Embedded Impedance Spectroscopy for Lab-on-Spoon Realization in Living Assistance Systems and Intelligent Environments

H.H. Pekmezci, D. Los Arcos, A. König
Institute of Integrated Sensory Systems (ISE)
TU Kaiserslautern, Dept. EIT
Kaiserslautern, Germany
koenig@eit.uni-kl.de

Abstract**—***Distributed integrated sensory systems enjoy increasing impact leveraged by the surging advance of sensor, communication, and integration technology in e.g., internet-of-things (IoT), cyber-physical systems (CPS), Industry4.0 Ambient Intelligence/Assisted-Living (AmI/AAL) applications. Smart kitchens and "white goods" in general have become a active field of R&D. ISE research has one focus on improvement of device efficiency and assistance for unskilled or impaired users by providing so called Culinary-Assistance-Systems (CAS). In this paper, the provision of multi-sensor context and assistance is regarded for the instance of a smart spoon device with embedded impedance spectroscopy capability. The current instance of the Lab-on-Spoon (LoS) project, reported here, uses the AD 5933 and low-power EnergyMicro Cortex M3 EFM32G890 F128 in a 3D-printed spoon package. Proven ISE computational intelligence techniques are applied to the obtained measurement data for liquid ingredient recognition and grading. Distinguishing of ingredients, e.g., soy sauce and vinegar as well as grading of milk and frying oil could be shown with the prototype. In future work, a complete wireless, self-sufficient LoS system with an improved dedicated analog CMOS front-end is aspired..*

Index Terms**— IoT, CPS, AmI/AAL, Smart kitchen, smart spoon, impedance spectroscopy, computational intelligence.**

I. INTRODUCTION

The joint surging advance of sensor, communication, and integration technology allow the realization of more versatile and pervasive systems in nearly all domains of industry and daily life. Established and emerging application domains are, e.g., measurement, instrumentation, and automation, Industry4.0, IoT, CPS, and AmI/AAL. Smart environments, in particular, in homes are a prominent example, where deeply embedded intelligent sensory systems add significant functionality unobtrusively merged in everyday life structures an devices. Miniaturization of such autonomous, potentially wireless, sensory systems for distributed measuring and observation can be found from sensate floors to leading edge integrated data loggers.

The information obtained by such sensory systems can serve to achieve improved or novel assistance functionality, e.g., to support unskilled for better performance or support impaired persons to restore lost sensing capability. In kitchen environment, numerous product and research activities can be found to improve device performance or to achieve assistance system functionality. Relevant professional and research work has been summarized in [5]., indicating the potential of sensing and sensory context to achieve a new class of assistance system for this domain, denoted as *Culinary-Assistance -Systems* (CAS) [5]. In ISE research work, a dedicated smart kitchen lab has been set-up, where a central server with a MS-Kinect-based gesture recognition interface serves as a the heart of the intelligent kitchen. An interactive electronic cookbook, inspired by professional tools like ChefTec (see [5]), is emerging as an CAS, where sensory context and support is a key feature (see Fig. 1).

Fig. 1. Gesture-controlled interactive cookbook for LoS sensor context.

To achieve this goal, pioneering work of MIT Media Lab on smart or intelligent spoons by , Dr. Ted Selker et al. [1] is picked-up and extended to wireless communication, and advanced packaging, and multi-sensor capability, in particular impedance spectroscopy (IS), which is a method of increasing impact and applicability [2]. However, in the majority of applications, powerful but expensive and bulky desktop equipment, e.g., HP4195A network analyzer with impedance measurement extension, Agilent 4294, LCZ Meter Model 4277A, or Xiton Hydra 4200 etc., is used. Applications are in the field of Bio-IS and Electrochemical-IS (EIS) and medical tasks like skin cancer or wound healing monitoring [10] or fish, liver. or meat freshness [8] determination as well as water monitoring and detergent concentration determination [9] in, e.g., dish washers, contradict the use of the named equipment beyond proof-of-principles prototypes. Dedicated PCB designs as well as dedicated chip design activities is the consequence . However, the existing commercial solutions, such as the AD 5933 chip, cover only a small part of the interesting impedance, frequency range, and measurement quality for the different applications domains.

