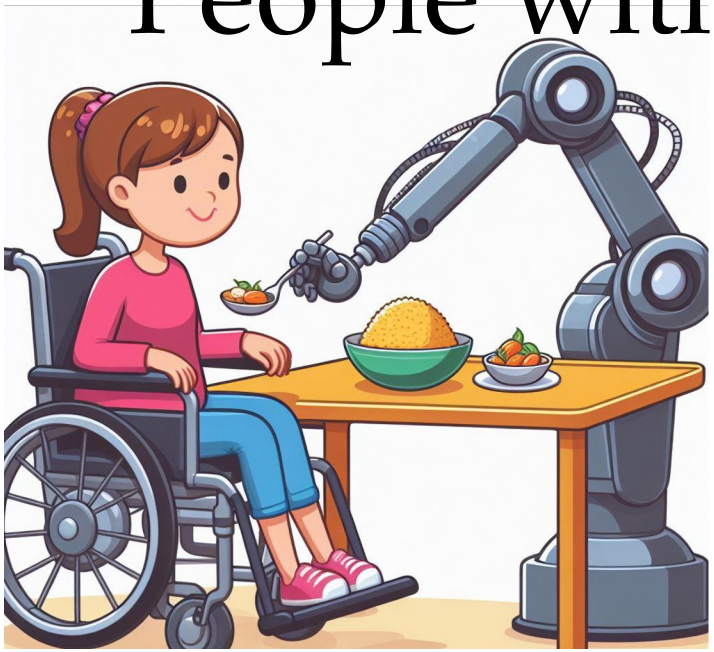
Achieving Deployable Autonomy in Robot-assisted Feeding for People with Motor Impairments



Amal Nanavati

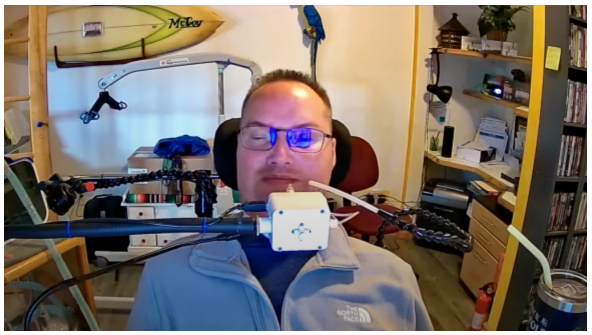
General Exam, 12-08-2023
Joint work with Sidd and Maya

UNIVERSITY of WASHINGTON

Think about a recent **enjoyable meal** experience.

What made it **meaningful**?

"Sometimes I wait little longer to ask [my caregiver] for a bite or a drink because it might mess up a conversation. It's definitely something that's always in the back of my mind while eating socially... Sometimes I find that I'm not eating or barely eating at all because I'm a little self-conscious of interrupting a conversation." (P2)

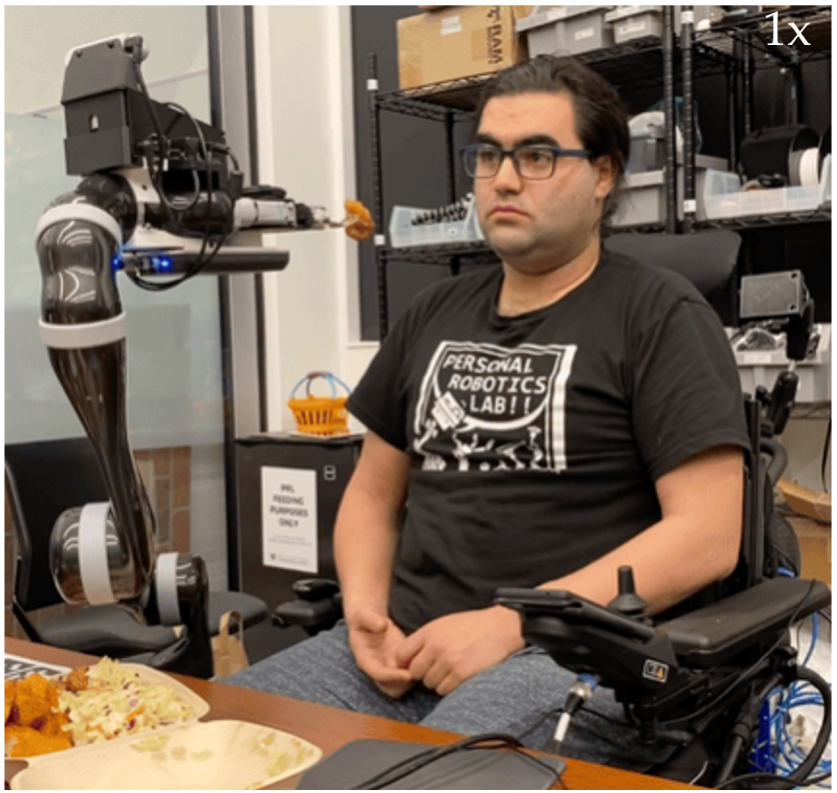


1.8 million Americans need assistance eating*

* as of 2010

Theis, Kristina A., et al. "Which one? What kind? How many? Types, causes, and prevalence of disability among US adults." *Disability and health journal*. (2019)

Deployable Robot-assisted Feeding (RAF)



generalize across users

usable without researcher intervention

generalize across environments

How can we develop a deployable robot-assisted feeding system that can feed any* user, in any* environment, a meal of their choice†, while aligning with their preferences?

customized

generalize across foods

* "any" = North Star. Demonstrate it with "multiple"

