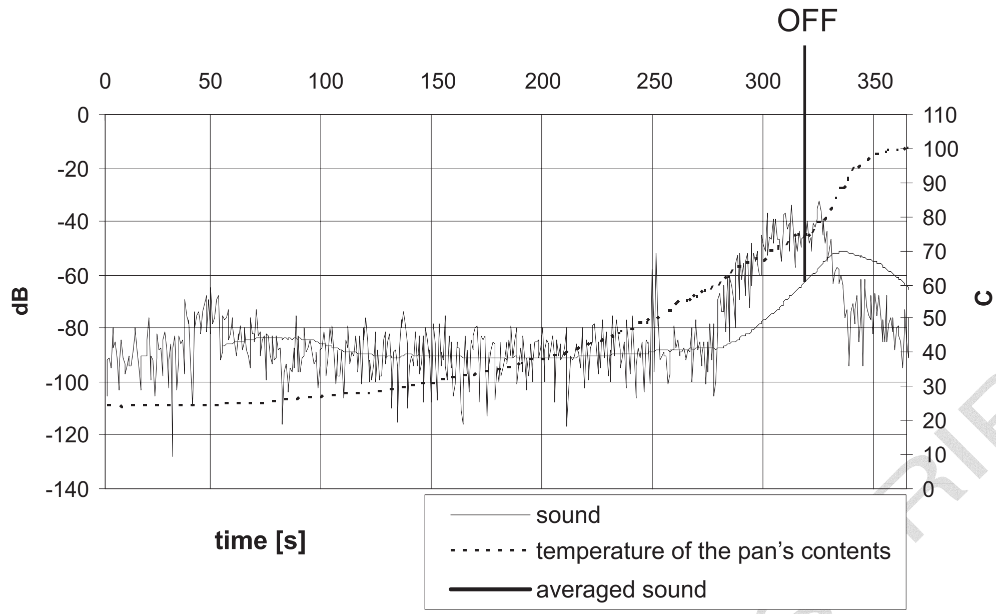

Fig. 16. Sound, averaged sound and temperature at the cooking process led by the fuzzy controller with changing membership functions.

the Fig. 15 and Fig. 16. Time difference (Δt - from the equation (1)) between the averaged sound and the temperature of the pan's contents is also more than 20 second.

To ensure the correlation between sound pressure and temperate and the success of the control there was a temperature sensor in the prototype (Fig. 1). Besides the sound pressure we measured also the temperature of the pan's contents, which means that the temperature was only our reference point during the experiments. After we determined that control is successful we removed the temperature sensor. As you can see in the Fig. 4 there is no temperature sensor in the final system.

As we mentioned before we did four different types of experiments and the results were very similar, that is why we stressed out just the difference between the process led by skilled cook and the one led by fuzzy controller.

We knew that we can control the hot plate based on the temperature of the pan's contents, but this method is useless because we have to put the sensor into the pan's contents and this is not acceptable in the final product. This is why we thought of using sound (noise) of bubble formation and bump to control the heating of the hot plate. We also knew that sound is getting lauder as the contents start to boil, but we had to find out if there is a correlation between the temperature of the pan's contents and the sound pressure, that is why both were measured. The testing environment in the kitchen was set up and the sound pressure as an acoustic signal through the microphone was captured. Captured signal was modified through filtering and smoothing. We

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found out that modified signal from the microphone has similar course than captured temperature which means there is a correlation. Besides faster increasing and decreasing of the sound pressure we have also found out that the strength of sound pressure is the highest before the actual boiling point which means that boiling point can not be missed. The important fact is that the contents can not get over the pan's edge when boiling. After our research we can conclude that automated control of boiling contents based on fuzzy controller is possible and even better that the control led by a skilled cook.

4 Conclusion

The control of the cooking process, based on sound pressure captured from inside the cover's handle is successful. It is more successful than control based on the temperature of the contents. The captured data had to be filtered and smoothed (sliding window method). From the point of view of industry we have to mention that it is important to build as many capabilities into the cover's handle as possible. With that the decision process will take place in the cover's handle instead in the kitchen range. Only data about the output power will be transferred to the kitchen range. The consequence is the reduction of the power consumption at data transfer.

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