Robotic End Effector for Autonomous Cleaning of Dishes in Homes and Offices

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Dishcare Inc. (2/23/2022)

Part 1: Elevator Pitch

Dishcare is proposing to develop a complete **end-to-end dish management solution [1]** that will replace traditional dishwashers by providing **autonomous loading, washing, and storing** of dishes. Dishcare's solution will leverage innovations in robotic arms, computer vision, and machine learning. In doing so, Dishcare will significantly reduce the environmental impact of dishwashing. Dishcare's first planned product will **clean a typical dish in 5-10 seconds** using **2x less water** and **10x less energy** than today's most efficient dishwasher.

The Customer:

- Dishcare's early adopters are expected to be tech-savvy customers with deep need and discretionary resources. To this end, we will launch a pilot program to replace existing dishwashers with Dishcare units in three tech-company kitchens in the San Francisco Area.
- Dishcare aspires to serve every home and office that wants to break free from loading and putting the dishes away while being environmentally responsible. In particular, we are inspired by the sustainable impact Dishcare could have on elderly wanting to live independently; working parents with limited time; and in general, freeing up time for meaningful activities that are more enjoyable & impactful.

The Value Proposition

- Dishcare's ***autonomous dishwasher*** helps ***homes and offices*** by ***allowing people to break free from loading and putting the dishes away*** while ***being environmentally responsible by using a targeted cleaning process that consumes 10% of energy and 50% of water relative to today's most efficient dishwasher.***
- Business Model: Dishcare will validate its commercial opportunity by offering its complete dish management solution for offices & homes with a subscription unit pricing of 10¢/dish. We expect this to result in an affordable cost of $36/month to an average U.S. home. We estimate that approximately one billion dishes are cleaned in the U.S. every day, leading to a $36B total addressable market in U.S. homes. We expect this market to grow significantly when we include offices in the U.S. and expand to global markets.

The Innovation

Dishcare's autonomous dishwasher will make use of a robotic end-effector designed to pick-up soiled dishes, support complex robotic maneuvers during cleaning, and drop-off clean dishes. While conventional dishwashers built the process of washing dishes around a rotary spray arm, Dishcare is rethinking the process by building a robotic end-effector for dishes. This returns the act of dishwashing to the hands-on task of allowing Dishcare's end effector to become the hands of the robot. Robotic hands allow efficient dishwashing techniques—such as targeted cleaning—completely inaccessible to conventional rotary spray arms of today. To achieve the above, we propose to develop the following:

- An end-effector with a mechanical design that can grasp and manipulate a wide range of dish types, such as plates, bowls, mugs, cups, silverware, pots, and pans.
- An end-effector that has the sensing capability to measure grasp quality using a matrix of pressure sensors embedded into the end-effector.
- Algorithms to monitor, maintain or improve the end-effector's grasp quality during picking up, cleaning, and dropping off of dishes using a range of autonomous motions.

Part 2: The Commercial Opportunity

Market and addressable market

The dishwasher market is part of the global kitchen appliance (Source: Grandview Research) market which is expected to grow to approximately $250 Billion by 2022. It includes refrigerators (37%), Cooking appliances (37%), Others (22%), and Dishwashers (4%).

- The global dishwasher market (Source: Grandview Research) is expected to grow to approximately $10 Billion by 2025, with a CAGR of 7.2% from 2019 to 2025. The US dishwashing market is $1.6 Billion, of which $600 Million is the residential market and $1B is the commercial market.
- Also of interest is the emerging global smart kitchen appliances market which is sized at US $11.2 Billion in 2020 with a growth rate of 18.6% from 2021 to 2028.
- In a conventional appliance business, appliances are bought and owned fully by customers. With such a conventional business model, Dishcare's U.S. addressable market would be about $1.5 Billion, which is a combination of the smart kitchen appliance market and the current residential dishwasher market.
- Dishcare's business model, however, is to charge based on usage. Customers won't have an upfront cost for buying a Dishcare. Instead, they would have a Dishcare unit installed for a small fee and would pay monthly based on the number of dishes their Dishcare cleans in a month. We are considering a unit pricing of 10¢ for cleaning a dish. So, if an office with 30 employees cleans an average of 2 dishes per employee in a workday, the office would pay about 30 x 2 x 20 working days x 10¢ = $120/month. If a household with 4 people cleans an average of 3 dishes per person in a day, the household would pay about 4 x 3 x 30 days x 10¢ = $36/month. With one billion dishes (329.5 million people x 3 dishes/day) being cleaned in the U.S. every day, we expect the above subscription model to create a $36B total addressable market in the U.S., a 24x increase over the conventional $1.5B market

Business economics and market drivers in the target industry

- Global trends driving growth (source: MarketResearch.Biz): Modular kitchen concepts with room for appliances, rising adoption of connected home appliances, higher per capita income, growing women workforce, and the increasing desire for a modern lifestyle are drivers for the global dishwasher market.
- There is a growing interest in smart, efficient and user-friendly home appliances. The prevalence of devices such as iRobot's Roomba, Google Nest and smart speakers such as Amazon Alexa has created an appetite for the evolution of traditional home appliances.
- The smartphone industry has commoditized sensors such as cameras. The emerging internet of things (IoT) industry has created computational chipsets for the edge-node. Advances in deep learning have made artificial intelligence models accessible for everyday devices such as phones. These mega-trends are leading to the emergence of a wide range of smart robotics products.

Customers, Business model, Revenue Potential:

- Dishcare will launch its pilot program by installing its first product at technology company kitchens in the San Francisco area. Being in the same geographic region as Dishcare, these early installations will allow us to quickly learn, iterate, and refine our product and validate Dishcare's commercial opportunity.

- With learnings from our pilot program, we intend to expand to more offices, while simultaneously launching a pilot program for homes in the San Francisco Area. We expect that some of our early adopters in homes would have experienced Dishcare at their workplaces.
- Equipped with the learnings from the San Francisco Bay Area, we intend to scale production to make Dishcare available to other major regions in the U.S. and the rest of the world.
- With operational learnings & revenues from the above, we expect to be able to optimize our product models and streamline our manufacturing processes.
- Dishcare will validate its commercial opportunity by offering a dishwashing service for offices & homes with a unit pricing of 10¢/dish. We expect this to result in a cost of an affordable $36/month to an average U.S. home. We estimate that approximately 1 billion dishes are cleaned in the U.S. every day, leading to a $36B total addressable market in U.S. homes. We expect the market to grow significantly when we include U.S. offices along with global homes & offices.
- We expect to launch an opt-in service for customers to allow us to analyze data from their Dishcare and present positive reinforcements and encouragements to benefit the individual well-being and the society at large. For example, "Congratulations! you saved 19kWh of energy and 18 gallons of water last month!", "Congratulations! you had 90% of meals with reusable dishes this month!", "Congratulations! your mealtimes appear more regular than 75% of users". Our analysis of soiled dishes will be of interest to a wide range of users. Individuals would like to see their personal trends. Businesses such as consumer product goods (CPG) companies and retail stores would be interested in ensemble trends for real-time insights on changes in consumer behavior.

