Software-Defined Cooking using a Microwave Oven

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Abstract

Despite widespread popularity, today's microwave ovens are limited in their cooking capabilities, given that they heat food blindly, resulting in a non-uniform and unpredictable heating distribution. We present *SDC* (software-defined cooking), a low-cost closed-loop microwave oven system that aims to heat the food in a software-defined thermal trajectory. SDC achieves this through a novel high-resolution heat sensing and actuation system that uses microwave-safe components to augment existing microwaves. SDC first senses thermal gradient by using arrays of neon lamps that are charged by the Electromagnetic (EM) field a microwave produces. SDC then modifies the EM-field strength to desired levels by accurately moving food on a programmable turntable towards sensed hot and cold spots. To create a more skewed arbitrary thermal pattern, SDC further introduces two types of programmable accessories: microwave shield and susceptor. We design and implement one experimental test-bed by modifying a commercial off-the-shelf microwave oven. Our evaluation shows that SDC can programmatically create temperature deltas at a resolution of 21 degrees with a spatial resolution of 3 cm without accessories and 183 degrees with the help of accessories. We further demonstrate how a SDC-enabled microwave can be enlisted to perform unexpected cooking tasks: cooking meat and fat in bacon discriminatively and heating milk uniformly.

Keywords

Radio actuation, microwave, digital gastronomy.

ACM Reference Format:
Haojian Jin, Jingxian Wang, Swarun Kumar, Jason Hong. 2019. Software-Defined Cooking using a Microwave Oven. In *The 25th Annual International Conference on Mobile Computing and Networking (MobiCom '19), October 21–25, 2019, Los Cabos, Mexico.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3300061.3345441

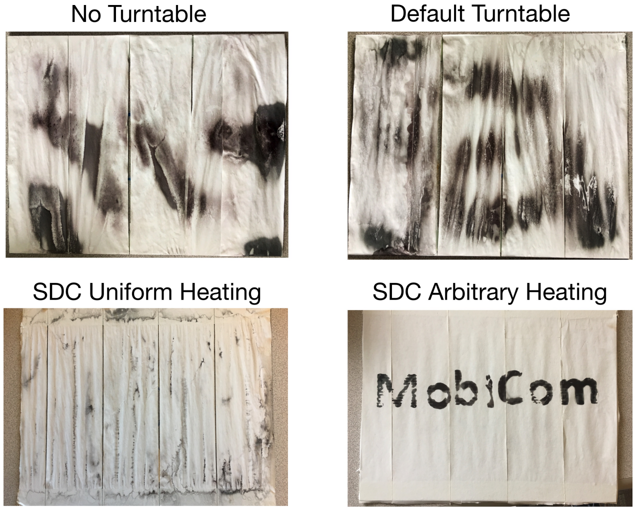

Figure 1: Results of microwaving wet thermal paper (black spots indicate high heat). (Top) A traditional microwave without/with a turntable. A turntable can mitigate uneven heating, but cold/hot spots remain. (Bottom) SDC, for uniform heating (fewer black spots show heat is spread uniformly) or heating to write "MobiCom". We use patterned susceptors and let SDC make sure that the text area has been heated in hot spots.

1 Introduction

Since their introduction to the consumer market in the 1970s, microwaves have seen widespread adoption and are today the third most popular domestic food heating method (after baking and grilling) [36]. Indeed, the original patents for the microwave by Raytheon Inc. in the late 1940s envisioned a universal food cooking instrument for all kinds of food ranging from meat to fish [1, 29]. While microwaves have indeed revolutionized the kitchen since their inception, today's consumer microwaves are mainly used as a blunt heating instrument (e.g., reheating pizzas) rather than a precise cooking equipment (e.g. cooking steak). The potential

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MobiCom '19, October 21–25, 2019, Los Cabos, Mexico

ACM ISBN 978-1-4503-6169-9/19/10…$15.00
https://doi.org/10.1145/3300061.3345441

of microwave cooking is limited by the fact that today's microwaves heat food blindly, resulting in a non-uniform and unpredictable heating distribution [45].

State-of-the-art solutions to remedy the microwave have made advances in both how food heating is sensed and controlled. Past work has used thermal cameras just outside the microwave chamber [23, 42] to map the heat distribution within a microwave, albeit at limited resolution and refresh rates [11]. Microwaves also deploy specialized radio-reflective stirrer blades or turntables to attempt to evenly distribute heat. Yet, despite these advances, undesired hot and cold spots within a microwave remain a known problem even in industry-grade microwaves [31] (see examples in Fig. 1). Indeed, the fundamental challenge in building a more precise microwave for cooking is the fact that modern electronics to both sense and control microwave heating are not inherently microwave safe. The resulting need to isolate the microwave control system from the chamber itself reduces the granularity of both heat sensing and actuation.

This paper presents SDC (software-defined cooking), a novel low-cost closed-loop system that can augment existing consumer microwaves to sense and control heating at a fine-grained resolution, all using microwave-safe components within the chamber. SDC's design can unlock numerous programmable heating opportunities (see Fig. 1). For example, when microwaving liquids (e.g. milk, baby formula), one need not worry about the uneven heating that may scald the mouth or destroy nutrients – a reason why microwaves are never advised to heat formula despite their convenience. Further, SDC can enable fine-grained forms of cooking, such as a computer generated Maillard reaction [52] patterns that heats the food's surface discriminatively and occurs when searing meats and pan-frying vegetables.

At the heart of SDC is a novel approach both to sense and control heat at different points in space within the microwave chamber. SDC senses heat using the phenomenon that produces heat in the first place: the electro-magnetic (EM) field. SDC aims to measure the amplitude of the electromagnetic field at any given point. While battery-powered sensors exist to sense both heat and EM fields, SDC must do so using only microwave-safe components which excludes typical commercial batteries [18].

SDC achieves this by relying on the fact that the EM-field within the microwave is a natural source of energy. This means that one can simply power the sensor of the EM-field by the EM-field itself. SDC uses tiny RF-powered neon lights (Fig. 6) that glow in response to the EM-field within the microwave. Specifically, the oscillating microwave results in a potential difference (of a few 100 V to a few kV) between two electrodes within each light bulb. Due to the potential difference, electrons are accelerated away from the cathode and give rise to collisions with the neon gas atoms or molecules, which will emit a characteristic glow in proportion to the amplitude of the field. Neon lights are inexpensive, compact and produce minimal disruption to the EM-field itself – meaning that they can be tightly packed at key locations around the chamber to sense the EM-field amplitude at high accuracy. Given that the neon lights may be obstructed from view due to the food placed in the microwave, we run optical fibers made of microwave-safe glass that carry the light signals outside the chamber to be sensed by a camera (Fig. 2). §5 describes our framework to fuse measurements from this hardware with IR cameras to estimate current and future spatial temperature distributions of the food.

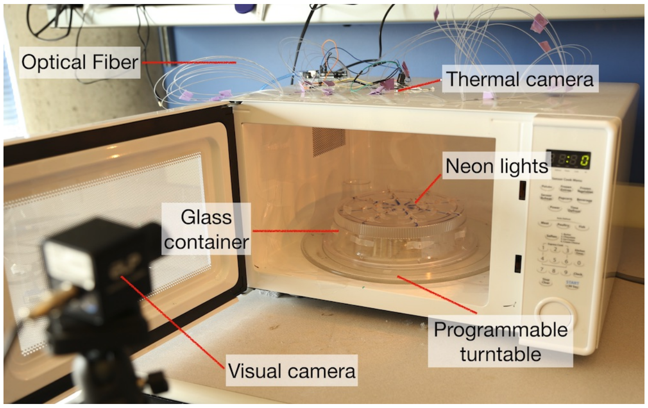

Figure 2: SDC's Hardware

Upon sensing food heating, SDC controls heat according to the user-specified thermal plan by building microwave shields that protect regions of the food that must not be overcooked (e.g. meat). SDC achieves this through small metallic spheres placed within the microwave at key locations. While conventional wisdom says that one must not place metal in a microwave, RF-propagation is more nuanced. Specifically, metallic surfaces within the microwave only produce energetic sparks at sharp edges, found in most kitchen utensils and bowls. Metallic spheres by definition do not have edges and are thus microwave-safe [43]. SDC carefully packs metallic-spheres at specific regions of the microwave to minimize RF energy-transfer at these regions. §6 shows how SDC accurately rotates the turntable to guide parts of the food that must not be over-cooked towards these regions.

