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Fuzzy cooking control based on sound pressure

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Abstract: This paper presents a new approach to the intelligent cooking process that is based on the correlation of the sound pressure in the cooking pan and the temperature of the interior of the pan. When captured from the cover's handle the degree of correlation between the sound pressure and the temperature of the interior is grater than the correlation between the outside temperature and the interior temperature. With this new non-invasive approach (i.e. one that does not physically alter neither the pan nor the pan's contents), we have 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, sound based control, automated cooking process.

1 Introduction

Cooking is used worldwide as the means of preparing food. The 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. What we have in mind with control is the time sequence of output power corrections that is sent to the hot plate.

In the given article we analyze the possibility of automated food preparation (i.e. its automated control). This means that all the time we need for preparing food is merely the time spent for the preparation of the ingredients and set up the hot plate. There will be no time spend for control of the cooking process.

Cooking process can be split into two phases:

- heating phase (we have to heat the content of the pan as quickly as possible from the room temperature to the boiling point)
- status quo phase (the temperature should stay around the boiling point, 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. Then we can develop appropriate control logic. There are several possibilities for the input data:

- measured temperature of the hot plate,
- measured temperature of the contents in the cooking pan,
- measured temperature in the cover handle, or
- measured sound pressure in the cover handle as a result of what is going on inside the pan.

The first case (temperature of the hot plate) is simple and accurate, but it does not give the data needed, that is the temperature of the content inside the pan. In this case we have to calculate the correlation between the temperature of the hot plate and the content inside the pan, which is mathematically very complicated. If we change the type of pan, this problem is getting 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 example is that we have put the sensor into the content of the pan, which is done invasively. This is not acceptable if we want to put this kind of product on the market. There is also a problem of a short time delay before heat reaches the contents of the pan. In this case the result of the control is shown with a delay which is usually longer than the control decision period.

In the third case we move the temperature sensor into the cover handle. There is no problem of the invasive putting of the sensor any more, but the time delay problem from the previous case is getting bigger. 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 of more 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 sound being captured in the cover handle for the input data of the control logic. We have assumed that the sound pressure in the pan is the most decisive 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.

2 Purpose

The first idea 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 idea is to present the comparison between cooking process led by a skilled cook and automated cooking process. The automation was achieved with a fuzzy controller with changing membership functions.

3 Sound pressure as an input variable

We have captured the sound pressure in four different positions: in the water, above the water, in the pan, and in the cover handle. We have got similar results in all three cases, which confirm that captured sound pressure in the cover handle is decisive data for the control of the cooking process. 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 filter the captured sound. The main goal of filtering is to get that part of the sound specter which is produced by heating content inside the pan.

In the first part of the analysis we have focused on the frequency components and sound pressure in the ideal (minimal noise) environment. We define the parts of the frequency specter, which we will later capture in the common kitchen environment (a lot of noise) and filter them to get the input data for the control. We have used microphone integrated in the cover handle to capture the whole frequency specter several times (from 0Hz to 22000Hz, sampling frequency by Nyquest was 44100Hz). We have examined the captured data and determined the area of frequency specter where there are the frequency components with larger amplitude. Figure 1 shows amplitudes of particular frequency components of the captured sound in the cover handle during the cooking process. We can see that the highest values are more at the lower frequency components.

We have chosen the area [500Hz, 1500Hz], which is shown with an arrow in Figure 1. In the second part of the analysis we have made more sophisticated analysis of the chosen frequency specter. 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.

In the third part of the analysis we have captured the sound once more, but this time in the regular kitchen environment. In the captured sound there were voices, sounds of kitchen appliances etc. We have captured the mixture of sounds typical for a kitchen. 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 have used the filtering method, which eliminates sounds hinder our control (more about this in subsection 3.1). Results from the filtering of the sound captured in the regular kitchen environment confirm those from the ideal kitchen environment.