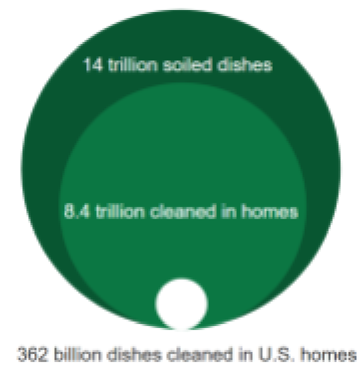


Figure 1 Soiled dishes cleaned in global and in U.S. homes in a year

Market validation

- The U.S. Energy Information Administration (EIA) reports that traditional dishwashers are among the least-used appliances in American homes. In a 2015 report, 20% of the 80 million households that have a dishwasher did not use it.
- Our user interviews have made it clear to us that traditional dishwashers do not meet the expectations of people in 2022. Our learnings from consumers include: (a) No one likes to do dishes, (b) Why do dishwashers take hours to clean?, (c) People like to use real dishes; even for take-outs, (d) Many pre-clean dishes before loading, (e) The drying issue (f) Low level is painful, (g) Dishwashers haven't meaningfully improved in years, (h) The choice between convenience & sustainability
- Our learnings from offices include: (a) Dishes cause workplace conflicts, (b) Dishes unveil gender & status biases, (c) The stigma of doing dishes at work, (d) The case for an office manager

- In light of the above learnings, we believe this market segment is ripe for innovation and disruption. In fact, few of our interviewees even mentioned “a dishwashing robot” and “a dishwasher with a hand” without any hint of what Dishcare was envisioning as its product.

Table 1: List of customer pain points based on customer interviews and market research along with Dishcare’s solution to each of these

Customer Pain Point	Dishcare Solution
Not enough dishes to justify running the dishwasher leading to wait time and drying up of food waste	Dishcare cleans dishes in real-time as soon as one or more dishes are dropped off
Batch cleaning leads to some dishes not being cleaned thoroughly in a traditional dishwasher	Each dish is individually cleaned using computer vision feedback
Preparatory work including rinsing and planning dish arrangement in dishwasher	Zero time wasted in preparatory work; unorganized dishes can simply be dropped off in Dishcare. Similar to how people drop-off dishes in a kitchen sink.
Customers often need to bend to load and unload dishes leading to aggravated back pains	Dishcare’s soiled cabinet rises to the level of the countertop when people have dishes to drop-off. The soiled cabinet then lowers for cleaning. Dishcare organizes each clean dish in its clean cabinet, so there will no longer be a need to put the dishes away. Also, Dishcare’s clean cabinet is at the level of the countertop, so people won’t have to bend while picking the dishes they need.
Dishwashers consume excessive energy and water due lack of perception for the cleanliness of an individual dish.	Dishcare's targeted cleaning allows it to spend resources wisely. We estimate that this will reduce energy consumption by 90% and water consumption by 50%, relative to the most efficient dishwasher in the market today.
Not safe for dishes with nonstick coatings due to hours of presence in a hot and humid environment	With its perception and computer vision feedback, Dishcare can adapt cleaning protocols to the dish being cleaned.

Competition

- Dishcare’s competitors are large appliance companies that make and sell dishwashers for home. A few examples of these are Electrolux, Samsung Group, LG Electronics, Whirlpool (includes Kitchenaid, Amana, Maytag), BSH (includes Bosh, Siemens, Thermador), Miele, and Haier Group (includes GE).
- Dishcare will also compete with commercial dishwasher companies such as Hobart and Dishcraft. Dishcraft notably uses a large SUV sized robotic equipment for commercial washing of a large number of identical dish types. Owing to the complexity of dish grasping, Dishcraft uses custom dishes with embedded metal discs to allow electromagnetic grasping by robots. While this approach may be suitable for commercial facilities with limited dish types, the large variety of dish types and limited under the counter space in homes and offices unfortunately render it unsuitable for our targeted market.
- Other potential competitors include companies like iRobot that make robotics based home appliances like vacuum cleaners. More recently, Tesla announced that it will develop a humanoid robot to perform repetitive and unsafe tasks. Neither of these companies have targeted our market segment yet. Should they choose to do so, Dishcare would be willing to explore partnership opportunities to leverage mutual capabilities and interests.
- We expect the following competitive landscape by the time our product enters the market
  - Smart and connected kitchen appliances with more sensors such as cameras
  - Incremental improvements in aesthetics & energy consumption along with a reduction in operational noise

Commercialization approach:
Initial development of a Dishcare prototype will be driven by internal team resources. Dishcare's approach to product development is to build prototype systems in-house, and to rapidly test and redesign in a flexible environment. Once prototypes have been thoroughly tested and validated, Dishcare will partner with an outsourced manufacturing firm for production quantity builds.

Throughout the life of the product, Dishcare will continue to conduct user interviews to understand evolving consumer desires for product features, pricing, and maintenance services.

Part 3 The Technical Solution

Origins of Innovation: Dishcare [1] is building an autonomous dishwasher for every home and office. Traditional dishwashing involves dealing with soiled dishes in overflowing kitchen sinks, arranging them carefully in racks, and bending repeatedly down to the level of dishwashers. With Dishcare, you can simply drop-off unorganized soiled dishes in its "Soiled" cabinet (like you'd in a kitchen sink). Immediately after drop-off, Dishcare cleans dishes individually with a process that targets dirt using 2x less water and 10x less energy than today's most efficient dishwasher. Dishcare then organizes each clean dish, so you always have clean dishes ready for use.

Technical Innovation Focus: Robotic handling of dishes requires a robot to gain expertise in a number of complex skills. Firstly, it requires the ability to pick-up, hold, and drop-off a variety of dish types such as plates, bowls, cups, mugs, etc. Secondly, dishes such as plates and bowls are often stacked to maximize space efficiency, so handling such stackable dishes requires the ability to pick up, hold, and drop-off a dish that is stacked together with another dish. Thirdly, handling dishes requires the ability to pick up, hold or drop-off a dish deep inside a cabinet. Finally, handling dishes may also require the ability to tilt or turn a dish to a specific angle (for example, upside down). Conventional robotic arms do not have the skills listed above for handling reusable dishes. Such conventional robotic arms are typically best suited for moving an independent object of a single type in an otherwise open unobstructed environment [2-8]. Accordingly, there is a need for an improved system to handle dishes. One that could pick up, hold, and drop-off a variety of dish types; one that could pick up, hold, and drop-off a stacked dish; one that could pick up, hold, and drop-off a dish deep inside one or more cabinets.