We implement a prototype of SDC by modifying a commercial Microwave oven (Sharp SMC1441CW). We place neon lamp arrays inside the microwave oven cavity and use a camera outside the cavity to monitor lamp flashes conducted via fiber-optic cables. We replace the coarse turntable motor with a step motor controllable via an Arduino board. Given a desired heating distribution pattern, SDC recommends the initial position where the user should place the food. During the heating, SDC continuously senses the real-time EM filed strength around the food and adjusts the actuation plan. Figure 2 illustrates the basic hardware setup of SDC. We conducted detailed experiments to evaluate SDC's sensing, uniform heating, and planned heating capabilities. Our experiments reveal that:

- SDC can improve the thermal heating uniformity by 633% compared to commercial microwaves with turntables.
- SDC can create an arbitrary temperature delta of 183°C with a resolution of 3 cm.
- We demonstrate SDC in performing two unconventional cooking tasks: cooking bacon and warming milk for an infant.

Contributions: SDC is a novel redesign of the microwave oven that both senses and actuates the EM-field at fine-grained spatial resolution. SDC introduces programmable RF-powered neon lights whose signals are conducted by microwave-safe optic fibers to sense the EM-field distribution. SDC then adjusts the spatial heat distribution within the microwave chamber by moving food carefully around hot and cold spots pre-designed using microwave-safe accessories. A prototype implementation of SDC by modifying an existing commercial microwave reveals an accuracy of 7-10 degrees respectively in accuracy of temperature actuation.

We envision software defined cooking as a future extension to molecular gastronomy [40]. Among all three common heating methods (convection, conduction, and radiation), radiation is the only one that can redirect energy towards the desired location. This redirect-able feature makes Microwave oven an ideal platform to experiment software-defined cooking, as it can effectively program energy transferring without physical hardware changes. Meanwhile, while there has been a great deal of past work on novel RF applications for communication [39], sensing [19, 20] and distributed power transfer [47], novel actuation mechanisms using RF signals are less explored so far. SDC is designed to innovate in this space.

2 Microwave Oven Primer

This section provides essential background on microwave heating. A typical residential microwave oven converts a large electrical input (≈1,000W) into microwave energy and heats food using microwave radiation. The microwave oven uses a magnetron, a high-powered vacuum tube, to generate a microwave signal at around 2.45 GHz from direct current electricity supplied to the vacuum tube [46]. This signal travels through a waveguide and creates an alternating electromagnetic field inside a metal cavity where the food is cooked.

Microwave Heating 101: In a microwave, water, fat, and other electric dipoles in the food will absorb energy from the microwaves in a process called dielectric heating [50]. Namely, when an electric field is applied, the bipolar molecules tend to behave like microscopic magnets and attempt to align themselves with the field. When the electrical field changes millions of times per second (e.g., 2450 million times per second for 2.45 GHz microwave signals), these molecular magnets are unable to keep up in the presence of forces acting to slow them. This resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the material exposed to the microwave radiation.

While strong direct microwave radiation can burn human body tissue as well as electronic devices, the cooking chamber works as a Faraday cage to significantly attenuate waves escaping the microwave chamber. The US federal emission standard [2] limits the amount of microwave leakage from an oven throughout its lifetime to 5 milliwatts (mW) per square centimeter at approximately 2 inches from the oven surface (a safety factor of 10,000 or more below levels that may harm people [29]),

Once the microwave signals enter the metal cavity, they are effectively reflected by the metallic walls. Original and reflected waves resonate in the cavity and form standing waves [46], which produce anti-nodes (heating hot spots) and nodes (heating cold spots). The EM field are weak at nodes and therefore nothing cooks there. In the contrast, EM fields at anti-nodes alternate at maximum amplitude to produce maximum heating. This is also the reason why microwaves have a rotating turntable so that the turntable moves food in and out of the hot spots to cook more uniformly.

Microwave Limitations: Despite efforts to make heating uniform, microwaves are unsafe for many foods and cookware [4, 18]. For example, uneven heating will cause eggs in a microwave to explode. Sharp-edged metals in a microwave (e.g. forks) spark and create a fire. Many plastics may release chemicals into the food when heated. Due to these constraints, the microwave remains inhospitable to most modern electronics.

3 Related Work

Related work falls under three broad categories:

Sensing in Microwaves: There has been much past related work on improving the heat sensing within microwave ovens. For example, advanced FISO Microwave Work Stations (MWS) [9] used in food research have special microwave-safe fiber-optic sensors to collect real-time fine-grained direct measurements inside the cavity, but cost $80k+. A recent startup, Cmicro [49], is building an energy-harvesting temperature sensor that can be run inside the microwave oven [34], which can only measure the air temperature in a container. A more inexpensive approach for direct temperature measurement is to attach regular/thermal pinhole cameras[23, 42]. Note that these holes are designed to be too small relative to microwave wavelength (≈12cm) and so continue to block radiation leakage. Unfortunately, measurements outside the cavity only provide limited accuracy and refresh rate [11]. Researchers [21, 48] have also used software radios to monitor the signal strength of the microwave leakage and recognize the type of food. However, many variables, such as food type, quantity, temperature and food location inside the oven impact microwave leakage unpredictably [46]. In contrast to these systems, SDC estimates both current and future temperature distributions by directly placing low-cost microwave-safe sensors within the cavity and modeling EM propagation.

Actuation in Microwaves: The most widely adopted microwave actuation is the turntable and the stirrer blade [54] that attempt to spread radiation uniformly. A recent patent application [5] proposed to place a smooth-edge metal body inside the chamber, which operates as a passive antenna to reflect the microwave, to achieve a better heating uniformity. However, these blind actuation approaches cannot eliminate hot/cold spots, due to the inherent unpredictability of the EM field distribution. More recent advances in the microwave generators such as an RF solid state cooker (SSC) adjust the transmitter's real-time power, frequency and phase to move the hot/cold spots around, albeit at high cost (∼ $10,000 [25]) and complexity. SDC also draws inspiration from many microwave accessories that have been developed to cook certain foods in a microwave – e.g. Corning Ware Microwave Browners [37], Microwave egg boilers [28], or the susceptors in popcorn bags [53]. Unlike this past work, SDC provides a generalized framework for heat actuation as per a user-specified thermal trajectory as well as the sensing results, without being tied to specific types of food or adding expensive components.

Computational Fabrication & Heating: Designing computational fabrication techniques [41] for digital gastronomy is an emerging topic [26, 55]. For example, Zoran et al. [55] uses a silicone modular mould to control the shape permutations in a recipe, allowing computational control of taste structures. So far, there is little work on computational heating. Phosphenes [41] allows users to experientially compose resistive heaters that generate heat spatially and temporally. The most relevant approach is laser cooking [14], which uses a computer-controlled laser cutter to heat a sequence of small spots of the food surface. While innovative, the rolling pixel-by-pixel heating process is known to be highly time-consuming. SDC overcomes the slow production time of laser heating while allowing for a high degree of flexibility in the numerous heating patterns produced.

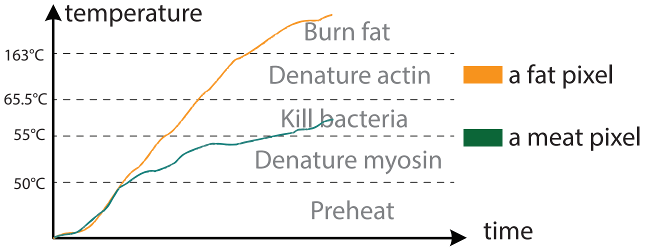

Figure 3: SDC recipe is a progression of desired temperature vs. time per-pixel of food.

