Software Defined Cooking (SDC) using a microwave oven

Haojian Jin
Jingxian Wang
Swarun Kumar
Jason Hong
Cooking is the application of heat to ingredients to transform them via chemical and physical reactions.
Cooking is the **application of heat** to ingredients to transform them via chemical and physical reactions.

**SDC = programmable heating**

heat the food in a software-defined thermal trajectory (recipe).

*Jeff Potter. Cooking for Geeks: Real Science, Great Hacks, and Good Food.*
overcooking the fat, without burning the meat.

https://www.huffpost.com/entry/bacon-mistakes-how-to-cook_n_3111706
Software-defined Cooking Recipe

Cooked = Temperature \times Time \times Space
Software-defined Cooking Recipe

Cooked = **Temperature** x Time x Space

- Preheat
- Denature myosin
- Kill bacteria
- Denature actin
- Burn fat

Temperature: 163°C, 65.5°C, 55°C, 50°C

Time: Preheat
Software-defined Cooking Recipe

Cooked = Temperature x Time x Space

- Preheat
- Denature myosin
- Denature actin
- Kill bacteria
- Burn fat

Graph showing:
- Temperature (50°C, 55°C, 65.5°C, 163°C)
- Time

Legend:
- a fat pixel

Equation:

Preheat

Denature myosin

Denature actin

Kill bacteria

Burn fat

Cooked
Software-defined Cooking Recipe

Cooked = Temperature x Time x Space

- Preheat
- Denature myosin
- Denature actin
- Kill bacteria
- Burn fat

Preheat: 50°C
Denature myosin: 55°C
Denature actin: 65.5°C
Kill bacteria: 163°C
Burn fat: a fat pixel
Denature actin: a fat pixel
Denature myosin: a meat pixel
Kill bacteria: a meat pixel
SDC (software-defined cooking): a novel low-cost closed-loop system that can sense and control heating at a fine-grained resolution.
SDC (software-defined cooking): a novel low-cost closed-loop system that can sense and control heating at a fine-grained resolution.

We have a demo booth!
Spoiler alert

No Turntable

Default Turntable

SDC Uniform Heating

SDC Arbitrary Heating

high heat
Spoiler alert

No Turntable

Default Turntable

SDC Uniform Heating

SDC Arbitrary Heating

high heat
Spoiler alert

No Turntable

Default Turntable

SDC Uniform Heating

SDC Arbitrary Heating

MobiCom
third most popular domestic heating method (after baking and grilling)
Today’s Microwave: a **blunt heating** device

reheating leftovers

**uneven & unpredictable** heating
Microwave can only heat food **blindly**

1. Don’t know how much heat each food pixel has absorbed.

2. Have no way to actuate heating on a specific food pixel.
A closed-loop system to heat smartly

1. Don’t know how much heat each food pixel has absorbed.
2. Have no way to actuate heating on a specific food pixel.
A closed-loop system to heat smartly
A closed-loop system to heat smartly
Heat Sensing
Most electronics & batteries are *not microwave-safe*.
Specialized microwave-safe sensors are delicate and expensive.
Neon lights

Glass

Electrodes

Low-pressure Neon gas mixture
Low-cost, wireless, battery-free, microwave-safe, glow in strong EM
Programming EM sensitivity

dark  |  glow -> brighter  |  burned

EM field strength
Programming EM sensitivity

can measure the EM field

cannot measure any EM field

cannot measure any EM field

dark  glow -> brighter  burned

EM field strength
Programming EM sensitivity

Wires as the antenna for energy harvesting

Glowing principles => Paper
Programming EM sensitivity

EM field strength

0 mm
- dark
- glow -> brighter
- burned

7.5 mm
- dark
- glow -> brighter
- burned

15 mm
- dark
- glow -> brighter
- burned

blue - 15 mm
Programming EM sensitivity

- 0 mm
  - dark
  - glow -> brighter
  - burned

- 7.5 mm
  - dark
  - glow -> brighter
  - burned

- 15 mm
  - dark
  - glow -> brighter
  - burned

EM field strength
Placement of Neon Lights

turntable with 32 neon lights  cover with 32 neon lights

3cm
Sensors

A web cam

A thermal cam
Sensors

A web cam

A thermal cam

Raw data

3D EM field

raw temperature
A web cam

A thermal cam

Glass container

Visual camera

Thermal camera

Sensors

Raw data

Raw data

3D EM field

raw temperature

Output

3D EM field

raw temperature

extended kalman filter

Temperature P

Gradient P'
Heat Actuation
Actuation related work

turn table for **blind** rotation

non-uniform and **unpredicatable**
A closed-loop turntable

Desired heat patterns from software-defined recipes

Current temperature distribution from Sensors

at time $t$
A closed-loop turntable

Desired heat patterns

Current temperature distribution

Heating gap

at time $t$
A closed-loop turntable

- Desired heat patterns from Software-defined recipe
- Current temperature distribution

Heating gap

Realtime heating power ($P'$)

temperature gradient

at time $t$
A closed-loop turntable

Desired heat patterns from Software-defined recipe

Current temperature distribution ®

Heating gap

Realtime heating power (P’)