Key technical challenges: The challenges that keep a robotic arm from being able to reliably handle dishes lie in the robotic end-effector. An end-effector is the part of the robotic arm that makes contact with an object with the intent to grasp or manipulate it. Traditional end-effectors such as grippers and suction cups are not designed for handling soiled dishes. When used with soiled dishes, these end-effectors often accidentally drop dishes because of their suboptimal grasping capabilities. This is because of three fundamental challenges. First, traditional end-effectors do not conform to the shape of dishes to deliver a uniform grasping force across their contact surface. Second, traditional end-effectors do not have the capability to sense the quality of their grasp. Third, they do not have the capability to adjust their grasp with the intent to improve grasp quality.

Proposed solution: Dishcare is proposing to develop novel **hydraulic** robotic end-effectors that are able to conform to the shape of a dish to deliver a uniform grasping force across its contact surface area. These shape-confirming (**pliable**) end-effectors will have integrated pressure sensors to measure grasp quality in real time.

Table 3: Key technical risks and corresponding mitigation strategies

Key Technical Risks	**Risk mitigation strategies**
Hydraulic gripper might become too bulky	Replace hydraulic with compact servo motors
Unable to integrate pressure sensors across the entire surface area of the gripper	Identify gripper contact regions with maximum impact and design control algorithms to make sure the robot places dishes under the identified gripper regions
Difficulty in integrating matrix pressure sensor electronics to robot	Consider a different pressure sensor that can be integrated easily

Intellectual property: Since its founding, Dishcare has developed a concept for an autonomous dishwasher, iterated prototypes, and has filed five utility patents in the U.S. Patent Office [9-10].

Part 4 - The Company/Team

Dishcare's mission is to create happy homes & offices with delightful dining experiences. We aspire to create a future where delightful dining is possible without spending time on dishes. Backed with a deep expertise in robotics, autonomy, and hydraulics, we believe that the time for an autonomous, affordable & compact dishwasher has arrived. Dishcare was founded in 2020 to change how the world cleans dishes in the age of AI. In order to make progress towards developing a consumer product, Dishcare has experienced the need to engage in R&D for developing a reliable robotic end-effector for dishes.

Dr. Prasanna Pavani is the Founder & CEO of Dishcare. Previously, Prasanna was the CEO of Exnodes, a company he founded to accelerate onboard wafer inspection for real-time tool & process monitoring. Prasanna was also the Head of Product Infrastructure & Engineering at Osmo (leader in making learning fun), Head of Content Infrastructure & Monitoring at Orbital Insight (leader in geospatial analytics), VP Engineering at Arecont Vision (leader in security video) and has held senior engineering positions at Ricoh Innovations (leader in enterprise imaging), KLA (leader in process control), and D. E. Shaw & Co (leader in computational finance). Prasanna has served as the Editor of Computational Imaging of OSA Applied Optics journal, Member of Program Committee of COSI, and as a Panel Member of U.S. National Science Foundation. Prasanna was a Postdoc in EE at Caltech and holds a PhD in ECE from the University of Colorado. Prasanna studied Business Strategies and Entrepreneurship at Stanford University. Prasanna's 29 patents and 45 publications have earned 2100 citations. Prasanna has been recognized by the University of Colorado Outstanding PhD Award, U.S. EB-1 Extraordinary Ability Classification, OSA Outstanding Paper Award, SPIE Science and Engineering Award, CPIA Awards, and GCT Coimbatore Gold Medal.

Mr. Pratik Chawla is the Co-founder and Senior Robotics Engineer at Dishcare. Pratik has built multiple robotic, mechanical and hydraulic systems during his work at Promaxo, and Larsen & Turbo. Pratik holds MS and BS degrees in Mechanical Engineering from Purdue University.

The core Phase I team consists of Dr. Pavani who will serve as PI and commit 85% full time equivalent (FTE) hours to this project and Mr. Chawla will commit 100% FTE hours.

In addition to the core team, the company is supported by extraordinary advisors from various technical and business backgrounds including Dr. Nicholas Conley, Dr. Amy Sullivan, Divya Raghavan and Dr. Anurag Agrawal. Dr. Conley holds a PhD in Chemistry from Stanford University and is advising Dishcare on optimal protocols for cleaning. Dr. Sullivan holds a PhD in Physics from the University of Colorado and is advising Dishcare on sustainability goals and user studies. Divya Raghavan holds an MBA from MIT and is advising Dishcare on go-to-market strategies. Dr. Anurag Agrawal holds a PhD in Electrical Engineering from the University of Colorado and is advising Dishcare on Research & Development.

Dishcare is backed by angel investors including Eliot Holowitz (Co-founder, Viam & MongoDB), Dr. Benjamin Braker (Co-founder, Chiarotech), Neha Narkhede (Co-founder, Confluent), Nathan Wheeler (Co-founder, Network Optix, Entropix), Naval Ravikant (Co-founder, AngelList), Noah Campbell (Co-founder, Built Robotics) and Edward Lando (Co-founder, Goody). Viam is actively engaged with Dishcare on the development of their matrix pressure sensor product along with other software components they are developing for their robotic platform (see support letter).

Part 5 - Intellectual Merits

Dishcare is proposing to develop an autonomous dish management solution that will make use of a robotic arm and machine vision algorithms to clean and store every single dish. Unlike traditional dishwashers that rely on the average cleanliness of a batch of dishes, Dishcare uses its resources wisely to save energy and water while increasing throughput (dishes cleaned per hour). The table below compares Dishcare's performance with the most efficient dishwasher currently on the market. Dishcare consumes about 10% of the energy and about 50% of the water while improving the throughput over a factor of 7x.

In order to achieve its goal of reliably grasping, cleaning and unloading every dish, Dishcare is proposing to investigate the feasibility of a novel robotic end-effector.