4 An Overview of SDC

This section presents the overview of SDC's architecture. SDC 's goal is to cook food as per software-defined specifications (i.e., software-defined recipes). Yet, this raises an important question: what is software-defined cooking and how do we describe a software-defined recipe in the context of microwave cooking?

Specifying SDC's Inputs, Outputs and Goal: at its most basic, "cooking" means applying heat to food, which can be specified in three main variables:
(1) Temperature: The most important variable in cooking is the temperature of food, which will trigger different chemical reactions (e.g., protein denaturation, Maillard reaction, and caramelization). For instance, if we want to cook a steak at least rare to kill bacteria and avoid denature protein actin, we need to heat the meat to a temperature between 55°C (the highest survival temperature for most bacteria) and 65.5°C (the denature temperature for protein actin) [32]. We note that across all three common heating methods (convection, conduction, and radiation), food is cooked from the outside in, i.e. the outer portions will warm up faster, and the heat conduction will heat the inner parts over time. So SDC focuses on controlling the surface temperature of food.
(2) Time: Time is an important factor in both cooking food accurately and killing bacteria. For example, the standard food safety rule [12] provided by the FDA states various time and temperature combinations: heating at 55°C for 89 minutes can achieve a similar effect as heating at 62.2 °C for 5 minutes to reduce Salmonella.
(3) Space: Different parts of food (e.g. meat vs. fat, egg white vs yolk) may need to be cooked with different specifications to obtain optimal tasting food. SDC therefore aims to specify heating requirements for each spatial "pixel" of the food's surface.

In summary, we envision that the future microwave recipes specify the desired thermal trajectory, i.e. temperature vs. time, for each "pixel" of the food's surface (see Fig. 3 for an example steak recipe). This is precisely SDC's input, with its performance dictated by how closely it follows this specification. We discuss the creation of such recipes in §10.5.

SDC's Heat Sensing: While SDC can deploy infrared cameras to sense the surface temperature of the food, doing so has two key disadvantages. First, cameras cannot sense heat in the presence of objects that blocks the food from view. Second, cameras would only measure the effect of heating after-the-fact and cannot prevent heating-damage that is already done. This motivates the need to sense "intent to heat" within the microwave rather than current temperature of the food content.

SDC addresses this challenge by deploying microwave-safe passive electronics that senses the underlying physical phenomenon producing heat, i.e. the electromagnetic (EM) field. Specifically, we deploy neon lights (see Fig. 4 and 6) that harvest EM energy in the microwave to glow in proportion to its intensity. We then measure the intensity of the light to infer field intensity and estimate the temperature distribution that would result. We do this via optical fibers that carry the visible light signal outside the chamber, allowing SDC to measure light signals from lights that are hidden from view. §5 discusses various challenges associated with such a design: (1) How many neon lights should be placed to optimally capture the EM field?; (2) How should the system be geometrically placed to best capture diverse cooking requirements?; (3) How do we map instantaneous EM field measurements and temperature to best anticipate future temperatures at high spatial resolution?

SDC's Heat Actuation: Having sensed the current and estimated heat distribution over space, SDC must now actuate the control system to focus energy towards some specific areas of the food and away from others. A traditionally available instrument for heat actuation within the microwave is the turntable. Microwaves use turntables to even out heat distribution, ensuring that hotspots do not hover statically over specific areas of the food. Yet, turntables are coarse actuators given that they spread out energy blindly rather than focusing it on specific parts of the food.

In contrast, SDC engineers specific hot and cold regions of the food by building specialized accessories that protect or focus specific regions of the food. We then electronically control the turntable to move food in and out of these sensed hot/cold spots as needed to cook food according to the desired heat pattern. §6 discusses two key innovations of our approach: (1) the design of metallic radio shields that are microwave safe; and (2) an efficient algorithm to move food to achieve the desired heating specification.

5 SDC's Heat Sensing

SDC's heat sensing aims to capture both the current temperature of food as well as the intent to heat. At first blush, one may assume that heat sensing can be readily achieved using a thermal camera which captures the current temperature of the food. By measuring thermal camera readings over time, one can make predictions about how food will heat in the future. Yet, thermal cameras have important limitations that limit a design that relies exclusively on them for heat sensing. First, the food thermal properties evolve on a time scale of seconds, and the carryover in cooking will continue heating even if the food is removed from the source of heat. However, thermal cameras often have limited refresh rates (<9 Hz) and modest accuracy (± 2°C) [11]. Therefore thermal cameras only measure the effect of heating after-the-fact and cannot prevent undesired heating, often until the damage is already done. Besides, thermal cameras are limited to measuring heating on the surface of the food in direct line-of-sight.

To mitigate this, SDC complements a thermal camera that senses current temperature with microwave-safe sensors that estimate future expected temperature. Specifically, we design sensors to sense the EM field – a set of neon lights, which glow in proportion to the EM field strength within the microwave. The rest of this section discusses the various challenges in achieving this design. First, we need to design microwave-safe hardware that is extremely sensitive to the EM field and can be readily probed from outside the microwave, even in the presence of blockages (e.g. food). Second, we need to build an expected temperature model that accounts time-varying energy transfer efficiency of the EM wave, the types of ingredients, temperature, and the placement of food.

Figure 4: A turntable with 32 neon lights (left) and a plate cover with 32 neon lights (right).

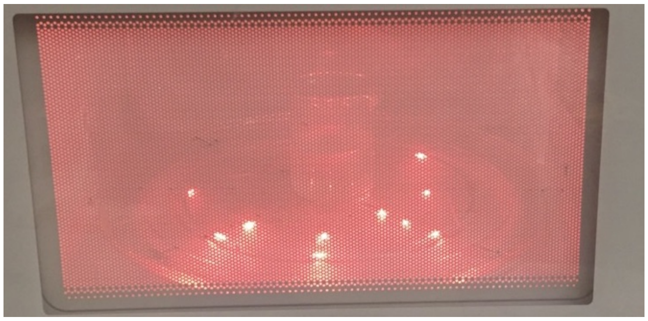

Figure 5: The turntable inside a running oven.

5.1 Sensing Hardware Design

SDC places an array of neon lights, each has a 5mm diameter and 13 mm length, inside the microwave chamber to sense EM fields. A neon light (Fig. 6) is a miniature gas discharge lamp, which consists of a small glass capsule that contains a mixture of neon and other gases at low pressure and two electrodes (an anode and a cathode). During microwaving, the electrodes will couple with the electromagnetic field and act as antennas. The oscillating microwave applies a potential difference between two electrodes. Due to the potential difference, electrons are accelerated away from the cathode and give rise to collisions with the neon gas atoms or molecules, which will emit a characteristic glow. The brightness of the lamp is proportional to the EM field strength at the placed location, and SDC leverages that brightness to measure the EM field strength.

The glow of the light is sensed by a visible light camera outside the chamber to capture real-time EM field strength (Fig. 5). However, neon lights are often blocked from direct view of the camera due to obstructions such as food on the turn table. To mitigate this, SDC conducts the light from the neon lamps to the camera using optic fibers (Fig. 7).

Is SDC's hardware microwave safe? Neon lights are rated microwave-safe because the metal electrodes are encapsulated with a glass capsule and the gas glow discharge can avoid the energy accumulation. Each neon light consumes minimal microwave energy (≈ 19.5 mW vs. the 1100 W available), producing negligible interference to the existing EM field patterns. Glass optical fibers are also microwave-safe.

The cameras used in SDC are not affected by the microwave because they are placed outside the microwave oven. The leakage through holes is negligible, since the mesh created for the optical fibers and the mesh in the front door are smaller than the 1/20 wavelength of 2.4 Ghz. Indeed, many commercial microwaves have holes of similar dimensions to support the turn table or stirrer fan.