Temperature gradient

Adjust rotation plan

at time t
Heating patterns from 3D standing waves

Microwave cannot heat individual pixels independently.
Determining the rotation plan

Realtime heating power ($P'$)
Determining the rotation plan

Realtime heating power ($P'$) = Heating gap
Determining the rotation plan

Realtime heating power ($P'$) = a knapsack problem

Heating gap

Optimization details => Paper
Spoiler alert
Spoiler alert
Microwave accessories

- Microwave susceptor
- Microwave shields
patterned microwave susceptor
effectively ensure coverage through SDC
Evaluation
Evaluation apparatus

thermal-chromatic pigment + rice
reusable
turn pink if \( p > 31^\circ C \)

Before heating

After heating

The room temperature is at 20°C.
Uniform heating

heat the rice in a plate **uniformly** to 60°C in 2 minutes.

**Baselines**: microwave oven w/o turntable
Uniform Heating

hot spots

cold spots

30 sec | 60 sec | 90 sec | 120 sec

no rotation

time
Uniform Heating

cold spots
Uniform heating

improve the thermal heating uniformity by 633% compared to microwaves with a blind turntable.

More quantitative results => Paper
Arbitrary heating

with a microwave susceptor ring

50°C

500°C
App: Cooking bacon
Heated meat and fat will shrink.

App: Cooking bacon
App: Cooking bacon

Default Rotation

SDC

Raw

More apps => Paper
Limitations

1. SDC cooking is slower.
2. Some heating patterns might be infeasible.
3. Not sure if it’s more delicious. :-)

Future work

1. 6 DoF turntable
2. Higher frequency microwave + beamforming
3. Replacing neon lights with rectifiers
Software Defined Cooking using a microwave oven

Haojian Jin, Jingxian Wang, Swarun Kumar, Jason Hong, Carnegie Mellon University
Why Microwave?

Radiation is most programmable because electromagnetic wave is **reflective and stackable**.
Why not thermal camera?

Place thermal camera outside

1. limited resolution (both spatial and temporal)

2. only measure the effect of heating after-the-fact

Existing solutions
Challenges: heat food *blindly*

<table>
<thead>
<tr>
<th>Sensing</th>
<th>Actuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. limited resolution (both spatial and temporal)</td>
<td>3. blind rotation.</td>
</tr>
<tr>
<td>2. only measure the effect of heating after-the-fact</td>
<td>4. limited degree of freedom.</td>
</tr>
</tbody>
</table>
Cooking is the application of heat to ingredients to transform them via chemical and physical reactions that improve flavor, reduce chances of food borne illness, and increase nutritional value.
Stochastic knapsack problem

The heat pattern is non-static and unpredictable.

Many factors can impact heat patterns. e.g., size, temperature, texture, material types
A greedy approximation algorithm

Greedy strategy:

At each step of the journey, heat at the rotation angle whose temperature gradient is most similar to the current heating gap.
Cooking is the application of heat to ingredients to transform them via chemical and physical reactions that improve flavor, reduce chances of food borne illness, and increase nutritional value.
onsen tamago/hot spring eggs/63°C eggs

Cooked = Temperature \times \text{Time}
onsen tamago/hot spring eggs/63°C eggs

set the temperature to 145°F (63°C) and let the eggs cook for anywhere from 45-90 minutes.

Cooked = \textbf{Temperature} \times \textbf{Time}
The process of protein denature is a function of the temperature & time.
Temperatures of common reactions in food

- 122°F / 50°C The protein myosin in meat begins to denature
- 131°F / 55°C Highest survival temperature of foodborne illness-related bacteria
- 150°F / 65.5°C The protein actin in meat begins to denature
- 310°F / 155°C Maillard reaction (causes meats to brown) becomes noticeable
- 356°F / 180°C Sugar begins to noticeably caramelize and turn brown
- 375°F / 190°C Oven temperature for baked goods that noticeably brown
- 350°F / 175°C Oven temperature for baked goods with little browning
- 325°F / 163°C Lowest effective oven temperature for roasting meats

136-150°F / 58-65.5°C Ideal temperature for cooked meat
A microwave oven converts a large electrical input (≈1000W) into microwave energy (2.45 GHz) and heats food using microwave radiation.
dielectric heating

https://www.youtube.com/watch?v=kp33ZprO0Ck
standing wave
https://www.youtube.com/watch?v=kp3Zpr00Ck
3D standing wave

Unpredictable cold/hot spots Influenced by the content (shape, surface, temperature, etc.)
sharp-edged metals (e.g., forks, most sensors, motors)

Microwave-safe plastic

Eggs

....

Microwave is dangerous
122°F / 50°C The protein myosin in meat begins to denature
131°F / 55°C Highest survival temperature of foodborne illness-related bacteria
150°F / 65.5°C The protein actin in meat begins to denature
310°F / 155°C Maillard reaction (causes meats to brown) becomes noticeable
356°F / 180°C Sugar begins to noticeably caramelize and turn brown
375°F / 190°C Oven temperature for baked goods that noticeably brown
350°F / 175°C Oven temperature for baked goods with little browning
325°F / 163°C Lowest effective oven temperature for roasting meats
136-150°F / 58-65.5°C Ideal temperature for cooked meat