In the work presented here, we present the concept and prototype status of our Lab-on-Spoon (LoS) project, which focused on achieving a low-cost high-volume multi-sensory integrated system in the comprehensive smart kitchen and interactive cookbook research context. It is based in its current form on the AD5933 chip [3] and minor extensions. Section II will describe concept and architecture of LoS, Section III will give the status of the currently implemented prototype, and Section IV will describe applications and conducted experiments. Concluding, the motivation for a custom CMOS chip and a reconfigurable MEMS-Based LoS will be discussed and a preview of ongoing activities will be given.

II. LoS Concept and Hardware Architecture

The LoS project targets on the implementation of a low-power embedded multi-sensor system packaged in the shape of the daily spoon. Figure 2 shows the concept of the LoS by a block diagram. The spoon is equipped with a low-power EnergyMicro Cortex M3 EFM32G890 F128 micro controller, that runs the simple measurement control, the sensor readings, and the communication with the smart kitchen host indicated also in Fig. 1. The aspired sensor palette includes a temperature sensor, e.g., a ceramic substrate pt10k of UST GmbH, a true color sensor of MaZeT GmbH, both we have used in previous research, a pH-Sensor, a viscosity sensor, and an impedance spectroscopy measurement facility.

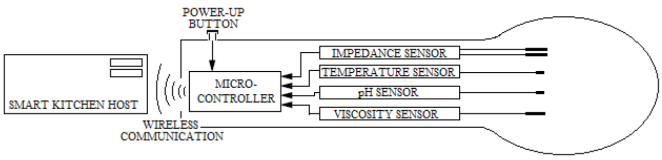

Fig. 2. Block diagram of the aspired LoS hardware.

For the color and temperature sensor standard programmable transimpedance amplifier and instrumentation amplifiers are available and will converted by the µC on-chip ADC. Suitable pH- and viscosity sensors with regard to cost and power issues are just under selection. The IS sensing is achieved with the already mentioned AD5933 chip, an analog extension for larger impedance range and simple electrodes to be embedded in the spoon surface. Several reconfiguration features, e.g., for self-calibration and range extension are included in the concept. Miniaturized switches, e.g., by DC-MEMS switches pursued in another strain of ISE research, are considered for the realization of these reconfiguration features. The µC will be extended by an RF-chip to communicate measurement data to the smart kitchen host, e.g., by Xbee standard. Like in electronic scales, it is anticipated, that the spoon is in sleep-mode and gets woken up by a button-press. The button is allocated in the spoon handle. Measurement will be taken, sensor context data will be communicated to the host., and the spoon will go back to sleep again. Both an autonomous, battery or accu based sensory system, as well as a more ambitious self-sufficient sensory system with an energy harvesting or scavenging device is envisioned. EnOcean's solar generator cell and unit seems to be an interesting candidate, as activated light can be assumed in the kitchen environment in general and the size is compatible with spoon shape and geometry.

Currently, the spoon, serving also as a package for the measurement system has been printed by the Makerbot 3D-printer. This printer system, as well as more powerful and costly 3D-printer systems on the market allow the generation of custom functional devices from prototypes to volume production. Though more powerful 3D-packgaging and MEMS technologies are available, for the sake of the goal of a low-cost system, electronic components in the LoS concept will be realized by standard miniature PCBs roughly tailored to the spoon shape in their aspect ratio and clicked into prepared chambers or locations of the design.

III. Current Prototype and Applications

The currently achieved prototype is implementing the IS capability of the concept described in Section II. With regard to the rather low impedances met for several common liquid cooking ingredients to be recognized and graded, a standard extension of the AD5933 [3] has been implemented. This extension reduces the voltage, and thus the required currents for small impedances to sustainable levels for the AD 5933. For cost reasons, a simple two wire measurement approach has been pursued and tested first, as the more precise and beneficial a four-wire approach requires substantial hardware extension to be realized. Switching from high to low impedance range, changing the feedback resistor in the I/U-amplifier, and alternating between calibration element and actual measurement impedance, e.g., emerged electrodes, are tasks requiring for electronics configuration, as already in Section II.