Table 4: Energy, water, and throughput comparison between a dishwasher and a Dishcare

	Traditional Dishwasher	Dishcare
Energy (Wh/dish)	9.6	0.1
Water (ml/dish)	126	63.1
Throughput (dish/hour)	96	720

Worksheet

Today's most efficient dishwasher	
Energy (kWh/cycle)	0.9
Cycle time (hour)	1
Water (liter)	12.1
Capacity (dish)	96

Throughput (dish/hour)	96
Energy (Wh/dish)	9.6
Water (ml/dish)	126

Dishcare	
Time/dish (s)	5
Throughput (dish/hour)	**720**

Robotics (W)	60
Fluidics (W)	10
Total power	70
Energy (Wh/dish)	**0.1**

Flow rate (ml/s)	63
Total water (ml/dish)	315
Recycling %	80%
Water (ml/dish)	**63**

The end-effector will be designed in the form of a pliable hydraulic gripper that can conform to the shape of various dishes with real time feedback from pressure sensors embedded inside the gripper to determine grasp quality in real-time. The various feasibility tasks, expected outcomes, and the timeline to achieve these tasks is shown in table 5.

Table 5: Milestone chart

Feasibility Tasks Months	**1**	**2**	**3**	**4**	**5**	**6**	**Milestones**
Invent pliable hydraulic grippers that conform to the shape of the dish							- Pliable grippers conform to shapes of different dishes to maximize contact surface area Hydraulics to allow lightweight grippers
Test grasp quality of a pliable hydraulic gripper for various dish types							- Established measurement of grasp quality based on dish drop rate (DDR) - Achieved a DDR of <1 dishes dropped per 10,000 interactions
Define slipping and non-slipping conditions based on the signals from a matrix pressure sensor							- Grasp quality measured using a matrix pressure sensor - Dish 'slipping' and 'not slipping' conditions established based on sensor readout
Develop feedback loop for controlling the end-effector based on grasp quality							- Real-time sensor measurement used to apply corrective actions when a dish is 'slipping'
Integrate the array sensor into Dishcare's rolling grippers and test it through the entire cleaning process							- Pliable hydraulic gripper used in conjunction with the pressure sensor and control algorithms through entire cleaning process while ensuring a DDR of <1 dish dropped per 10,000 interactions

In the following sections, we will present a brief background of the shortcomings of traditional dishwashers followed by the technical details of the tests and experiments planned to achieve the tasks listed above.

Background: Preparing, consuming and storing food inevitably leads to soiled dishes. Cleaning soiled dishes prior to reuse has been a pervasive chore for humans across cultures and geographies. Before the advent of dishwashers, handwashing these dishes was the only viable option. Although hand-washing of dishes can be efficient in terms of energy and water consumption (when a tub of water is reused instead of leaving the faucet open), it does require people to bend, scrape, scrub, rinse and stack dishes. With the advent of dishwashers, the chore of washing dishes was made somewhat easier. However, conventional dishwashers suffer from various shortcomings that have not been addressed in the 100+ year history of dishwasher development. A few of these are as follows:

Batch washing - Conventional dishwashers lack the perception capability necessary for cleaning. They employ a turbidity sensor to detect the quantity of dirt present in water during the cleaning process, and use this single measurement to assess the cleanliness of dozens of dishes. At their best, they prioritize the average cleanliness of a batch of dishes over the thorough cleanliness of an individual dish.

Preparatory work - A slew of preparatory work such as scraping, rinsing, and arranging of dishes (according to shape, size, and material) is necessary to maximize the chances of soiled dishes coming out clean in a conventional dishwasher.

Unsanitary - In order to maximize the number of dishes being cleaned and minimize energy and water usage, people tend to load dishwashers to their full capacity prior to turning them on. This wait time creates conditions where food residues attract and multiply germs on dishes.

Loading and unloading - Loading a dishwasher is physically painful as it requires repeated bending to transfer a dish from the kitchen sink which is typically located at a substantially higher level than an under the counter dishwasher. Putting clean dishes away is equally painful and is often the reason for delayed emptying of dishwashers and consequent piling up of dishes in the kitchen sink.

Energy and water usage - Conventional dishwashers found fundamentally suffer from a tradeoff between the duration of the dishwashing cycle and cleanliness of each dish. Without the ability to perceive the cleanliness of an individual dish, these dishwashers resort to longer dishwashing cycles, spanning hours, to increase the chances of removing dirt from dishes, thereby causing significant wastage of time, energy and water.

Accordingly, there is a need for an improved system to clean soiled dishes thoroughly and efficiently. One that could clean each dish with individual attention to ensure every dish comes out clean; one that could perceive soiled regions of dishes; one that could target soiled regions for deep cleaning; one that could conserve energy and water; and one that could be as fast as hand washing of dishes.

Dishcare solution: Dishcare is developing an autonomous dishwasher for homes and offices, by leveraging innovations in robotics, computer vision and machine learning. Dishcare has the same size as a standard dishwasher, so it will be an easy upgrade for homes & offices. A schematic of the Dishcare design and its working principle are shown in Figure 2.

The process of cleaning a dish in Dishcare consists of the following steps:

Step 1 - Dish loading: When users have soiled dishes ready for cleaning, Dishcare's soiled cabinet rises up to allow users to simply drop-off their dishes without requiring them to bend. Users don't need to arrange dishes; instead, they drop-off unorganized dishes similar to how they would drop dishes off in a kitchen sink.

Step 2 - Perception and Planning: Using onboard cameras, images of the soiled dishes are captured. The dishes are then classified into one of various categories: plates, bowls, spoons, etc. The six-dimensional pose (3D position and 3D orientation) of dishes are estimated using deep learning-based computer vision models. This information is then sent to the robotic arm.

Step 3 - Dish Handling: The robotic arm picks up a single dish and moves it to Dishcare's wash module. During the cleaning process, the robotic arm maintains a good grasp of the dish while maneuvering the dish through a computer vision guided motion path.