Programming EM sensitivity: Much like EM fields in radio communication, it is important to tune neon lights to the correct range of sensitivity to obtain useful EM field strength. We define sensitivity of the neon light as the change in brightness for a given change in EM field strength. It is important to tune the sensitivity of the neon light to be in tune with the magnitude of the EM field. A highly sensitive neon light may be saturated by a strong EM field and burn the antennas, while a poorly sensitive neon lamp may not light up under a low EM field.

SDC programs the sensitivity of a neon light by changing the length of electrodes wire extensions (Fig. 6). Each neon light is characterized by two threshold voltages: the ionizing voltage and the maintaining voltage, which depend on the type of electrodes, their coatings, the composition of the gas, and its pressure, etc.

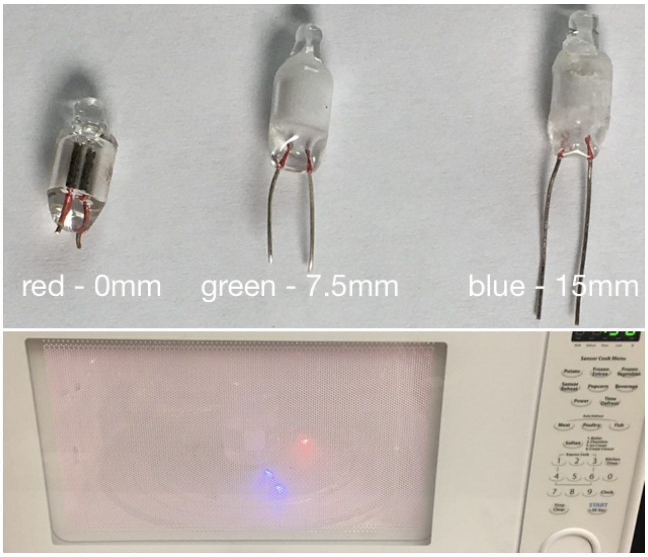

Figure 6: We place neon lights with different lengths of wire extensions (red: 0mm, green: 7.5mm, and blue: 15mm) under the turntable. We then measure the percentage of glowing time to quantify the sensitivity.

The neon light is dark when the gas is not ionized. When the voltage between two electrodes exceeds the ionizing voltage, the lamp switches on and the brightness is in proportion to the current when the light switches on. The ionizing voltage is the minimum voltage required to keep the gas ionized. When the lamp is on, and the voltage drops below this threshold, the gas loses its ionization, and the light turns off. The sensitivity of the neon light to the EM field is a function of how the EM field affects the voltage applied at the electrodes. We note that this process is completely dictated by the wires connected to the electrodes, which behave like RF antennas. SDC thus strives to tune the length of the wire extensions to the electrodes to achieve optimal sensitivity.

While antennas are known to resonate best at the length of one-half-wavelength, this quantity can vary as a function of antenna design and the RF frontend [22, 27]. SDC therefore chooses to measure the optimal antenna length for the neon lamps experimentally. Specifically, depending on the EM field strength, a neon light may experience one of the following three states when running the microwave: constantly off, flashing at various intervals, and constantly on. The flashing state (flashing frequency) and consistently on (brightness) offer more fine-grained resolution of the EM field than the consistently off state. An ideal neon light sensitivity would ensure that a good percentage of the neon lights in the oven should be in the flashing and consistent on states. To tune the

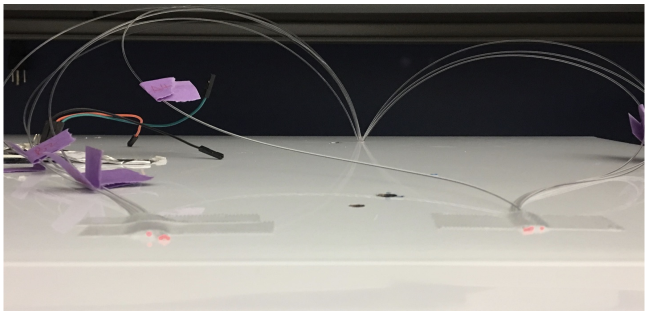

Figure 7: The optical fiber carries the signal outside of the chamber.

optimal antenna length (i.e., the wire extension length), we empirically tested various types of loads in the microwave and found that a wire extension of 8mm achieves the desired sensitivity.

Placement of Neon Lights: We place 48 T2 fixed orange neon lights (65 VAC, 0.3 mA) with a 3 cm spacing at the surface of the Microwave cavity. We set this spacing to be significantly below the wavelength of the 2.4 GHz EM signal of the microwave oven. The neon lights are placed below the turntable, as well as around the inner walls of the oven. To avoid visual occlusion, we used optical fibers to connect the lights to a ventilator scoop, carrying the light signals outside the chamber (Fig. 7). We experimented with optical fibers at different sizes and found that 1 mm diameter fibers provide good flexibility and operability.

While our sensing platform surrounds the food within the microwave chamber, one still needs to interpolate the EM field within the microwave in 3-D space at locations where neon lights are not present. Fortunately, the EM field within the microwave is that of a standing wave which has predictable voltages over space with a modest amount of sampling [33]. SDC applies the cubic spline interpolation [3] to approximate the expected brightness of neon lights should they be placed at remaining 3-D points in the microwave.

To further refine SDC's resolution particularly within the vicinity of the food, we develop two sensing containers: one microwave plate cover (Fig. 4) and one measuring cup, to measure the EM field in the air. We embedded 32 neon lights around a glass container and attached 32 neon lights to a microwave plate cover. We mainly use orange T2 neon lights intermixed with a few blue neon lights at known locations as reference points, which help SDC track the location and identity of each container as they rotate on the turn table. Since the containers are placed on the turntable, we do not connect these neon lights to the optical fibers.

5.2 Modeling Heat Over Time and Space

Next, we describe how measuring the brightness and flashing frequency of strategically placed neon lamps will help us model the current and future temperature of food over 3-D space and time.

Creating a Spatial Heatmap: The visual camera (ELP 4mm Lens Prototype Camera) captures the brightness of neon lights in a real-time video stream with a 640× 480 resolution at 120 fps. The visual camera is placed at the front of the microwave oven. The top part of the frame tracks the signals carried by the Optical Fiber which contains the brightness information of all the fixed neon lights. The camera also observes the brightness of neon lights on the sensing containers through the front door mesh (Fig. 6).

SDC measures the brightness of the lamps every 0.1 seconds (i.e., 12 frames of image capture). The ends of optical fibers are static. SDC uses optical flow [10] to track the movable neon lights. For each frame, SDC converts the image to grayscale, finds the pixels around the neon light or the end of an optical fiber, and sums up the pixel values as the brightness score. We manually calibrate to normalize the brightness score between the neon light in direct view and those connected to optical fibers. As mentioned previously, since the location of the neon lights are known as prior, we interpolate the brightness at remaining locations using cubic-spline interpolation. We then map neon light brightness and flashing frequencies to EM field strength empirically by comparing results from co-located neon lamps. This, coupled with spatial interpolation allows us to generate a 3D EM field intensity view within the microwave chamber. SDC can therefore estimate the EM field strength given a specific location at fine-grained spatial resolution.

Modeling Temperature over Space-Time: As mentioned previously, SDC can measure current temperature of the food surface by placing a thermal camera (AMG8833 IR Thermal Camera) on the roof of the microwave oven to sense the food surface in a top-down view. The thermal camera provides an 8x8 temperature readings with an accuracy of ± 2.5°C at 10 Hz. SDC interpolates the raw sensor input into a 240x240 square array using cubic-spline interpolation. However, using a thermal camera exclusively to model temperature has two limitations: (1) first, the camera only measures temperatures on the food's surface in its direct field-of-view; (2) second, the camera only measures current temperature and not future expected temperature.