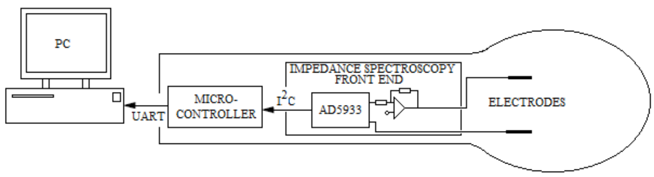

Fig. 3. Block diagram of the current prototype.

Currently, the achieved prototype is still reconfigured by physical rewiring. Fig. 3 shows the block diagram of the current prototype. The µC of the development system still communicates by a wired interface with the host computer, where the data is taken by a Python-based dedicated software unit., which can trigger single or repeated batch measurement. Further processing of the measurement data, including the application of efficient methods from the field of computational intelligence (CI) can be achieved in Python and related tools as well as Matlab or the ISE QuickCog tool [6]. In the latter one, feature maps for interactive data visualization and analysis can be generated. These can help in understanding and optimizing both data acquisition and processing for recognition or grading in new applications. An example is given in the following Fig. 4, where 511-dimensional spectra of a two-class application regarded in the following, have been plotted in a two-dimensional feature map employing a distance preserving mapping, i.e., Sammon's mapping [4]. The feature map or feature space projection has been complemented with by class information as well as AD5933 chip temperature from its internal sensor .

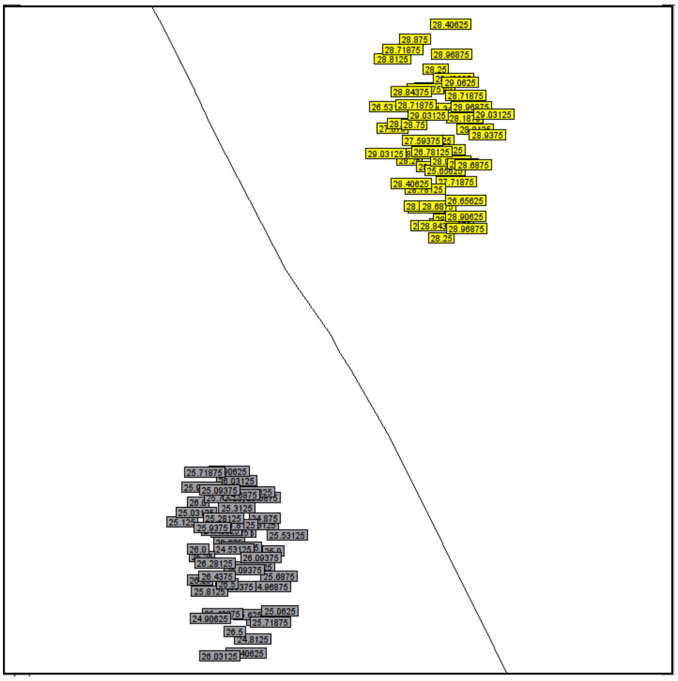

Fig. 4. Temperature-annotated feature map from the current prototype.

For instance, the distribution of the temperature values in the feature map help to determine, whether the significant scatter in repetitive measurements is dominantly caused by thermal effects in the sensor electronics or by alternative noise phenomena.

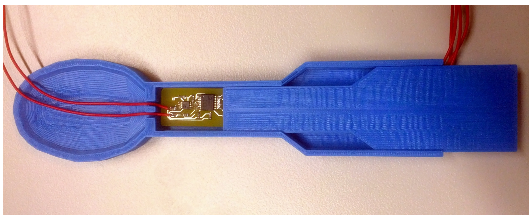

Fig. 5. IS front end in a 3D printed spoon of current LoS prototype.

Fig. 5 shows the picture of the 3D-printed spoon packages with the inserted AD5933 circuit and analog extension of the current prototype. In the front and the handle back locations for the µC module (see Fig. 6), communications, and electrode tips (see Fig. 7) are prepared and ready to host the PCB modules. Rather simple and cheap to produce tips are used in the first-cut experiments.