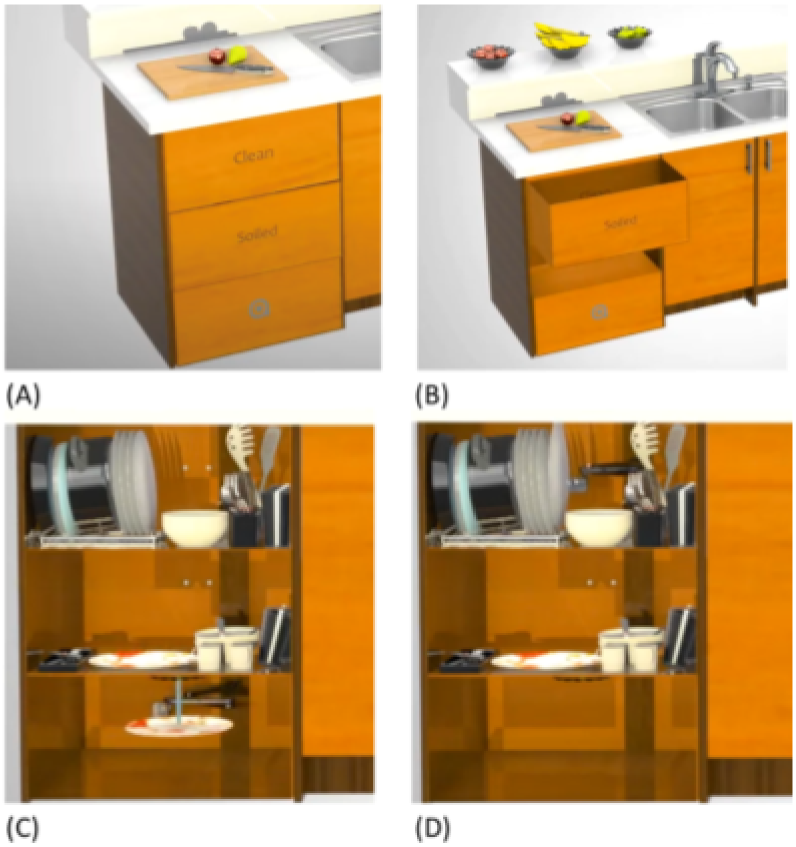


Figure 2: Proposed design and working of Dishcare (see video [1]). Dishcare will be integrated into existing homes and will fit right under the kitchen sinks replacing existing dishwashers. As shown in figure (A) shows the clean, soiled & wash cabinets in their closed configuration (B) shows how Dishcare's soiled cabinet rises up to allow customers to drop-off their soiled dishes without bending. After dishes are dropped off, the soiled cabinet lowers and settles between the clean cabinet and the wash cabinet. The wash cabinet consists of a fixed jet spray nozzle configured to spray a variety of fluids such as clean water, recycled water, detergent, and rinse-aid. A robotic arm is located behind the cabinets. The robotic arm picks up a single dish from the soiled cabinet and cleans it as shown in (C). Once cleaned and drained, the dish is organized along with other clean dishes in the clean cabinet located in the top shelf as shown in (D). Dishcare allows customers to break free from loading and putting the dishes away. Dishcare's real-time cleaning process has no wait time; this when combined with its organizing capability makes clean dishes always available for use

Step 4 - Targeted dish cleaning: A camera in the cleaning area images the soiled dish and estimates the location of stubborn soiled regions on the dish. A fixed nozzle placed next to the nozzle is configured to spray a *variety of fluids such as clean water, recycled water, detergent, and rinse-aid at several flow rates.* Cleaning algorithms calculate optimal spray timing, flow rate, fluid type along with the robot's motion plan under the nozzle to clean the dish with maximum efficiency. The spray nozzle uses a combination of fluid jets to target the soiled areas on the dish. This process is repeated until all the soiled regions on all sides of the dish are cleaned. Figure 3 shows an example.

Step 5 - Dish unloading: Once a dish is cleaned, the robotic arm moves the dish to the clean cabinet and organizes it at an optimal location making it available for easy pickup. The entire process is then repeated for each soiled dish in the soiled cabinet.

Through each of the above five steps, Dishcare's robot needs to securely handle a dish with its end-effector. Conventional robotic arms and their end effectors do not possess the necessary skills for the complex tasks listed above. They are best suited for moving an independent object of a single type in an otherwise open unobstructed environment. Hence, Dishcare is proposing to develop a novel end-effector that can reliably carry out each of these tasks.

The various objectives and associated tasks required for the development of the robotic end-effector are listed below:

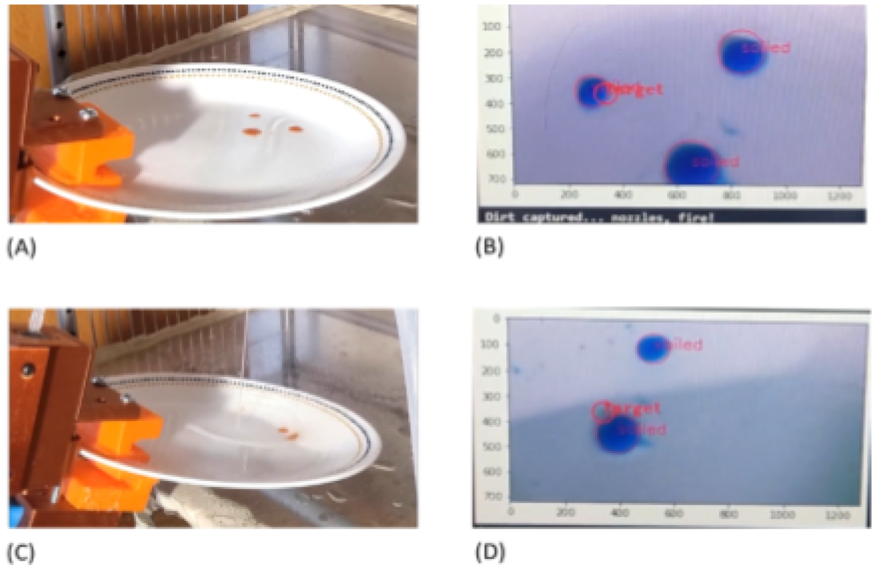


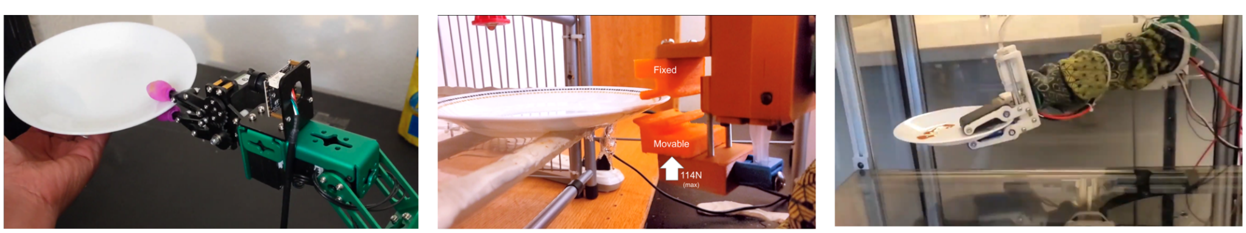
Figure 3: Targeted cleaning of a soiled dish. (A) Robotic arm moves a soiled dish into the cleaning area. (B) A camera in the cleaning area images the dish and determines the soiled areas and decides which of the soiled areas need to be targeted first. (C) The targeted area is then sprayed with a combination of soap and high-pressure water jet. (D) The cameras then detect the remaining soiled areas and target the next one continuing this process until the entire dish is clean.