SDC estimates future heat by integrating measurements of the EM field obtained from the neon lamps. Specifically, the heating of any given point in space of the food is proportional to the EM field intensity of that location. This means that integrating the observed field intensity, while accounting for the rotation of food over time can provide a robust estimate of its future temperature. Yet, two challenges remain in making this mapping accurate: (1) First, the temperature of the food for the very same EM field may change owing

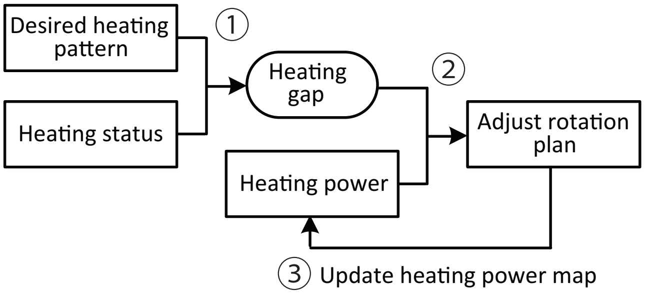

Figure 8: Workflow of SDC's heat actuation: ① SDC first computes heating gap by comparing the desired heating pattern with the current status from the thermal camera. ② SDC then adjusts the actuation plan accordingly and ③ updates the distribution continuously.

to the material composition of the food itself; (2) Second, integrating EM field intensities over time may cause errors to build up progressively as well.

SDC mitigates the limitations of both the thermal camera system and the EM field estimation by combining them and obtaining the best of both worlds. Specifically, at each point in time we reconcile the integration of EM field estimates with those of the thermal camera over space. We then use this to refine our model for mapping EM field to temperature. We repeat this process over time to continuously avoid any drift of our EM field to temperature mapping, as well as accounting for material properties.

Mathematically, SDC constructs an Extended Kalman Filter (EKF) model [15] to capture both the current temperature and its gradient over time of the microwave. Specifically, it is well known that the temperature gradient P' of the microwave for a current temperature P is proportional to the electromagnetic field strength E, i.e. $P' = kE$, where k is a constant that depends on the material properties of the food. [13]. Then we can write the following recursive equation for future temperature based on current temperature at time t:

$$P(t+1) = P(t) + P'; P' = kE; z(t+1) = P(t+1) + n$$

Where n is noise and $z(t+1)$ is the observed temperature. The above follows the formulation of EKF and can be used to estimate k as well and refine the temperatures P and gradients P' over time.

6 SDC's Heat Actuation

Today's microwave ovens actuate the heating process in a crude manner. The oven turntable rotates the food blindly without any precise control. The magnetron, the heating engine of the microwave oven, achieves power control by periodically turning itself on and off. SDC augments these existing blind actuation hardware into a closed-loop control system by incorporating the results of heat sensing.

6.1 Actuation Hardware

Smart Turntable: We modify the default turntable inside a commercial microwave oven (Sharp SMC1441CW). More specifically, we replaced the motor with a low-cost stepper motor (Yosoo 57oz-in 1Nm Nema 17 Stepper Motor), and 3D printed a plastic coupler between the motor head and the glass platform to enable precise control. We also connected the magnetron to an Arduino and programmatically sent pulse-width modulation signals to control the ON /OFF of the magnetron.

SDC sets the rotating speed of the turntable to 12 RPM. The heat actuation will only start after the cycle once SDC collects an initial spatial distribution of the EM fields. Rotating the food around can manipulate the heat pattern mildly (e.g., uniform heating), but it is insufficient to create an arbitrary heat pattern.

Programmable accessories : To achieve a more skewed heating pattern, SDC develops programmable accessories (Fig. 9) that leverage the reflective property of microwave heating, redirecting energy towards desired locations and shield undesired locations, to achieve an arbitrary heating capability.

SDC installs a horizontal glass plane above the turntable and carefully packs metallic-spheres (3.175 mm diameter) (Fig. 9 right) at specific regions of the plane to minimize RF energy-transfer at these regions. Metallic spheres by definition do not have edges and are therefore microwave-safe [43]. These metallic spheres effectively form a microwave mirror to reflect microwave energy at the specific region.

The most common dielectric dipole in the food is water, so microwave heating rarely achieves temperature beyond the boiling point of water. However, some important food chemical reactions occur well above water's boiling point, such as Maillard reactions and caramelization. We introduces microwave susceptors to address this limitation. Materials like silicon carbide (Fig. 9 left) can effectively absorb microwave energy inside the oven and reach 200+°C within 1 minute microwaving. Attaching silicon carbide to the food surface can then trigger desired high-heat reactions.

When to use accessories? Given the desired heating pattern, SDC first determines if the accessories are needed to achieve the goal. We empirically find that using only the smart turntable, SDC can achieve a maximum peak-to-peak temperature difference of 21°C.

To obtain a more skewed thermal distribution, SDC can either involve the accessories at the beginning (e.g., preheating a microwave susceptor to a high temperature and then attaching it to a desired region) or involve them at a later stage (e.g., placing microwave shields to protect certain areas if it's close to being overcooked). SDC 's actuation algorithm will dynamically adjust the actuation plan in either case. Involving accessories does not change the nature of our sensing or actuation optimization as the neon lights still reflect the real time EM field strength around the food.

6.2 Recipe and Actuation Representation

Having developed programmable actuation hardware, this section formally states the actuation optimization problem that attempts to heat the food in accordance with the input heating recipe.

Heating Recipe: A SDC heating recipe will specify the desired temperature trajectory and duration for each part at different temperatures. Mathematically, we can formulate the recipes as follows. Let us imagine that the food surface is divided into a set of discrete pixels. Given n pixels $B = \{B_1, B_2, ...B_n\}$ on the surface of the food, the 3D coordination of the pixels are $\{x_i, y_i, z_i\}$ where $i \in \{1, 2, ...n\}$. The receipt is a mapping function f that maps the pixels and the timestamps to desired temperatures throughout the D minutes cooking journey:

$$f(B_i, j) = p_{ij}, \quad i \in \{1, 2, ...n\} \quad 0 < j < D \tag{1}$$

where j denotes the timestamp since start of the cooking process, and p_{ij} refers to the desired temperature for i-th pixel at the timestamp j.

SDC's Optimization Problem: Our goal of the smart turntable is to find a rotation plan S^* that can move food in and out of these hot and cold spots as needed to cook food according to the desired heat trajectory P, which contains collection of desired temperatures p_{ij} across the space and time. SDC defines a rotation plan S as a sequence of angle-duration and magnetron on-off-duration tuples:

$$S = \begin{bmatrix} \{\theta_1 : d_{\theta 1}\}, \{\theta_2 : d_{\theta 2}\}, \{\theta_3 : d_{\theta 3}\}, ... \\ \{o_1 : d_{o1}\}, \{o_2 : d_{o2}\}, \{o_3 : d_{o3}\}, ... \end{bmatrix} \tag{2}$$

$$D = \sum \{d_{\theta 1}, d_{\theta 2}, d_{\theta 3}, ...\} = \sum \{d_{o1}, d_{o2}, d_{o3}, ...\} \tag{3}$$

where $\{\theta_k : d_{\theta k}\}$ indicates that the turntable will stay at the absolute offset angle θ_k for a duration of $d_{\theta k}$, $\{o_k : d_{ok}\}$ describes the duration d_{ok} for keeping the magnetron on or off (o_k). Based on these definitions, we now formulate SDC's core optimization problem as follows:

$$S^* = \arg\min_{S} \sum ||\bar{P}(S) - P||^2 \tag{4}$$

where $\bar{P}(S)$ denotes the temperature trajectory for the n pixels using a rotation plan S over time.