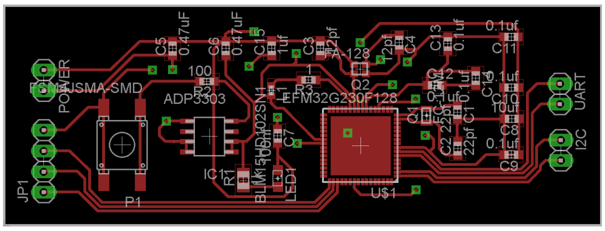

Fig. 6. Microcontroller PCB fit for 3D spoon package handle.

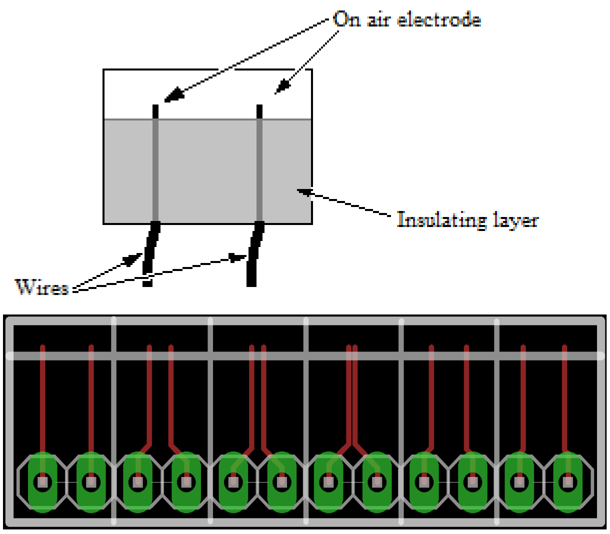

Fig. 7. Selection of simple PCB-tips for LoS measurements.

Different geometries with regard to thickness and spacing of the planar tinned electrodes have been conceived and employed in the following experiments. With regard to the objective, that he LoS prototype shall serve as a probe in our ISE smart kitchen lab to provide sensory context/feedback for the individual preparation steps of a recipe and give information on the category, quantity and potentially quality, e.g., freshness, of ingredients, to the central host and cookbook application, tasks for liquid ingredients classification or discerning have been chosen as the first category, i.e., discerning pure water, salty water in various concentrations, soy sauce, and vinegar has bee regarded. In the next step, quality of an ingredient has been examined, using frying oil and its quality or aptness after multiple use. The last example dealt with observation of the freshness of milk over a longer period of storage and the implied rotting process.

For these examples, data acquisition by the described prototype system and ensuing processing by intelligent methods has been carried out.

In particular, the frying oil classification or grading opens the door to a separate application system, i.e., a stationary oil sensor for indication of wear-out determined oil exchange.

IV. Experiments and REsults

As a first task, the recognition of small number of different liquid ingredients was examined. These were in the first two experiments pure water, salty water in various concentrations, soy sauce, and vinegar.

TABLE I. shows the corresponding data sets with class information and number of acquired patterns, as well as the details of the observation window from the full frequency range of the AD5933.

TABLE I. Acquired data sets for Ingredient Recognition

Liquid Type	*Class No.*	*Frequency Range*	*Frequency Increment*	*No. of samples*
EXPERIMENT 1				
DW[a]+2% Salt	1	1-100kHz	194	4/511
Soy Sauce	2	1-100kHz	194	3/511
Vinegar	3	1-100kHz	194	3/511
EXPERIMENT 2				
DW[a]+1% Salt	1	10-100kHz	1000	4/91
DW[a]+2% Salt	2	10-100kHz	1000	4/91
DW[a]+3% Salt	3	10-100kHz	1000	4/91
DW[a]+5% Salt	4	10-100kHz	1000	4/91
DW[a]+7% Salt	5	10-100kHz	1000	4/91
DW[a]+10% Salt	6	10-100kHz	1000	4/91
DW[a]+15% Salt	7	10-100kHz	1000	4/91
DW[a]+20% Salt	8	10-100kHz	1000	4/91
DW[a]+25% Salt	9	10-100kHz	1000	4/91
Soy Sauce	10	10-100kHz	1000	4/91
Vinegar	11	10-100kHz	1000	4/91

a. Distilled Water

Only a limited number of data samples have been recorded for both of the first experiments, which can be taken from TABLE I.