3.1 Transformation of the sound pressure

We have 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. Only the artificially generated sound can consist of only one frequency component. That means that despite filtering, other sounds also influenced the frequency component of 1 KHz. During the cooking process sounds from the pan were consisted mainly from of the aforementioned frequency component, which is why we can conclude that influence of the other sounds is minimal at the mentioned frequency component.

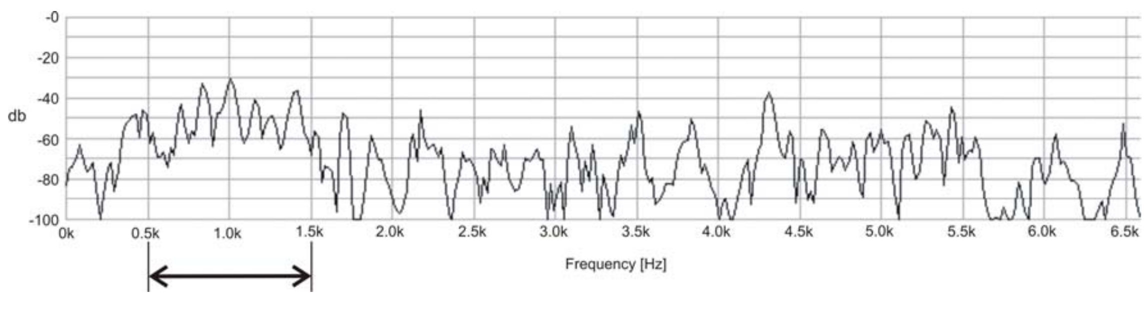

Figure 1: Strengths of the individual frequency components of the captured sound in the cover handle in a certain moment.

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.
Figure 2 presents typical rapid changing of frequency component of 1 KHz (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 hot plate. We have also to consider the length of control decision period. If we choose long control decision period and function from Figure 2, we can easily capture only values that deviate the most from the average value. Large deviations of captured sound pressure are the result of the nature of sound, which changes rapidly through time. We have found the solution to this problem in the transformation of the captured sound pressure. We have used a sliding window of the last *N* history samples. The effect of the transformation is presented in Figure 2 (marked as average sound). A larger sliding window gives a smoother curved line of the captured sound pressure. The disadvantage of this solution is that the smoothed time function artificially generates time delay. We can conclude that the sliding window method generates time delay but with no noticeable effect to our control.

3.2 Correlation between captured temperature and captured sound pressure

The temperature of the pan content was not included in the final prototype. It was earlier determined that there is correlation between the captured sound pressure and the temperature of the pan content. We assumed equation (1) holds for the most critical point of the cooking process (point of boiling):

$$T(t+\Delta t) = f(sound(t)). \qquad (1)$$

Time difference Δt shows that with the sound pressure at this moment we can predict the temperature in the future. Figure 2 presents the function of the captured sound pressure and the function of the pan content temperature. According to the functions in this figure we can confirm our assumption. 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).
Throughout several experiments we have determined that time difference (Δt) in the most critical stage is approximately 20 seconds (at a sliding window length of 200 samples).

3.3 The constants

In this subsection all of the used constants are described. We have determined them through several experiments:

- *N* – the sliding window length, value of 20 was used, sampling rate was 2 Hz, this means that the sliding window method artificially generates a time delay of 10 seconds,
- $f_{sampling}$ – sampling frequency component for the captured sound pressure, the value of 1 KHz was used.

4 Design of fuzzy controller

The core of a fuzzy logic controller are linguistic rules, which are closer to the human language then to the mathematical language.