6.3 Actuation Algorithm

Solving this optimization problem is challenging for two reasons. First, microwaves heat the food through a standing wave, so they cannot heat individual pixels independently. Heating one pixel will inevitably heat other pixels as well. To achieve the desired heat pattern, we need to select a set of heat patterns whose union is equivalent to the target heat pattern. Second, the heat pattern, the result of the EM-ingredient coupling, is non-static and unpredictable. The EM field distribution changes gradually when the turntable rotates the food and when the food heats up. SDC cannot predict the output heat pattern until the food is heated.

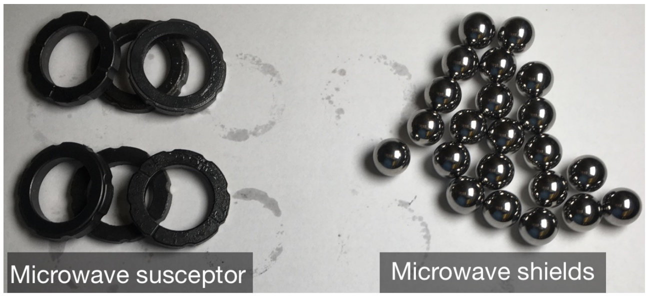

Figure 9: Programmable microwave accessories.

The Stochastic Knapsack: At a high level, this problem is a variant of the stochastic knapsack problem [7, 30], a classic resource allocation problem of selecting a subset of items to place into a knapsack of given capacity. Placing each item in the knapsack consumes a random amount of the capacity and provides a stochastic reward [30], which are only observable after the item is placed. Finding exact solutions to the stochastic knapsack problem is PSPACE-hard [8]. Indeed, a cyberphysical system like SDC cannot afford long computational processing times, since once food is heated too much, it cannot reverse the heat applied.

Due to the intrinsic uncertainty of stochastic knapsack problems, adaptive and closed-loop strategies often perform better than open-loop ones in which the items chosen are invariant of the remaining time budget [8]. So different from the traditional 3D printer, which computes the motion trace in advance, we design SDC to calculate the rotation plan on-the-fly, based on the real-time sensing feedback.

Approximation Algorithm: We propose a greedy approximation algorithm to determine the immediate rotation plan on-the-fly based on the sensing result in §5. Our greedy strategy is as follows: "*at each step of the journey, heat at the rotation angle whose temperature gradient is most similar to the current heating gap*".

Fig. 8 illustrates the workflow of the greedy algorithm. In SDC, the thermal camera continuously senses the current food temperature at the n pixels: $C = \{c_1, c_2, ..., c_n\}$. SDC then compares the desired heating pattern $f(B_i, j)$ with the observed thermal distribution, and computes the real-time heating gap (i.e., available capacity) $G = \{g_1, g_2, ..., g_n\}$. SDC also maintains a dictionary $\left\{\theta : P'_\theta\right\}$ to document the temperature gradient P'_θ at each offset angle of the turntable.

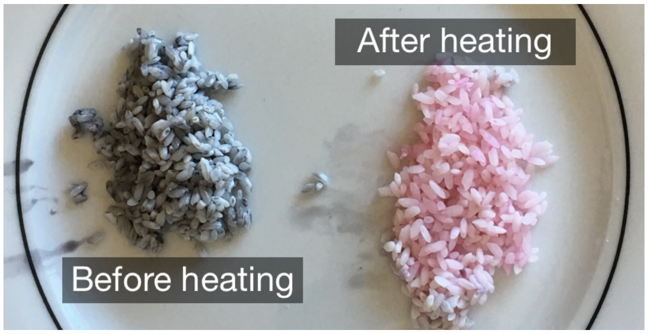

Figure 10: We color rice grains with thermal-chromatic pigment, which turn pink in a predictable manner as their temperature increases.

SDC then queries the vector $P'_\theta = \{p'_1, p'_2, ..., p'_n\}$ using the pixel coordinates.

When running, SDC continuously computes the similarity Sim_θ between the temperature gradient at θ and the current heating gap using the cosine of an angle between these two vectors.

$$Sim_\theta = \frac{P'_\theta \cdot G}{|P'_\theta| \cdot |G|} \tag{5}$$

Once computed, SDC rotates the turntable to θ^*, which has the most well-aligned temperature gradient. We note that the turntable may not reach all the targeted angles θ^*, as the most well-aligned temperature may change during the rotation and a new rotation command will override the earlier one.

$$\theta^* = \arg\max_\theta Sim_\theta \tag{6}$$

Simultaneously, as explained in §5.2, SDC updates the dictionary of temperature gradients based on the EM field and real-time observation of temperature from the IR camera at each rotation angle θ.

7 Implementation and Evaluation

We implement SDC by modifying a commercial Microwave oven (Sharp SM1441CW). As explained in Sec. 5, our setup contains an array of neon lamps on the bottom of the turntable whose signals are conducted to a ELP 4mm Lens Prototype camera outside the microwave via fiber-optic cables attached to the base of the microwave (see Fig. 1). We perform actuation with an Arduino board connected to a Yosoo 57oz-in 1Nm Nema 17 Stepper Motor. We implement SDC's optimization in real-time with SDC's actuation algorithms implemented in Python. We conduct experiments in an indoor space on a kitchen table with a variety of food types including meat, rice, milk and fish and evaluate SDC's heat sensing and actuation.

Performance Metric : To characterize SDC's performance, we focus on the two metrics: (1) ΔP: peak-to-peak temperature differences (i.e., the difference between the maximum and the minimum temperature) and (2) thermal delta, $P_{Dev} = \sqrt{\sum ||\bar{P}(S) - P||^2}$ (Eq. 4), i.e., the collective temperature deviation between the actual output and desired pattern. To quantify the thermal delta, we measure the temperature at 9 discrete points on the surface in a 3x3 grid with 2cm spacing.

Ground truth : To obtain ground-truth temperature data, we use a non-contact infrared thermometer (Etekcity Laser-Grip 630), which provides ±2°C resolution from -50°C to 580°C, as well as the thermal camera we used in the SDC.

8 Results

8.1 Uniform Heating

Non-uniform heating is a major drawback associated with today's microwaves [45], which not only affects the quality of the food but also compromises food safety when the microorganisms may not be destroyed in the cold spots. This experiment evaluates SDC when provided with a Uniform heating plan, a commonly input thermal trajectory provided to SDC, in which we aim to heat all the pixels to the same temperature at a uniform pace.

Method : We conduct our evaluation by heating raw rice grains using SDC. While the specific type of material heated does not impact our evaluation result, we choose raw rice grains for three reasons: (1) First, rice grains are known to absorb microwave energy; (2) Second, the limited contact surfaces among the grains conduct heat in a limited manner, allowing us to visualize pixel-by-pixel heat more clearly; (3) Third, rice grains are reusable across multiple evaluation sessions once cooled, so we can keep the food that we heat consistent across experiments.

To visualize the heat pattern, we color the grains with thermal-chromatic pigment (Fig. 10), which will turn into pink as the temperature increases. We use the thermal-chromatic pigment approach because it can provide a rich and analog temperature visualization, while thermal cameras have a limited resolution and the final output image are based on the interpolation.