The experimental data from the low-power embedded system was transferred to host and Matlab/QuickCog [4] for further analysis and classification.

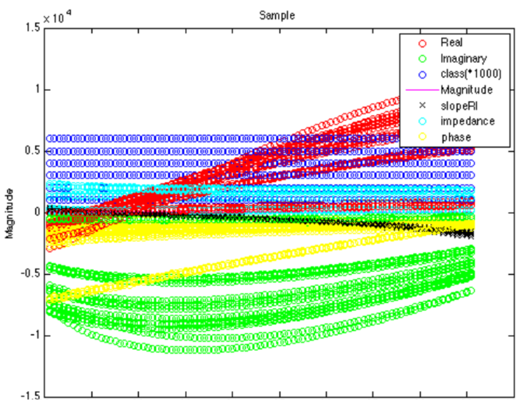

Fig. 8. Visual assessment of discrimination information of IS sweep..

In the first step, spectral features and features computed from the spectrum were investigated with regard to their discrimination ability (see Fig. 8). The analysis showed that the highest spectral component, index 511, is the most important raw feature for this EIS task. This also implies that the 100 kHz measuring range probably is too constrained and needs extension. The impedance values were approx. from 100 Ω to 2 kΩ, thus requiring the activation of the AD5933 analog extension board.

In the following, the impedance magnitude spectra were chosen as a feature set with 511 points of frequency which each point designated as a feature. Fig. 9 shows the feature map of this problem and data extended by one representative impedance spectrum for the vinegar and soy sauce classes. Due to the limited amount of data, leave-one-out (LOO) approach [5] was investigated in addition to hold-out method. In each round of this approach 9 training and 1 testing samples are applied.

LOO was employed with Reduced-Nearest-Neighbor classifier (RNN) and returned 100% recognition rate. In addition to this straight forward classification approach, based on the analysis discrimination contribution of the spectral components, dimensionality reduction has been applied.

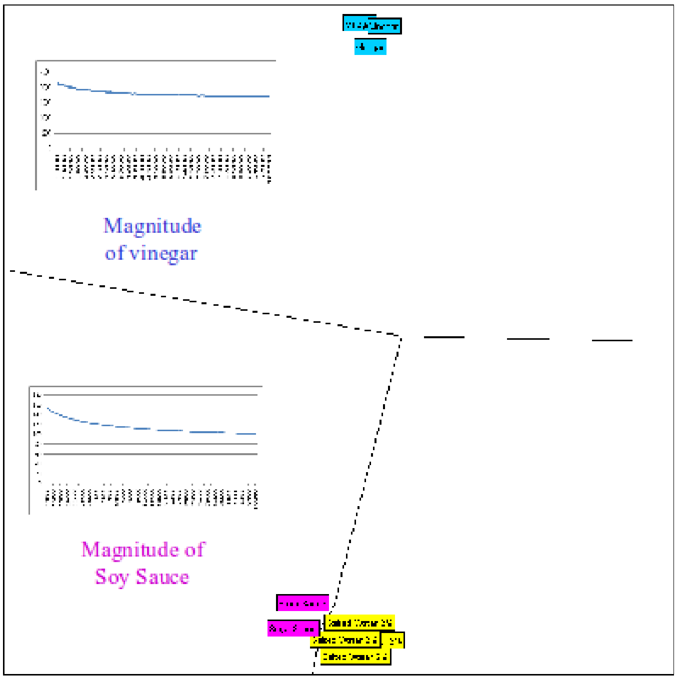

Fig. 9. Experiment 1 data features space projection.

One general problem, that could observed throughout all experiments was, that the transition of the sensor/LoS from one liquid ingredient to the next required careful cleaning to avoid spurious responses due to unknown mixtures on the electrodes as well as transport from one container to the next and corresponding mixture or impurification.