<u>**Objective 1: Invent a robotic end-effector for grasping dishes reliably**</u>

<u>Task 1: Invent pliable hydraulic grippers that conform to the shape of dishes</u>

Dishes come in a variety of shapes, sizes and textures. Therefore, a robotic end-effector designed for dishes needs to be able to pick-up, hold and drop-off a variety of dishes reliably. Traditional end-effectors such as grippers and suction cups are incapable of handling the wide variety of dishes used in a typical home.

The evolution of the grippers developed and prototyped by Dishcare is shown in Figure 4. The first version of the gripper was based on a mechanical gripper where the motion of the gripper is controlled by a motor and the grasping mechanism involved the use of two fingers. The main disadvantage of a mechanical gripper is that the weight of the motor is proportional to its torque and grasping force. As a result, a larger grasping force needs a bulkier end-effector. Hydraulic grippers on the other hand rely on the pressure generated by compressing a fluid and can generate a high grasping force. As their compressor motor can be placed away from the end-effector, the end-effectors themselves can become lighter when compared to mechanical grippers with similar grasping force. (B) shows the first prototype of a hydraulic gripper that Dishcare designed and prototyped. In this proposal, we will further evolve our design to develop a hydraulic gripper that is pliable and has an embedded matrix pressure sensor array. An initial prototype of is shown in (C).



(A) Prototype 1 - Mechanical gripper | (B) Prototype 2 - Hydraulic gripper | (C) Prototype 3 (proposed) - Pliable Hydraulic gripper using a rolling grip

Figure 4: Evolution of Dishcare's end-effector for grasping dishes. (A) The first prototype was a mechanical gripper that used two fingers to grasp dishes. Although versatile and fast, mechanical grippers require use of motors near the end-effector thus making it heavy. (B) Prototype of our hydraulic gripper which allows for much larger grasping forces without the need for heavy motors in end-effector assembly. (C) Latest prototype of the pliable hydraulic grippers that uses a rolling grasp and can conform to the shape of the dish.

<u>Task 2: Test grasp quality of the pliable hydraulic gripper for various dishes</u>

The grasp quality of a pliable gripper is related to the total contact surface area between the gripper and a dish. For large dishes such as plates, an ideal grasp would be close to 100% of the gripper surface area. Whereas for smaller dishes (e.g. forks, spoons, etc.), an ideal grasp would equate to a much smaller area of the gripper. Dishcare's perception module can categorize a dish into one of many categories; and can provide a priori information that will be used to determine nominal dish-specific grasp quality values. In order to qualify Dishcare's end-effector, we will measure grasp quality values for various dishes as a function of dish drop rate (DDR) where DDR is the percentage of dishes dropped. DDR will be determined for each dish type. We expect to achieve a DDR of < **0.01%** i.e. **1 drop** per **10,000 cleans**.

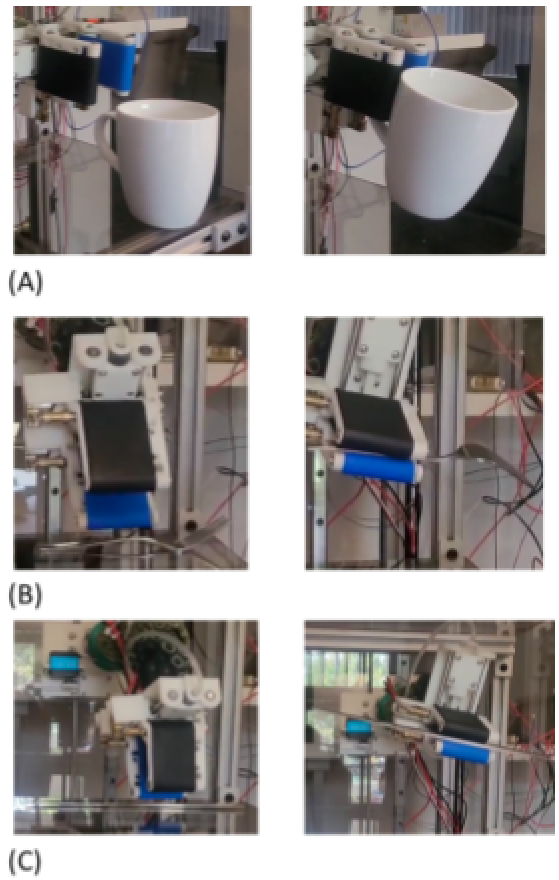


Figure 5: Prototype of the pliable hydraulic end-effector gripping different dish types. Our prototype pliable end-effector conforms to the shape of the item being picked allowing it to pick items like cups (A), forks (B), knives (C). The same end-effector can also pick plates (small and large), spoons, chopsticks, etc.

Our initial tests show promising results with the rolling gripper in terms of its ability to pick up a variety of dishes as shown in Figures 5 and 6.

<u>Objective 2: Integrate matrix pressure sensor with end-effector to measure grasp quality in real time</u>

An ideal robotic end-effector will not only ensure good grasp quality but also provide real time feedback of the grasp quality to allow decisions to be made on the next set of actions based on this feedback. This will not only allow a significant reduction in DDR but also increase cleaning throughput (i.e. # of dishes cleaned per hour) by taking appropriate actions before a dish is potentially dropped. To achieve this, we will embed a matrix pressure sensor into the gripper to enable real time readout of pressure values across the entire area of the gripper. The matrix sensor will be provided by Viam, Inc. - a robotics platform company that is building modular components to make robotics more approachable (see support letter). The tasks for this objective are listed below

<u>Task 1: Define slipping and non slipping conditions based on pressure sensor measurement</u>

The matrix pressure sensor that we are currently testing consists of an array of 21 point (3x7) 10-bit pressure sensors covering an area of 900 mm^2. In order to test the sensor, we embedded it under the contact surfaces of one of our hydraulic grippers (prototype 2). When not in use each value in the matrix nominally reads 0 as shown in Figure 6 (A). Figure 6 also shows the readout of the pressure sensor when pressed against different dish types. As can be seen, different dish types activate different areas of the pressure sensor and the pressure values depend on the force exerted on the dishes. In this task, we will test the matrix pressure sensor for different dish types under the following conditions

(a) When a dish is picked up for cleaning. Depending on the orientation and position of the dish, the end-effector will pick it up in different ways.

(b) When a dish is subjected to a range of motions: for moving the dish to the wash module or the clean module; to position and orient it under the jet spray nozzle; to position and orient it for draining

(c) When a dish is dropped off in the clean cabinet.