We begin our experiment at a room temperature of 20°C. We set a target temperature of 60°C over 2-minutes of microwaving, based on multiple empirical runs evaluating the typical temperature achieved over this period. We create a uniform heating recipe that requires that the food be heated uniformly from 20°C to 60°C over 2 minutes uniformly over space as per the recipe provided by the thick blue line in Fig. 12. We note that the thermal trajectory is identical across

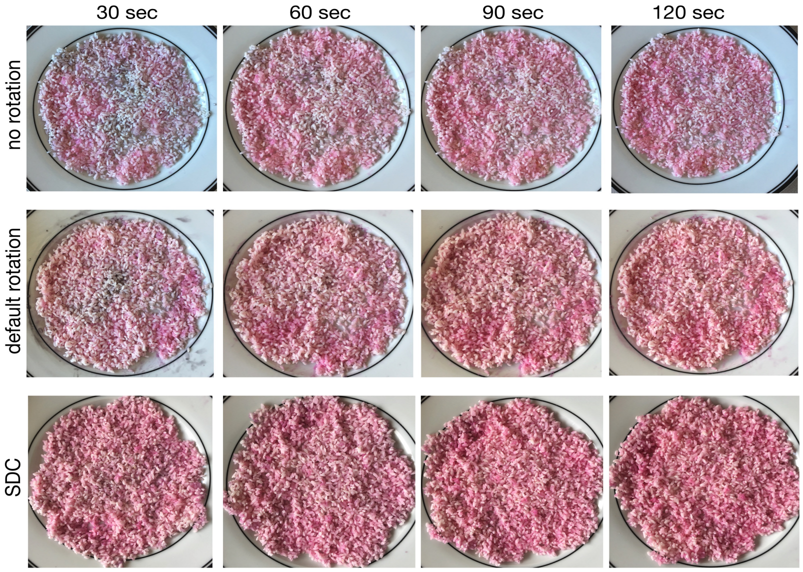

Figure 11: Visualization of heating of rice as a function of time for no rotation, default rotation and SDC. SDC results in the most uniform heating.

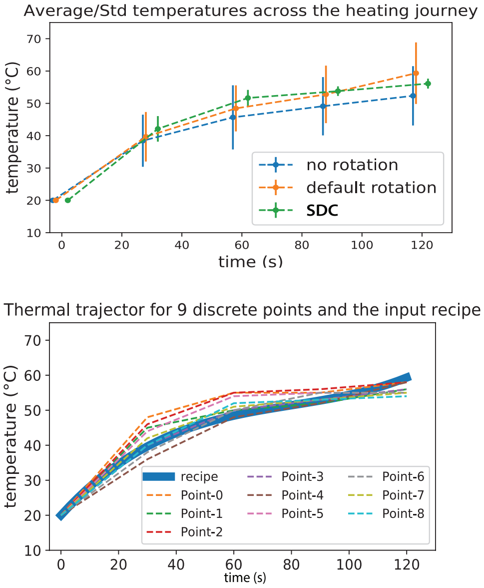

Figure 12: (above) Temperature variance of SDC is low vs. baselines; (below) points on food closely follow heating recipe.

Recipe geometry SDC without accessories SDC with accessories

Figure 13: Left: An input recipe for stress test. Middle: SDC without susceptors. Right: SDC with susceptors. Susceptors can help build more skewed thermal distributions.

Scheme	ΔP	σ_P	$\frac{\Delta P}{d}$
without accessories	21°C	99°C	3°C/cm
with accessories	183°C	42°C	61°C/cm

Figure 14: Mean (ΔP) and Standard Deviation (σ_P) of thermal delta for arbitrary heating. The final column ($\frac{\Delta P}{d}$) denotes the temperature gradient per unit distance that can be achieved.

all pixels of the food's surface. However the temperature increase is not designed to be linear over time, instead mimicking the smoothed average temperature trajectory for raw rice within a microwave under normal microwave operation.

To characterize the benefits of SDC, we use two blind microwave heating as the baselines: the same microwave oven (1) with and (2) without turntable rotation. To collect the immediate temperature during heating, we take out the food every 30 seconds to measure the ground truth temperatures.

Results : Fig. 11 shows a visualization of the thermal-chromatic pigment, which changes color at 31°C and progresses to darker shades of pink with increased temperature. The rice colored (dull white) regions denote spots of food that remain below 31°C. We observe that SDC achieves a uniform pink hue that darkens over time, while the baselines (no rotation or default rotation) continue to have cold spots through time. Note that SDC visually appears to have the deepest shade of pink vs. the baselines at t=120 seconds as it achieves more spatially uniform temperature relative to the baselines. In actuality, there are also some hot spots of the baseline schemes that achieve even higher temperatures (over 70 °C), while SDC achieves uniform temperature closer to 60 °C as desired.

Validating Heat Sensing and Actuation: Fig. 12 (bottom) shows the trajectory of the temperature over time for nine discrete uniformly spaced points of the food using SDC. Note that all points closely follow the recipe over time, , which demonstrates SDC 's high accuracy in modeling the temperature gradient through EKF. Fig. 12 (top) compares the average and standard deviation of the trajectory across the same discrete points measured over multiple experiments vs. time. Of particular interest here is the standard deviation of the temperature of the food where one can clearly observe that SDC achieves a lower spatial variance in temperature when compared to the baseline schemes. This validates our findings that while microwaves heat food blindly and non-uniformly, SDC can achieve significant uniformity in heating.

The table to the right measures two quantities for SDC and the baselines: (a) P_{Dev}: standard deviation of temperature across space for any given time; (b) ΔP: The difference between maximum and minimum temperature over space on the food.

Scheme	P_{Dev}	ΔP
No Rotation	9.2 °C	29.5 °C
Default	9.5 °C	24.8 °C
SDC	1.5 °C	6.5 °C

Our results validate the correctness of both heat sensing and actuation, both of which must operate correctly to achieve the desired heating objective.

8.2 Arbitrary heating

In real-world cooking, different ingredients often require to be cooked at different temperatures. SDC can support these activity computationally by specifying thermal trajectories for different surface pixels. In this section, we aim to stress test SDC by exploring the maximum heating resolution, i.e., the maximum temperature difference that can be created in a fine-grained spatial resolution. The apparatus, performance metric, and the ground truth acquisition method are the same as the uniform heating experiments. The only difference is the input thermal recipe to SDC.

Method : We create an imaginary recipe that heats a unique thermal pattern (depicted in Fig. 13 – left). The recipe sets the target temperature for the inner ring area at 500°C and the rest area at 50°C. We deliberately set an unachievable goal of 500°C for SDC to stress-test the system and evaluate how well SDC can approximate to the targets. We conduct two independent experiments with and without the help of microwave accessories.

Results : Fig. 13(right) shows a visualization of the thermal-chromatic pigment, which aligns well with the desired pattern (Fig. 13 – left), without and with microwave accessories. As expected, we observe that the presence of accessories helps improve the contrast between the high temperature and low temperature rings. This is precisely why accessories are needed to improve SDC's performance during tasks such as searing, where extreme temperature gradients are needed on the food.

Figure 14 on the right summarizes the mean ΔP and standard deviation σ_P of the maximum temperature difference between the inner and outer ring achieved in SDC with and without microwave accessories. We also note that with microwave accessories, SDC can cause extremely high temperature gradients (up to 61°C per centimeter) at very fine spatial resolution.

8.3 App – Microwaving Milk

Microwave ovens are frequently used for reheating leftover food, and bacterial contamination may not be repressed if the safe temperature is not reached across the food's surface. This results in the risk of foodborne illness, as with all inadequate reheating methods. While microwaves can destroy bacteria as well as conventional ovens, they do not cook as evenly, leading to an increased risk that parts of the food will not reach recommended temperatures [44]. More fundamentally, microwaving liquids may cause uneven heating so that some parts of the liquid may scald the mouth. This is precisely why microwaves are not recommended for heating liquids such as milk, particularly for infants. In this section, we evaluate the effectiveness of SDC in uniformly heating a cup of milk.

Method : We specify a uniform heating recipe that requires a spatially uniform final temperature of 71°C [38]. We place 200 ml milk in a 500 ml measure cup across multiple experiments. We measure the ground truth temperature at the end of the experiments using a contact-based thermometer (ThermoPro TP18). We measure the temperature at 9 different points of the cup. We use a contact based sensor for this experiment since the non-contact infrared thermometer only measures surface temperature.

Results : Figure 16 presents the thermal delta (deviation) between the planned and observed temperature per-pixel across experiments for the milk. We observe a temperature between 67°to 74°at all the 9 points. The whole milk is heated uniformly without parts that may scald the mouth or be too cold and therefore preserve bacteria.

8.4 App – Cooking Meat (Bacon)

In this section, we evaluate SDC's performance in cooking with advanced thermal recipes. We consider bacon with different heating requirements for the meat and fat.