In the second problem or task, the plant oil of a home frying machine, e.g., for french fries preparation, was investigated with regard to wear-out and need for oil exchange. Fresh one was compared to used one, which according human impression of look, smell, and numbers of use was due to exchange. Two classes with fifty samples each were acquired, based on the AD5933 settings of experiment 1, by repetitive measurement. Figure 10 shows the corresponding feature map with two distinct, well separated clusters for fresh (top right) and heavily used (bottom left) frying oil.

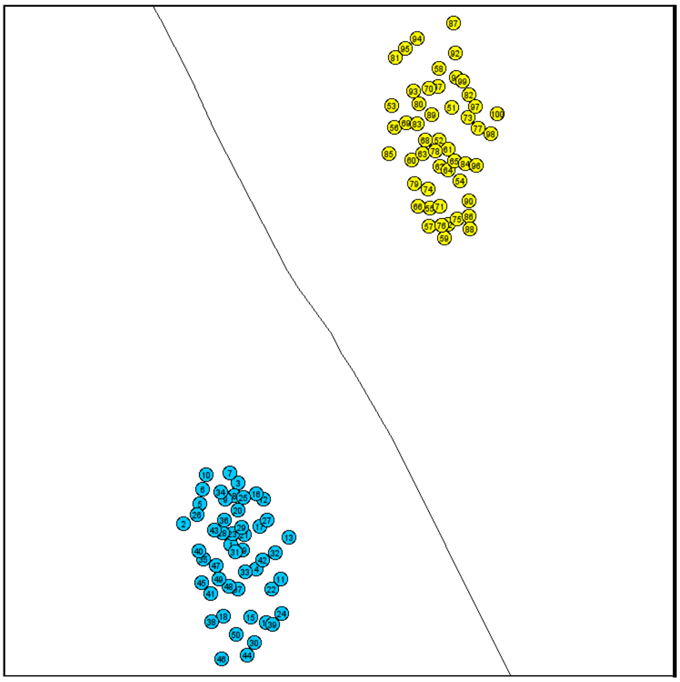

Fig. 10. Features space projection of frying oil data set.

The impedance values in this case were approx. from 400 kΩ to 8 MΩ, thus requiring the deactivation or bypass of the AD5933 analog extension board and a feedback resistor of 220 kΩ. A calibration resistor of 219 kΩ has been applied before measurement. Also, normalization of the impedance data to the range of [0,1] was investigated for these rather large dynamic ranges of the data. Due to the larger amount of sampled data, the hold-out method could be applied. Further, automated-feature-selection (AFS), Sequential-Backward-Selection (SBS) based on overlap assessment q_{oi} [4] was applied for the search of the most meaningful spectral components. For the given data, the component 510 was found to be most meaningful and sufficient for robust classification. Due to the rather straight class boundary, simple RNN method in hold-out approach with 50 % training and 50 % testing data was sufficient for perfect generalization of the normalized complete as well as selection reduced data. The same holds for the not normalized case. Thus, experiment 3 showed the basic feasibility of two-level ingredient grading and the achievement of an simple oil quality sensor at the same time. The third tentative experiment deals with spoiling of food due to ageing or rotting process. This was investigated here by observing fresh milk poured in a glass container of about 100 ml under ambient conditions for the following time steps. Freshly poured milk was measured first, followed by a three days old probe stored under ambient conditions. Then on four more consecutive days, the ageing process was monitored about the same time of day. Unfortunately, between the third and fourth measurement the interval had bee doubled to two days, which is reflected by a slightly larger gab in the feature map given in Fig. 11. The intricacies of the rotting process, i.e., which kind of contamination or bacteria become effective in the regarded environment, is difficult to control and assess. This also relates to the speed and required sample intervals. Thus, the experiment is denoted as tentative. But the overall objective is more simple, as the LoS shall just give a warning if the product is no longer fit for consumption, not a fine grading of the ageing/rotting process.

At each time step, corresponding samples have been taken in repetitive measurement. Only 5 samples for classes 1 and 2, and 30 samples for classes 3 to 6.