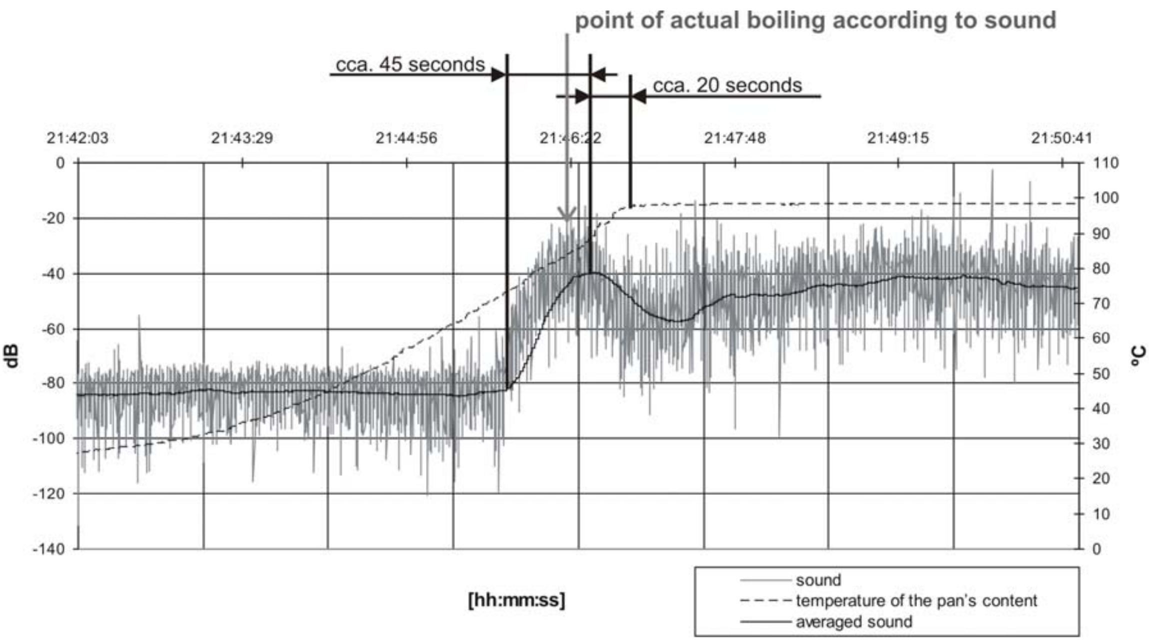

Figure 2: The sound pressure function and the pan content temperature through time.

We have assumed that we can set a group of linguistic rules based on captured and averaged sound pressure. The fuzzy logic controller [1, 3, 7] will be based on those rules. We can describe the decision process as:

$$\Delta Out(t+1) = f(sound(t)), \quad (2)$$
$$Out(t+1) = Out(t) + \Delta Out(t+1). \quad (3)$$

Out(t+1) is the output power control 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 captured sound pressure and *f* is the controller's translation function.

We have decided to use fuzzy logic [2, 4, 5, 8] because it is easy to build the fuzzy controller 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.

The curved line of the captured sound pressure in Figure 2 can be split into three segments:

- constant low sound pressure,
- rapidly increasing sound pressure,
- and constant high pressure with slight oscillations.

According to the before mentioned segments we define an input linguistic variable *sound*, which has three membership functions (Figure 3):

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

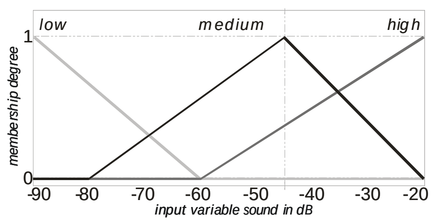

Figure 3: Definition of the membership functions of the linguistic variable *sound*.

The curved line in Figure 2 was captured during the cooking process led by the skilled cook. We can see that the sound pressure function at the normal cooking process never returns to the first segment. Because of that, we decided that at the beginning the controller has to be more robust. When it comes to the third segment it has to be more precise, which will result in the minimal oscillate of the sound pressure function. To reach this goal we changed the membership functions (Figure 4, 5 and 6) according to the strength of the averaged sound.

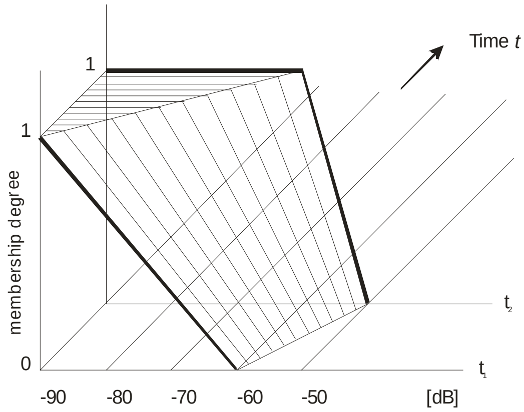

Figure 4: Membership function *low* is changing through time.

