Towards Adaptive, Real-time Monitoring of Food Quality using Smart Sensors

Elia Henrichs and Christian Krupitzer
Department of Food Informatics and Computational Science Lab
University of Hohenheim
Stuttgart, Germany
{elia.henrichs, christian.krupitzer}@uni-hohenheim.de

Abstract— **Adaptive software systems can reduce food waste and improve food safety. Such systems include smart sensors to monitor the food's condition and machine learning-based data analysis to predict the food's quality and shelf life. In particular, monitoring is challenging for several reasons, e.g., the energy supply/demand and the reliability of the sensors. Therefore, this work sketches how the Multi-Level Observer/Controller architecture from Organic Computing might be applied for the adaptive monitoring of packaged foods.**

Index Terms—**food supply chain, adaptive monitoring, Multi-Level Observer/Controller architecture, intelligent packaging**

I. INTRODUCTION

Approximately 931 million tons of food were wasted globally in 2019 [1]. The major proportion is generated in private households. The main reasons are related to durability: Food products are wasted in processing and households due to damage or spoilage, and retail due to reaching the best-before date [2]. In the case of packaged food, intelligent packaging can communicate the current food quality and condition for identifying potential hazards, recommending actions to prevent foods from being damaged, or providing more detailed information on the remaining shelf life [3].

However, intelligent packaging requires energy to operate sensors and transmit data for calculations and investigations of the entire food's life cycle, i.e., until consumption or spoilage. This is particularly challenging since food packaging is not rechargeable. Further, the reduction and selection of the monitored data are necessary to perform the data analysis efficiently. Therefore, adaptive monitoring is a promising approach to balance data sampling and energy consumption [4].

This work sketches how the Multi-Level Observer/Controller architecture from Organic Computing might be applied to monitor packaged foods adaptively. Since the food supply is a distributed and complex system, this architecture provides an optimal framework for intelligent monitoring due to its layered structure.

II. BACKGROUND

Adaptive monitoring is defined as the ability of a monitoring system to adjust "its structure and/or behavior in order to respond to internal and external stimuli such changes in their execution context, functional and non-functional requirements, systems under monitoring or the monitoring system itself" [4]. The adaptations aim to enhance the system's efficiency and are executed without disrupting the running system.

In particular, adaptive monitoring describes the adaptation of the monitoring activity, i.e., adapting the sensor sampling rate in the case of sensors or selecting data sources in the case of monitoring systems. On the one hand, the reasons to adapt are reducing resource or energy demands, compensating for sensor faults and failures, or changing the monitoring system's environment. On the other hand, data need to describe the current state of the monitored system with regards to the accuracy and reliability to avoid delayed reactions which are particularly important for foods.

Adaptive monitoring is applied in many fields, such as sensor networks or service-based system monitoring [4]. However, there is no approach to adaptive monitoring of packaged foods.

III. CURRENT STATE

We are currently focusing on identifying the interplay of sensors for specific food and adapting the sensor sampling rates. Therefore, we built a testbed to generate data. We use raw milk as a food example since this milk often spoils due to lactic acid bacteria, which results in decreasing the pH value. The testbed consists of an Arduino UNO R3, a pH sensor (SEN0161) to monitor the spoilage based on a pH drop, a temperature sensor (DS18B20) to monitor the environment, a real-time clock (DS1307), and a SD card module including an SD card. The milk was continuously stirred (approx. 300 rpm) and stored at room temperature during the experiment.

First results show that we are able to monitor the spoilage based on lactic acid bacteria, as shown in Figure 1. Worth mentioning is that the pH value is dependent on the temperature. Further, the temperature is an important parameter to be monitored since its affects the growth of lactic acid bacteria. Therefore, we consider adapting the pH sensor's sampling rate depending on the (environmental) temperature. Additionally, the effect of different storage conditions on shelf life must be taken into account. The following section describes the corresponding system model.

This work is funded by the *Vector Stiftung* within the project "The smart, digitized food supply chain" (P2021-0093).

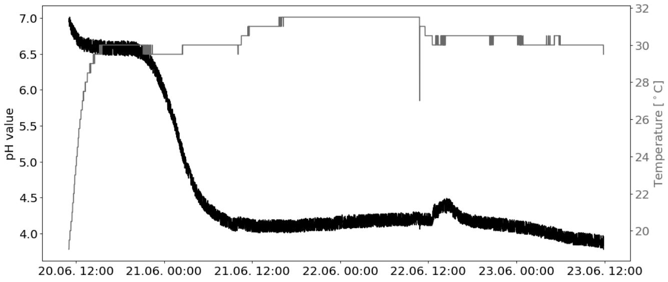

Fig. 1. Time course of pH value and temperature

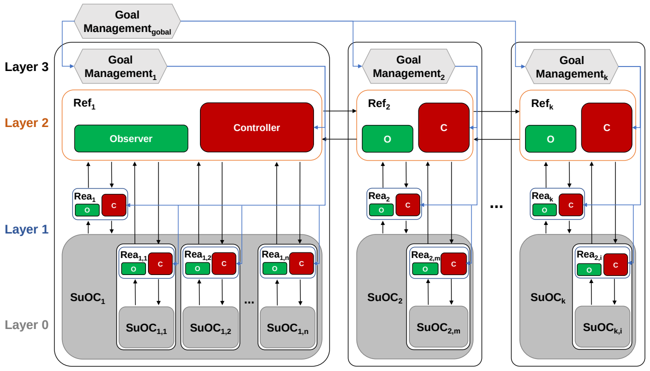

Fig. 2. The adapted Multi-Level Observer/Controller Architecture for adaptive food monitoring

