Measuring meat temperature is among the key challenges of modern society in the 21st century, significantly affecting different cultures and subcultures, such as beef, pork, or poultry. Representing an interface between human, nature and technology, precise measurements of meat temperature facilitate social cohesion among individuals involved in grilling, barbecuing, and smoking. This paper describes the implementation of a wireless monitoring system for sensor-based Internet-enabled temperature analysis, termed “WIMOSIT”, which is deployed for remote measurements of meat temperature. WIMOSIT, a prototype monitoring system originally designed to advance facility management of buildings, has been implemented by a group of students at the Chair of Computing in Civil Engineering at Bauhaus University Weimar. In this paper, the design of the WIMOSIT system is presented, which automatically measures and analyses meat temperature through intelligent sensor systems, and it provides data relevant to the meat of interest remotely via Internet. As will be shown in this paper, a validation test is performed at a barbecue party, serving as a proof of concept of the WIMOSIT system. Also, its societal impact on human, nature and technology and particularly on future systems, structures and machines to be designed for intelligent meat temperature measurements is demonstrated.

Introduction

Grilling is not an art. Grilling is a science. The science of grilling was first coined more than 500,000 years ago by Homo erectus, an extinct human species first utilizing fire to grill meat [1]. In recent years, the science of grilling has been coupled with two other branches of science, the science of barbecuing and the science of smoking [2], hereinafter referred to as the sciences of grilling, barbecuing, and smoking (“GBS sciences”). The three branches within GBS sciences can be distinguished depending on temperature, time, and smoke the meat is exposed to. According to [3], grilling requires high temperature for a few minutes with optional smoke, barbecuing requires medium heat for some minutes to a few hours with some smoke, and smoking requires low heat for multiple hours with nearly constant smoke. Taking into account the personal preferences of human individuals as well as temperature, time and smoke, the societal impact of GBS sciences, integrating human, nature and technology, becomes evident.

With recent advancements in modern physics, thermodynamics have gained strong influence on GBS sciences in the past century, significantly enhancing the quality of grilling, barbecuing, and smoking. In addition to temperature, time and smoke, the scientific principle of heat transfer has been introduced to GBS sciences, comprising convection, conduction, and radiation [4]. Convection describes the heat transfer caused by bulk movement of molecules, such as air, water, or oil. In other words, molecules act as heat carriers circulating around the meat, while the meat is not in contact with the heat source (“indirect grilling”). Although research on indirect grilling is still in its infancy, it has been proven that indirect grilling (or convection grilling) is an appropriate means for barbecuing and smoking [5]. Specifically, convection occurs at the top of the smoker, which requires the smoker to be closely covered with a hood. Ventilation is an important parameter to be considered to ensure that air circulation avoids accumulation of air above the meat. Conduction is the heat transfer by microscopic collisions of particles and movement of electrons. In GBS sciences, the process of conduction refers to the heat transfer caused by direct contact of the meat to the heat source, e.g. at the grilling surface between meat and grill grate in classical grilling. Infrared grilling, for example, takes advantage of conduction [6]. Radiation (more precisely: thermal radiation) is the process of heat transfer caused by emission of electromagnetic waves that carry the heat away from the heat source. The principle of radiation, in association with conduction is primarily used in traditional grilling.

All branches of GBS sciences have in common that temperature plays a crucial role in the success of grilling, barbecuing, and smoking. While other variables, such as time, can easily be measured with clocks or watches, temperature measurements require temperature sensors to be attached to the meat being grilled, barbecued, or smoked. Various types of meat thermometers are available in the market to measure internal meat temperature [7]. A meat thermometer typically consists of a metal probe with
Design and implementation of a wireless monitoring system for sensor-based Internet-enabled temperature analysis—a meat thermometer

The architecture of the WIMOSIT system is shown in Figure 1. The main components of the system, wireless sensor nodes and a server, are described in the following subsections.

Wireless sensor nodes

In the WIMOSIT system shown in Figure 1, up to 253 wireless sensor nodes can be connected to a wireless sensor network, each node being equipped with one or more sensors. Although temperature measurements are of interest in this study, different sensor types may be attached to a sensor node, such as motion sensors, humidity sensors, or accelerometers. Embedded algorithms are implemented into the wireless sensor nodes, enabling each node analyzing the data recorded by the sensors and communicating with other wireless sensor nodes. As shown in Figure 1, a designated sensor node, referred to as “base station”, acts as an interface between the wireless sensor nodes and a wireless router. The wireless router fulfills two main functions. First, it sets up a wireless local area network for the WIMOSIT system, secured by a firewall and Wi-Fi Protected Access 2 (WPA2) encryption. Second, it offers a wireless access point enabling communication of the sensor nodes with a server as well as communication between server and authorized clients accessing the WIMOSIT system through the Internet.

Server

The server includes (i) a database server for storing and managing the data recorded by the wireless sensor nodes and (ii) a web server for providing the sensor data via the Internet to authorized clients. The database server houses a database that stores the sensor data in several tables (“relations”), similar to Excel spreadsheets. The web server delivers the sensor data, stored in the database, to the Internet; given that authorized users access the WIMOSIT system to request sensor data, the web server processes the requests and responds with the sensor data requested. For security, communication between clients and server is implemented using the Hypertext Transfer Protocol Secure (HTTPS) over Transport Layer Security (TLS) encryption. Last, but not least, the web server supports server-side scripting, i.e. sensor data requested by users is provided in form of dynamic documents that are retrieved, independent from user locations, in the web browsers of the clients.
Prototype implementation of the WIMOSIT system