For each of these tests, the pressure values will be recorded continuously up until either the dish is dropped, or the task is completed successfully. Each test will be evaluated as ‘slipping’ (bad grasp) or ‘not slipping’ (good grasp) based on whether a dish was displaced or dropped. The data will be used as a training set for a deep learning model to identify if a dish is slipping or not.

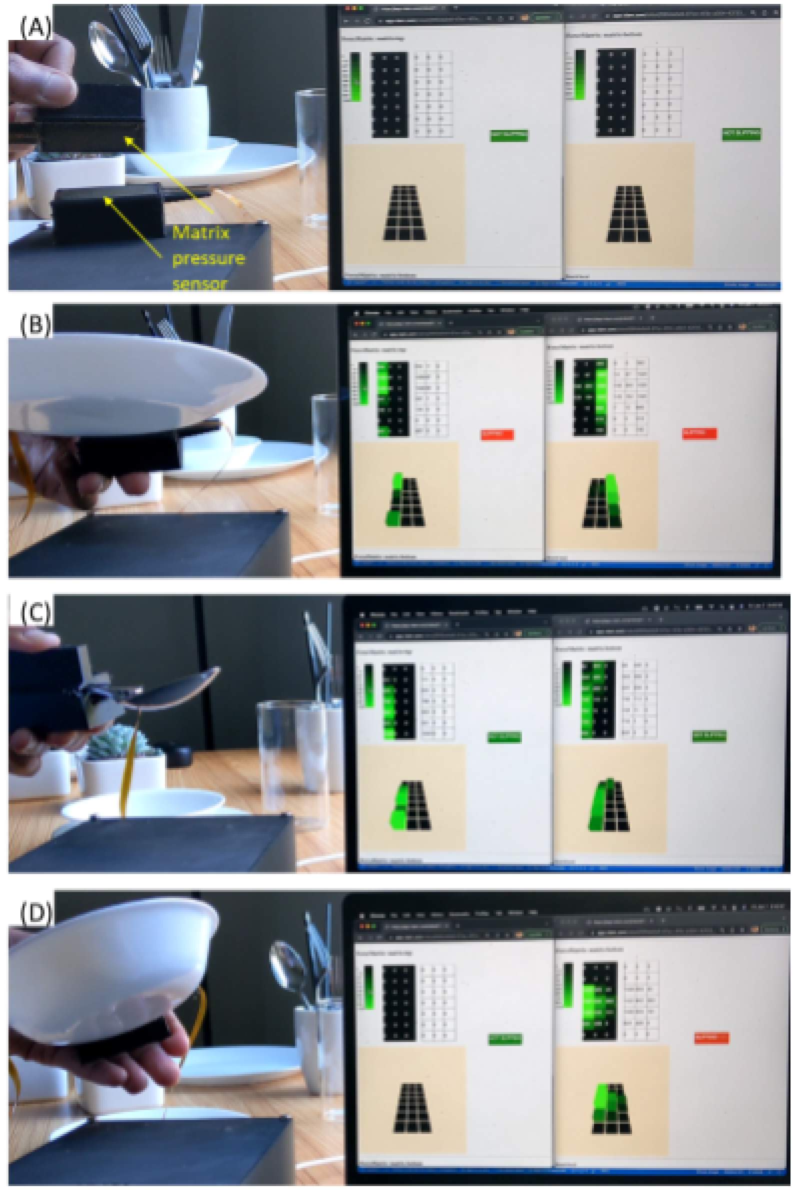


Figure 6: Testing of the 21 point (3x7) pressure sensor to determine grasp quality on a variety of dish types. As shown in (A), two matrix pressure sensors are embedded in top and bottom grippers; when no pressure is applied, each point on the matrix shows a zero value. A ‘good’ grip is determined based on the distribution of pressure as determined for different dish types. (B) – (D) show example matrices of a ‘good’ grip for different dish types

<u>Task 2: Develop feedback loop for controlling end-effector based on grasp quality</u>

In this task, data from the matrix pressure sensor will be combined with control algorithms to identify possible corrective options if the sensor detects a ‘bad grasp’. The feedback to the control systems will be in real-time throughout the entire operating cycle of Dishcare. Figure 7 shows a flowchart of how this will be carried out.

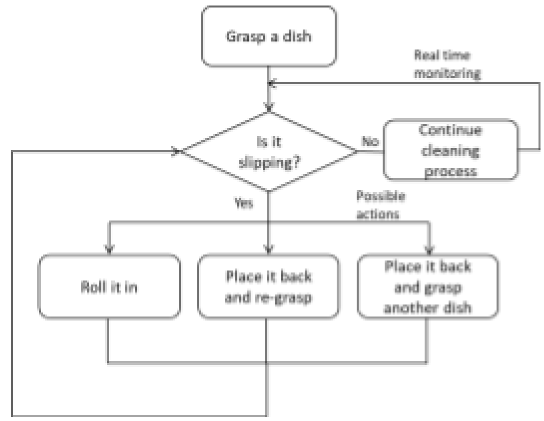


Figure 7: Flowchart describing possible corrective actions that Dishcare’s rolling gripper can apply to a dish that is ‘slipping’.

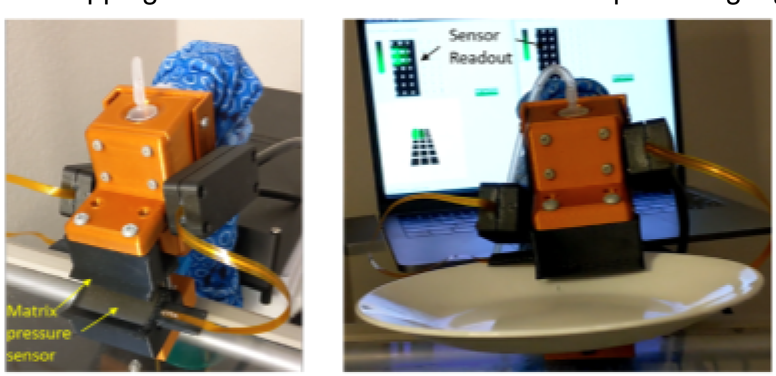
When a dish is being hand washed, people subconsciously sense (using nerve endings in fingertips) and evaluate if they have a good grip on a dish and whether a dish might slip. We apply corrective actions like increasing the contact area between our fingers and the dish; grasping in a different position/orientation to improve our grip; or simply increase our grasping force. We learn these corrective actions from childhood and hone them when we experience handling various objects over time.