IV. SYSTEM MODEL AND FUTURE CHALLENGES

Figure 2 presents our general approach for the adaptive monitoring of packaged foods based on the Multi-Level Observer/Controller architecture [5]. In the following, this section describes the system model and open challenges.

Although each food packaging must be treated as a single and independent unit, multiple packages will share their environment in several stages of the food supply chain, e.g., on pallets during distribution or a cooling shelf in retail. Therefore, the **System under Observation and Control** (SuOC) and the **Reactive Adaptation Layer** (Layer 1) will be divided. The system's main objective is to achieve high reliability in determining the food's quality throughout its life cycle. Since it is hard to determine the lifetime of a food product, energy management is crucial. On the one hand, the SuOC is the monitoring system of each packaging consisting of the sensor itself and the power supplement to provide all necessary information on the food's condition. In order to adapt the sensor sampling rate depending on the remaining energy and environmental conditions, e.g., temperature, light, or humidity, a Reactive Adaptation logic is directly assigned to each $\text{SuOC}_{k,i}$. On the other hand, multiple packages in a shared environment can be aggregated as a more overarching SuOC_k. The related Layer 1 will then select devices to monitor the environment; hence, this Layer 1 is responsible for structural adaptations.

The composition of the **Reflective Adaptation Layer** (Layer 2) is more overarching than the layers below. Developing new rules is difficult and ineffective for single packaging. Further, other packages might also require these rules in the future. In addition, many food packages are non-returnable, resulting in information loss in directly mapped layers. Hence, the meta-adaptations in this layer should be based on aggregated information from several subsystems and, afterward, distributed again.

The **Collective Layer** (Layer 3) serves mainly as a communication interface, including the communication between several subsystems and access points for human users. The information exchange between the monitoring systems of different products occurs in this layer. Further, external information can be included, e.g., seasonal weather data to estimate the food's shelf life and, hence, the required energy supply. Additionally, the user could gain information to optimize the food itself, the packaging, or the delivery conditions.

As mentioned in Section III, adaptations must be made based on the packaging environment and the remaining shelf life. Therefore, future work includes revising the experimental setup to simulate more realistic packaging and determine dependencies between environmental and quality-related parameters. Further, the development of digital twins might assist with this [6]. Another challenge relates to structural adaptations in shared environments: Sensors to monitor the environment must be selected to gather sufficient data and avoid redundancies. Adaptation decisions should be triggered using machine learning algorithms. Therefore, the use of, among others, multiple regression, time series forecasting, and classification will be investigated in order to determine the best suitable method. We will further analyze how to generalize the result to other types of sensors and other food products and, additionally, how to automatize the choice of analysis algorithms, e.g., relying on previous work on time series forecasting recommendation systems [7]. Finally, the prototype should be evaluated experimentally regarding its performance and accuracy.

REFERENCES

[1] H. Forbes, T. Quested, and C. O'Connor, "Food Waste Index Report 2021," United Nations Environment Programme, Nairobi, Tech. Rep., 2021, [Online] https://wedocs.unep.org/bitstream/handle/20.500.11822/35280/FoodWaste.pdf (accessed 14/07/22).

[2] R. Herzberg, T. G. Schmidt, and F. Schneider, "Characteristics and Determinants of Domestic Food Waste: A Representative Diary Study across Germany," *Sustainability*, vol. 12, no. 11, 2020.

[3] M. Vanderroost, P. Ragaert, F. Devlieghere, and B. De Meulenaer, "Intelligent food packaging: The next generation," *Trends in Food Science and Technology*, vol. 39, no. 1, pp. 47–62, 2014.

[4] E. Zavala, X. Franch, and J. Marco, "Adaptive monitoring: A systematic mapping," *Information and Software Technology*, vol. 105, pp. 161–189, 2019.

[5] C. Müller-Schloer and S. Tomforde, *Organic Computing - Technical Systems for Survival in the Real World*. Springer International Publishing AG, 2017.

[6] E. Henrichs, T. Noack, A. M. Pinzon Piedrahita, M. A. Salem, J. Stolz, and C. Krupitzer, "Can a Byte Improve Our Bite? An Analysis of Digital Twins in the Food Industry," *Sensors*, vol. 22, no. 1, 2022.

[7] M. Züfle, A. Bauer, V. Lesch, C. Krupitzer, N. Herbst, S. Kounev, and V. Curtef, "Autonomic forecasting method selection: Examination and ways ahead," in *2019 IEEE International Conference on Autonomic Computing (ICAC)*, 2019, pp. 167–176.