Clearly, the data set, given in Fig. 11, represents a multi-class problem, where each class stands for a step in the ageing or decay process. Also, it become clear, that the clusters potentially can be less well separated and more overlapping, which can result in more complex class boundaries and the need for a more powerful classification method, i.e., the Support-Vector-Machine (SVM).

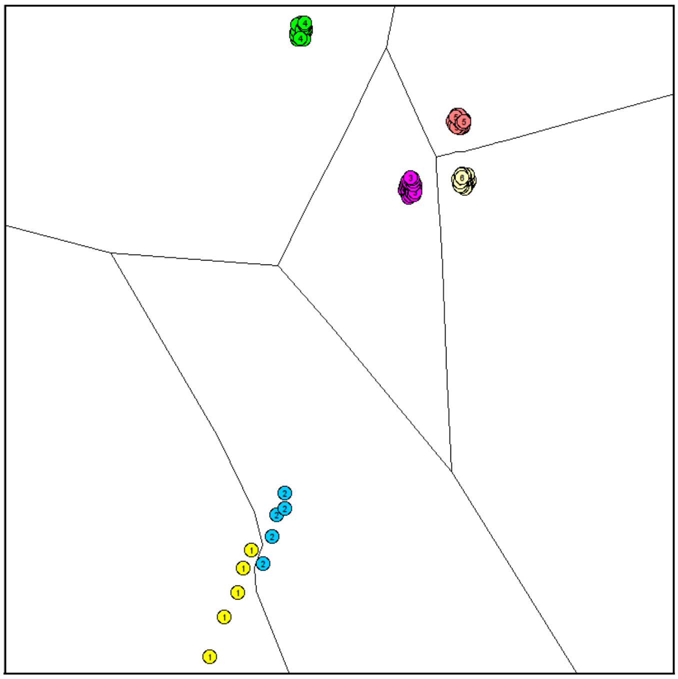

Fig. 11. Features space projection of milk ageing data set.

The encountered impedance range of this data is approx. 105 kΩ to 113 kΩ , and is measured under the same conditions as the previous oil data. Though the sample numbers of class 1 and are rather small, the hold-out method is applied, separating class 3 to 6 data in a 50% training and 50% test ratio, while class 1 and 2 data was split 40% to 60 % ratio. Due to the operations of normalization and feature selection, four experimental permutations have been conducted. AFS with SBS and overlap assessment q_{oi} returned 136 features for the not normalized and 11 features for the normalized case as sufficient for the separation of the training set. Again, the simple but effective RNN classifier has been applied again. The results were 100 % recognition rate for three of the four cases, the forth one of normalized and selected data is given in TABLE II in more detail. The sampling of the sparsely populated and overlapping classes 1 and 2 has influence, so that a less lucky choice might add to the error rate by additional confusion between class 1 and 2. Currently, the data is quite noisy, so that the current feature selection is not stable enough for a physical interpretation of the selected spectral components.. The employment of powerful SVM promises improved robust classification quality for all the raised issues.

TABLE II. MILK AGEING DATA RECOGNITION RESULTS FOR NORMALIZATION AND AFS.

	Class1	***Class 2***	***Class 3***	***Class 4***	***Class 5***	***Class 6***
Milk data: normalized and selected						
Selected Features: 4, 21, 27, 30, 32, 36, 46, 52, 59, 67, 451 of 511						
Class 1	100	0	0	0	0	0
Class 2	0	100	0	0	0	0
Class 3	0	0	100	0	0	0
Class 4	0	0	0	100	0	0
Class 5	0	0	13.33	0	86.66	0
Class 6	0	0	0	0	0	100

The extension to continuous grading parameters estimation by, function approximation, e.g., RBF networks [5] and/or Support-Vector-Regression SVR, for oil, milk and related liquid ingredient assessment is currently in progress with promising perspective.