Similarly, we will teach appropriate corrective actions to the robotic end-effector by introducing it to different scenarios. Typical corrective actions include rolling the dish further in to increase contact area, laying the dish back if possible and grasping it at a different angle/position, placing it back and grasping a different dish, etc. The constant signal from the pressure sensor array will provide the real time feedback to the control systems enabling constant monitoring and corrections as required.

<u>Objective 3</u>: <u>System integration and testing</u>

<u>Task 1: Embed a matrix pressure sensor into Dishcare’s rolling grippers and test it throughout a typical cleaning process</u>

We previously integrated the matrix pressure sensor onto the V2 hydraulic grippers as shown in Figure 8. The real time readout of the pressure sensor was also validated by pressing down on dishes. In this task, the matrix pressure will be integrated into the rolling gripper and tested throughout the entire cleaning process. The ‘good’ and ‘bad’ grasp metrics developed in the previous task will be put to test under realistic scenarios as various soiled dishes are picked up, cleaned and dropped off by the end-effector. Any discrepancies between expected slipping and non-slipping cases will be fed back into the deep learning algorithm to further improve the model.



(A) (B)

Figure 8: Matrix pressure sensor in action using Dishcare’s prototype hydraulic grippers (see video [14]). (A) shows the 21-point matrix pressure sensor attached to the top and bottom grippers whereas (B) shows real-time readout of pressure points as the gripper grasps a ‘dish’. The readout is shown in the background where pressure levels vary from zero (black) to maximum (light green). Depending on dish type, the amount and distribution of pressure will determine if the grasp quality is adequate to continue with the cleaning process. The signals will be monitored through the entire process.

Our initial tests of cleaning a plate using the rolling gripper are shown in Figure 9. We will perform similar tests with different dish types placed at different positions and orientations with differing amounts of food residues on them. We will also establish DDR metrics for various dish types.

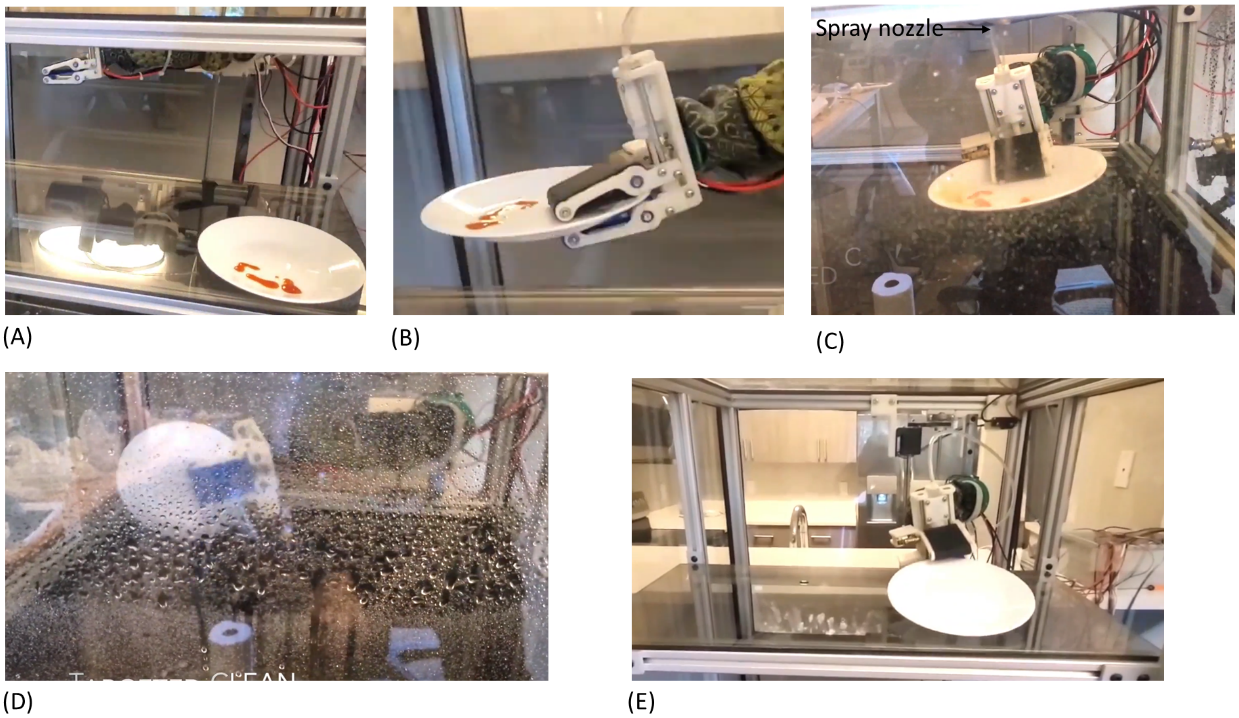


Figure 9: Demonstration of the cleaning process using the prototype rolling pliable hydraulic end-effector. (A) A soiled dish is placed in the soiled cabinet. The gripper identifies the object and determines how it should be grasped, as shown in (B). The gripper then moves it to the wash module where, as shown in (C), the dirt is perceived and targeted using a spray nozzle that sprays both soap and water at a variety of flow rates. Once cleaned, the robot tilts the dish to drain any remaining water as shown in (D). Finally, the dish is brought to the clean module and dropped off as shown in (E).

Part 6 - Broader Impacts

- Dishcare's dishwasher has the potential to save 90% of energy and 50% of the water compared to today's most efficient dishwasher. This is in line with the U.S. goal of promoting efficient technologies as well as the global need to reduce individual carbon footprints.
- Dishes with food residues are known to attract germs if left uncleaned. Traditional dishwashers are typically turned on only when they are loaded to full capacity. In comparison, Dishcare cleans soiled dishes in real-time immediately after drop-off. Dishcare therefore has the potential to keep kitchens cleaner than ever before, thus promoting health and wellbeing of people in homes & offices.
- Dishcare launched its 'Inviting Doers of all Ages' program, where users can help annotate and identify dish types in multiple scenarios. This not only takes advantage of crowdsourcing to train Dishcare's machine learning models but also inspires people of all ages and backgrounds to participate in an enjoyable educational activity.
- Dishcare's proposed robotic end-effector capable of handling a variety of dish types has the potential to pave the way for other consumer robotic solutions that can handle other chores

around the household. This disruptive technology can save significant time and energy and improve the general quality of life for every individual. Furthermore, Dischare's success will demonstrate how robots can be crafted to help with something as fragile as dishes. This elegant principle could become the ethos of good design for the manner in which robots deliver services to people in the days ahead.