Method : We use the heating recipe required per pixel for the meat vs. the fat as shown in Fig. 3. Based on the package instruction, we set the heating time to 1 minute. We place strips of bacon on the microwave plate across multiple experiments. We measure the continuous ground truth

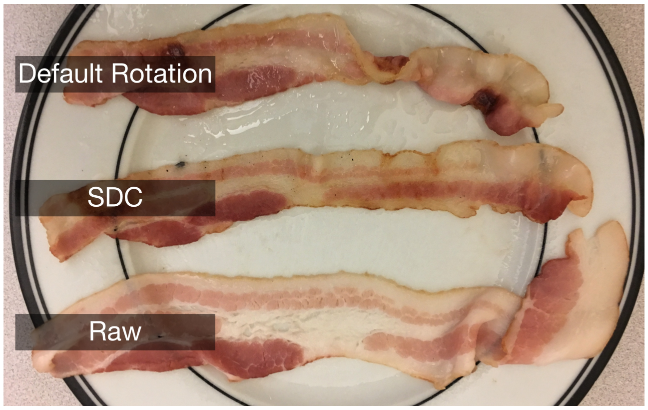

Figure 15: The raw bacon, and slices of bacon cooked with SDC and the original turntable. These three slices of bacon are from the same package, so the original fat patterns are nearly identical. Heated meat and fat will shrink. SDC applies heat to meat and fat discriminatively, so the fat shrinks more than the meat.

Scheme (HF=SDC)	ΔP	σ_P
HF with milk	7°C	N/A
HF with bacon (meat)	10°C	6°C
HF with bacon (fat)	8°C	5°C

Figure 16: Mean and Standard Deviation of thermal delta for cooking milk and meat. We don't have σ_P for milk since the thermal camera can only sense the surface temperature.

temperature using the thermal camera, and measure the final temperatures at discrete points using the non-contact infrared thermometer (Etekcity LaserGrip).

Results : Table 16 presents the thermal delta (deviation) between the planned and observed temperature per-pixel for the bacon, across experiments. Fig. 15 depicts the initial and final product over the cooking process. Note that while default rotation heats the bacon unevenly (resulting in the uneven shape), SDC heats the microwave more uniformly while differentiating between the heat applied to meat and fat. Indeed, we observe that the cooking process does not overcook/burn the meat, while at the same time avoiding colder spots that may pose a health hazard.

9 Limitations

We emphasize the following limitations of our current implementation. (1) Thermal Camera: The accuracy of the commercial thermal camera we are using maintains a high accuracy only between 0°C and 80°C. Beyond these temperatures, the accuracy of thermal camera will decrease. (2) Neon Lights: Our current prototype handles up to 64 neon lights (32 on the microwave plate and 32 on the glass container) and scaling to larger numbers makes our system too bulky. We believe this can be addressed in commercial implementations. (3) Heating Model: Our heating model makes no assumption and does not use prior information on the material type of the food. Using this information (via user input or through image recognition) can greatly improve the performance of SDC. We leave this task for future work. (4) Some hardware (e.g., silicon carbide) used in the SDC prototype may not be FDA approved.

10 Discussion

10.1 Actuations beyond turntable

SDC mainly modifies the EM-field strength to desired levels by accurately moving food on a programmable 2D turntable. However, the proposed techniques, e.g., the EM field sensing (§5.2), the greedy algorithm (§6.3), can be applied to 3D actuation directly. Throughout our development, we had experimented several 3D actuation hardware designs, e.g., using strings to suspend the food container in the air [24], adding an elevation platform to the turntable. However, either approach requires a large chamber space, making the oven clumsy and hard to clean. So we decided to retain the default 2-D turntable design, and leave alternate designs for future work.

Beyond food movement, there also exists other degrees of freedom in actuating the microwave energy. First, we can dynamically adjust the chamber size or place a microwave-safe reflector inside to change the standing wave formulation. Second, we can replace the magnetron with solid-state microwave ovens and apply RF beamforming on the food. We leave these options for future work.

10.2 Alternative hardware design

Retrofitting existing commercial microwave ovens for new contexts allows us to re-imagine the design of future microwave ovens. Commercial microwave ovens use either 900 MHz or 2.4 GHz, which fall into the unlicensed spectrum. Future microwave ovens may consider supporting a higher frequency mode (e.g., 10 GHz). 10 GHz radio has a smaller wavelength (i.e., 3.0 cm), resulting in a lower food penetration (0.4 cm vs. 2cm at 2.4 GHz [35]), which might allow the microwave to produce cooking effects like searing or frying.

A pure electrical mechanism may also replace the neon bulbs. The bulbs currently harvest energy through small dipole antennas, which can potentially be fed into a rectifier to make direct electrical measurements of EM field strength. The challenge of such a solution is to tune the circuit to ensure it will not absorb too much RF power and burn itself.

10.3 Cross-technology interference

Microwave leakages create cross-technology interference on Wi-Fi communication [21], which can potentially improve the cooking process as well. Different types, positions, and quantities of food will absorb the microwave energy differently, impacting the microwave leakage [46]. Throughout our development, we run several pilot studies to understand the relationship between the content inside microwave and microwave leakage. For example, we noticed that different food temperature and internal moisture would change the leakage frequency. This might allow future systems to determine if the food is starting to dry out.

10.4 Energy efficiency & cooking process

Microwave heating is a wireless power transfer application, which converts electrical energy into microwave radiation and then transferring the heat into the food. The energy efficiency of the microwave generation is relatively consistent (around 65% for a modern magnetron [51]), while the food heat absorption depends on the food size, material, and the standing wave formulation [17]. Our technology may cook faster than the blind heating approach because we can intentionally heat the cold spots while the traditional method relies on the slow heat conduction to cook cold spots.

There also exists a trade-off between heating accuracy and duration. One extreme example is that SDC can turn off the magnetron during rotation and only heat the food at the position when it has the most well-aligned temperature gradient. The heating process would then be more accurate but slower. Besides, the shape of the food will impact the performance of discriminative heating as well: too large or small food surface will make SDC hard to rotate the food in/outside of the hot/cold spots.

10.5 Recipe Creation

In this paper, we assume that the desired heat distribution is available to SDC either through manual user input or from an auxiliary food-sensing system. We envision that the future cooking recipes will detail the desired temperature and time duration for each “pixel” of the food. Since the food will be cooked from outside in, the recipe can be represented as the combination of surface temperatures and time durations. Chefs can develop such recipes through empirical experiments, or the food developers can computationally model the ingredient (e.g., using computer vision [16]) and generate a heating recipe through cooking principles (e.g., the ideal temperature to cook a medium-rare steak is between 55°C to 60°C [6]).

11 Conclusion and Future Work

This paper presents SDC, a novel next-generation microwave oven that both senses and actuates heating at fine-grained spatial resolution. SDC uses programmable RF-powered neon lights whose signals are conducted by microwave-safe optic fibers to sense the EM-field distribution. It adapts the spatial heat distribution within the microwave chamber by moving food between regions whose temperature is controlled using microwave-safe wave-guides. A prototype of SDC reveals promising accuracy in heat sensing and actuation, opening up the microwave to new cooking applications such as searing steak and defrosting fish.

We believe our current work opens up a range of directions for future work: (1) While our system considers only rotation of the turntable, allowing for more degrees of freedom could lead to finer actuation accuracy. (2) While we assume recipes are statically provided by the user, learning recipes over time and recognizing food through EM/image recognition is an exciting topic for future work. (3) Exploring inexpensive ways of performing high power RF beamforming as a more refined actuation mechanism remains an open challenge.

Acknowledgements We thank the reviewers and our shepherd for their feedback. We also thank Vaibhav, Akshay Gadre, Diana Zhang and Fanglin Chen for their valuable inputs. This research was supported by NSF grant 1718435 and 1837607.

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