V. CONCLUSIONS

This paper presented a contribution to the smart kitchen AmI/AAL related research work at ISE, with the focus on providing sensor context to the preparatory steps of recipes in an interactive cookbook. This is achieved by an embedded device denoted as Lab-on-Spoon, which targets on qualifying and quantifying the ingredients for the preparatory steps, thus supporting by such CAS [6] both unskilled or challenged persons with improved or restored perceptive and assessment ability . The current LoS implementation features embedded impedance spectroscopy based on a rather basic commercial chip, the AD5933, and a low-power μC system. Exemplary applications of ingredient discerning and quality classification for binary or multi-class grading have been successfully tackled with the prototype and ISE CI standard methods and tools. However, for stability, repeatability, and accuracy issues improvements in the prototype and the measurement conduction, starting with the electrodes, are required.

In the next steps of the work, the multi-sensor LoS architecture, with color, temperature, pH-value, and viscosity sensing, as well as related sensor fusion techniques and efficient yet compact feature computation techniques shall be completely developed and integrated. This includes also 3D-package and wireless communication. For that aim, the use of Arduino μC family due its well known salient properties and rich choice of modules is considered as an alternative and has been used for IS in related ISE research [7] Particular care is required for design of cheap, yet robust electrodes in the spoon surface for stable, repeatable measurement and related cleaning and hygienic issues..

The work is also a case study for the conception of a more able dedicated CMOS-IS chip for a wide range of integrated/embedded IS applicability [6-10], that is currently pursued at ISE. From the results on frying oil, and preliminary experiments on combustion engine oil, an extension or spin-off of the project to simple and low-cost motor and gear oil sensors seems to be promising and straight forward.

ACKNOWLEDGEMENT

The contribution of Abhay C. Kammara to the smart kitchen research and the support of Dennis Groben in software and electronics issues is gratefully acknowledged.

REFERENCES

[1] T. Selker. (2008) Counter-intelligence project. Last visited: 02/02/2013. [Online]. Available: www.media.mit.edu/ci/

[2] J. R. Macdonald, "Impedance Spectroscopy", Annals of Biomedical Engineering, Vol. 20, pp. 289-305, 1992

[3] Analog Devices, AD5933 datasheet. Analog Devices, Inc. 2011

[4] Institute of Integrated Sensor Sytems, "QuickCog v2.0 Anwenderhandbuch", October 1999. *(online version)*

[5] S. Haykin, "Neural Networks, A Comprehensive Foundation" Second Edition, Pearson Education Inc., 1999

[6] A. König, "Automated and Holistic Design of Intelligent and Distributed Integrated Sensor Systems with Self-x Properties for Applications in Vision, Robotics, Smart Environments, and Culinary Assistance Systems." Invited Talk, Int. Conf. On Neural Information Processing of the Asia-Pacific Neural Network Assembly (ICONIP'08), Book of Abstracts, pp. 69-70, November 25-28, Auckland, New Zealand, 2008

[7] L. Li, T. Bölke, A. König. "Can Impedance Spectroscopy Serve in an Embedded Multi-Sensor System to Improve Driver Drowsiness Detection", In: Abstract Book, Int. Workshop on Impedance Spectroscopy IWIS 2013, pp. 48-49, Chemnitz, Sept. 25-27, 2013

[8] M. Guermazi, O. Kanoun. "Feature Extraction for Meat Characterization", In: Abstract Book, Int. Workshop on Impedance Spectroscopy IWIS 2013, Poster, pp. 95, Chemnitz, Sept. 25-27, 2013

[9] R. Gruden, W. Köbele, D. Tran, O. Kanoun. "Online Detection of the Critical Micelle Concentration of Commercial Detergents by Impedance Spectroscopy", In: Abstract Book, Int. Workshop on Impedance Spectroscopy IWIS 2013, Poster, pp. 56-57, Chemnitz, Sept. 25-27, 2013

[10] A. Schröter, G. Gerlach, A. Rösen-Wolff, J. Wendler, A. Nocke, C. Cherif "Miniaturized Wound Sensors for Chromatin Detection", In: Abstract Book, Int. Workshop on Imp. Spectr. IWIS 2013, Poster, pp. 95, Chemnitz, Sept. 25-27, 2013