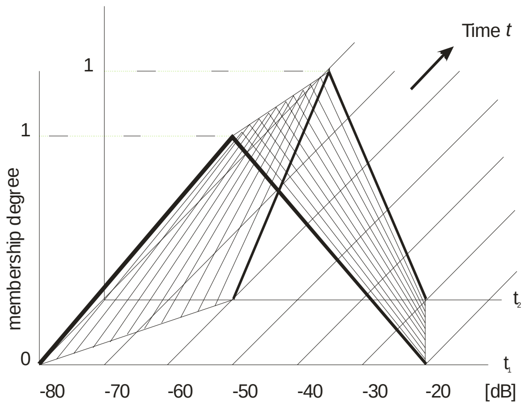

Figure 5: Membership function *medium* is changing through time.

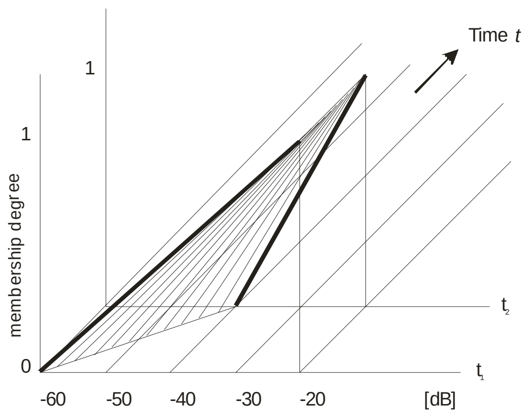

Figure 6: Membership function *high* is changing through time.

If the averaged sound was below -80dB the membership functions from the Figure 3 were used, if the averaged sound was above -55dB next values were used:

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

When the averaged sound (x) was between -80dB and -55dB membership functions limits were determined linearly as follows (MATLAB code):

```
if (x < -85) and (x > -55)
  l1 = -90 + min(max((x+90)/40,0),1)*(-60-(-90));
  l2 = -90 + min(max((x+90)/40,0),1)* (-60-(-90));
  l3 = -60 + min(max((x+90)/40,0),1)* (-50-(-60));
  m1 = -80 + min(max((x+90)/40,0),1)* (-60-(-80));
  m2 = -45;
  m3 = -20 + min(max((x+90)/40,0),1)* (-20-(-30));
  h1 = -60 + min(max((x+90)/40,0),1)* (-40-(-60));
  h2 = -20;
  h3 = -20;
  low ([l1, l2, l3]);
  medium ([m1, m2, m3]);
  high ([h1, h2, h3]);
end;
```

After that we define an output linguistic variable $\Delta Out(t+1)$ as an output of the fuzzy controller, which is defined with three membership functions:

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

According to that maximum change of the output power of the fuzzy controller ($\Delta Out(t+1)$) was 0.3.
If we compare manual cooking with controlled one, we can see that the output power of control is set to its maximum value. The fuzzy controller also sets the output power of control to its maximum value ($Out(0) = 1$).
Fuzzy inference takes fuzzy input and calculates fuzzy output. Fuzzy inference is based on a set of rules. In our case the rules were:

- if (sound is **low**) then (ΔOut(t+1) is **increase**),
- if (sound is **medium**) then (ΔOut(t+1) is **hold**),
- if (sound is **high**) then (ΔOut(t+1) is **decrease**).

We have used the COG (*center of gravity*) method for the defuzzification, which returns crisp values. Those values were used in equation (3) to calculate the output power control $Out(t+1)$. We have to stress out that mathematical operation (addition) in the equation (3) is defined as follows:

$$a + b = max\ (min\ (a+b,\ 1),\ 0) \qquad (4)$$

This means that the output power control $Out(t+1)$ is a real number from the interval [0,1].
We have built the model in the LabVIEW environment with MATLAB script (fuzzy logic calculations) included in it.