The WIMOSIT system is prototypically implemented for sensor-based Internet-enabled temperature analysis. For the prototype implementation of the wireless sensor network, Raspberry Pi low-cost single-board computers are used (Figure 2). More specifically, for each wireless sensor node, a Raspberry Pi 1 Model A is deployed, featuring a 700 MHz single-core ARM processor and 512 MB SDRAM, while for the base station, a 900 MHz Raspberry Pi 2 Model B with 1 GB SDRAM, is used. For wireless communication, Wi-Fi USB adapters (type Edimax EW-7811Un) are attached to the Raspberry Pi single-board computers, operating on the 2.4 GHz band and supporting net data rates up to 150 Mbit/s in compliance with the IEEE 802.11n wireless networking standard. For temperature measurements, IKEA Fantast digital meat thermometers, heat-resistant up to 250 °C (480 °F), are disassembled and connected to every Raspberry Pi 1 Model A. Supplying power to the Raspberry Pi single-board computers, 10,400 mAh Li-Ion power banks (type Thumbox Power Tube) are connected to the Raspberry Pis’ USB ports. At server side, a MySQL database server is set up for the prototype implementation of the database server. The web server is an Apache HTTP server, and for server-side scripting, PHP scripting language is used to provide websites with dynamic content to the clients.
Validation test

The purpose of the validation test is to confirm that the WIMOSIT system operates as expected under operational conditions. Therefore, a barbecue party is devised. The WIMOSIT system is employed as an intelligent tool for sensor-based Internet-enabled temperature analysis or, more precisely, as a meat thermometer. Its purpose is to precisely measure (i) the ambient grill temperature and (ii) the internal temperature of a chicken being barbecued. A further purpose of the WIMOSIT system is to generate alerts as soon as the internal chicken temperature reaches 90 °C (195 °F), indicating that the chicken is done according to the scientific barbecue rules provided by GBS sciences. The setup of the barbecue party is subdivided into an outdoor test setup and an indoor test setup, as illuminated in the following paragraphs.

Outdoor test setup

Under harsh weather conditions, i.e. air temperature around 0 °C (32 °F) and rainfall, the barbecue party takes place in February 2018. Figure 3 shows the chicken that is fully prepared. It should be noted that, to account for all religions involved, a halal chicken is barbecued, and no pork or beef participates in the validation test. Figure 4 illustrates the outdoor test setup. The chicken is installed in a charcoal kettle grill to achieve and maintain low ambient grill temperature and a slow increase of internal chicken temperature required to professionally barbecue the chicken. To achieve grilled flavor, smoking wood chips are added. A thermometer is fixed on a halved potato, which is also barbecued in the kettle grill, to measure the ambient grill temperature. For measuring the internal chicken temperature, another thermometer is pushed into the chicken. Both ambient grill temperature and internal chicken temperature are continuously recorded by a sensor node situated below the grill. All temperature readings are automatically analyzed by the sensor node and, through a Wi-Fi USB adapter, sent via the base station to the database server located indoors at the Chair of Computing in Civil Engineering.

Indoor test setup

The indoor components of the WIMOSIT system include the server, i.e. database server and web server, for storing the temperature data and for providing it, through the Internet, to authorized clients. The server as well as a client computer to remotely display ambient grill temperature and internal chicken temperature are located in a seminar room at the Chair of Computing in Civil Engineering. Different from the outdoor test setup, the weather conditions in the seminar room are very convenient at about 22 °C (71 °F) room temperature without rainfall. Figure 5 shows the ambient grill temperature and internal chicken temperature displayed through a client computer that is remotely connected to the

Figure 3: Chicken prepared by grill aficionados. Figure 4: Outdoor test setup with chicken before the validation test.
server. After several hours, the internal chicken temperature reaches the threshold of 90 °C (195 °F), and an alert is sent indicating that the chicken is done.

![Client-side website with temperature data.](image)

**Figure 5: Client-side website with temperature data.**

**Validation test results**

The result of the validation test is shown in Figure 6. As compared to Figure 4, the difference in chicken appearance is obvious: While the chicken before the validation test (Figure 4) appeared rather pale, the chicken after the validation test (Figure 6) looked golden brown, fully barbecued. Due to the accurate Internet-enabled temperature analysis of ambient grill temperature and internal chicken temperature provided by the WIMOSIT system, a tender, lean, and perfectly barbecued chicken is achieved. The chicken showcased in Figure 7 appears in form of a delicious chicken burger, refined with sauces, spices, and vegetables. As a result, the societal impact of the WIMOSIT system can be seen from Figure 8: Upon serving the chicken burgers, all participants are happy (after waiting for food for several hours).

![Chicken after the validation test.](image)

**Figure 6: Chicken after the validation test.**

![Result of the validation test.](image)

**Figure 7: Result of the validation test.**
Conclusions and future work

This study has presented a wireless monitoring system for sensor-based Internet-enabled temperature analysis, termed “WIMOSIT”, which has been originally designed by a group of students at the Chair of Computing in Civil Engineering at Bauhaus University Weimar to advance facility management of buildings. A validation test has been performed at a barbecue party, serving as a proof of concept of the WIMOSIT system. In the validation test, the WIMOSIT system has been deployed as a meat thermometer for measuring and analyzing ambient grill temperature and internal temperature of a chicken that has exclusively been prepared for the validation test. Unlike common “smart” meat thermometers, the WIMOSIT system can be extended by additional sensing or decision making modules relevant to grilling, barbecuing, and smoking. It could be proven that the WIMOSIT system performs as expected under operational conditions; it automatically measures and analyses meat temperature through intelligent sensor systems and provides data relevant to the meat of interest via Internet. Also, its societal impact on human, nature and technology has been corroborated, given the happiness of the participants once the raw chicken had turned into a delicious chicken burger. Future research efforts will include further temperature measurements that will not be restricted to meat; rather, temperature of vegetarian food, such as potatoes and corn, may be measured by WIMOSIT at future barbecue parties.

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