5 Results

We compared cooking process led by the skilled cook with the cooking process led by the fuzzy controller with changing membership functions. Graph on Figure 7 shows three curves, sound, averaged sound and temperature. The skilled cook turned off the kitchen range when the content started to boil (at index 650). At that point the temperature was around 95°C.

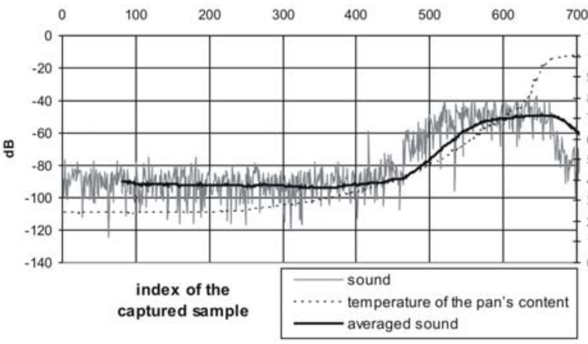

Figure 7: Sound, averaged sound and temperature at the cooking process led by the skilled cook.

Graph on Figure 8 also shows all three curves. We can see the difference in sound and averaged sound curve. The fuzzy controller turned off the kitchen range when averaged sound reached certain value (at index 478). At that point the temperature was around 80°C. We have to stress out that if we compare curves on Figure 7 and Figure 8 boiling point is not at the same index.

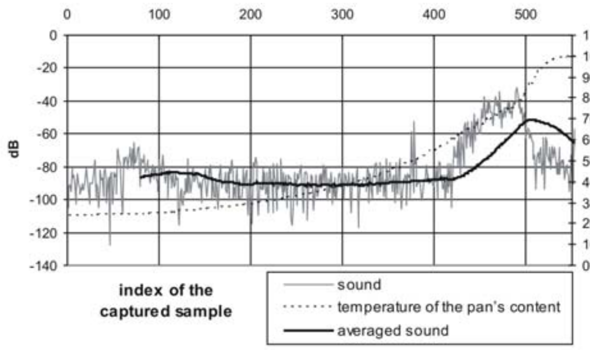

Figure 8: Sound, averaged sound and temperature at the cooking process led by the fuzzy controller with changing membership functions.

The reason is processing of the inference result. When the cooking process was led by a skilled cook there was no processing (fuzzy inference) just capturing and saving the data, which means less time spent for one cycle. As a consequence there were fewer samples captured in the same period of time when the cooking process was led by the fuzzy controller. Our controller turned off the kitchen range before the skilled cook did. If we take under the consideration power consumption, we can determine that the fuzzy controller spent less power.
To ensure the success of the control, we measured not only the sound pressure, but also the temperature of the pan's content, before we have made the final prototype. The pan content temperature was our reference point during the experiments.
We have limited our experiments to four types as follows:

A.) boiling tap water,
B.) boiling salted tap water,
C.) cooking of rice in salted tap water, and
D.) cooking of pasta in salted tap water.

We have got similar results with all four types of experiments. If we take a look at the results of several experiments, we can be sure that in the second segment the sound pressure increases in the time interval smaller than one minute. Our controller can detect this increase, which means that it is capable of controlling the cooking process.

6 Conclusion

The control of the cooking process, based on the sound pressure captured non-invasively in the cover handle, is possible, successful and if we take under the consideration power consumption also better. It is more successful than the control based on the pan content temperature. The captured data had to be transformed (smoothed) with the sliding window method.
From the professional point of view (industry) we have to mention that it is important to build as many process performances as possible into the cover handle. With that the decision process will take place in the cover handle instead in the kitchen range. Only data about the output power control will be transferred to the kitchen range. The main idea is to reduce the power consumption at data transfer.
There is still a lot of work to be done with the automated control of the cooking process, especially concerning the different types of fuzzy controllers. This shall be our future work.

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