† that can be acquired with a single arm using a fork

Roadmap

1. Motivation
2. Robot-assisted Feeding Overview
3. RQ1: Users' Needs Assessment [Completed]
4. RQ2: Generalizing Bite Acquisition [Completed]
5. RQ3: Developing a Deployable System [Ongoing]
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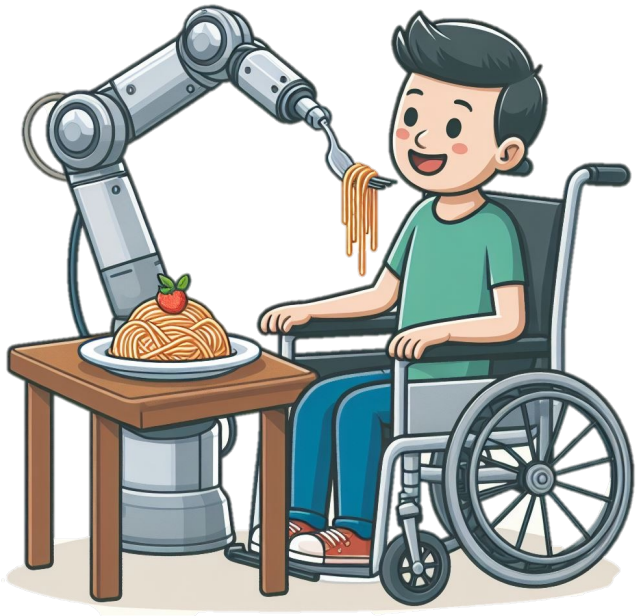
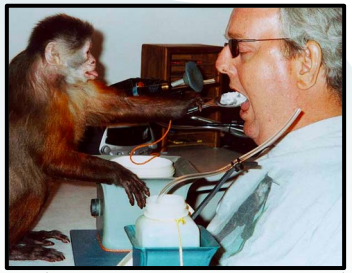


Self-feeding has been a research goal since the 1970s

Commercial

1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Research



monkey service animals, 1977

Hien, Emmanuelle, and Bertrand L. Deputte. "Influence of a capuchin monkey companion on the social life of a person with quadriplegia: an experimental study." *Anthrozoös*. (1997)

Envisioning Access: Our Past

Self-feeding has been a research goal since the 1970s

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1970s | 1980s | 1990s | 2000s | 2010s | 2020s

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Morewood Spoon Lifter, 1974

monkey service animals, 1977

Philips, G. N. "Feasibility Study for Assistive Feeder". *Southwest Research Institute*. (1986)

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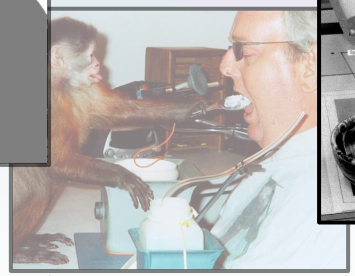

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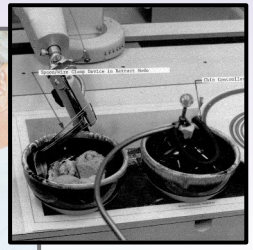
Robot Arm Worktable, 1986



Seamone, W., and G. Schmeisser. "Early clinical evaluation of a robot arm/worktable system for spinal-cord-injured persons." *Journal of rehabilitation research and development* (1985)

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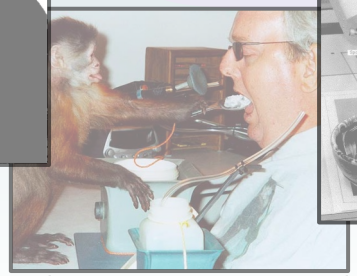

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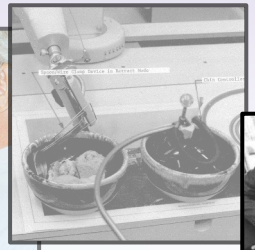


Handy 1, 1987

Topping, Mike. "An overview of the development of Handy 1, a rehabilitation robot to assist the severely disabled." *Artificial Life and Robotics* (2000)

1970s-80s: Deployments & Clinical Evaluations

The staff reported that most individuals who were shown the original spoon lifter were negative towards gadgets and preferred to have someone feed them. However, one C_4 level quadriplegic subject was able to functionally feed himself a complete meal using the device. This subject requested permission to take the device home, and arrangements were made for him to do so. He continued to use it in the home situation for almost three years. This individual found it necessary to put Reston Foam under the front of the head band to relieve the pressure against his forehead and to help to keep the head band from slipping. The staff at this center made the initial suggestions that were incorporated in the modified feeder, and this subject's spoon lifter was modified. The staff also reported that the subject had to have good trunk balance in order to use the feeder and that the motor would stall if food was stuck to the bottom of the spoon.

Morewood Spoon Lifter (1970s):

- 16 veterans with spinal cord injuries
- 3 year home deployment

Progress—Through December 1984, 20 male quadriplegics between 21 and 60 years of age at evaluation had been involved in the evaluation in three geographical areas, i.e., Baltimore-Washington, Richmond, and Cleveland. They ranged from five to 26 years between time of injury and evaluation. The levels of injury ranged from C-2 to C-5. Individual accumulations of time actually working with the equipment ranged from one hour to over 100 hours; 316 meals were eaten by these individuals using the Robot Arm. Among the nine quadriplegics who tested the equipment at the Richmond VAMC, seven indicated that they found the equipment gratifying to use, especially for self-feeding. Among the seven

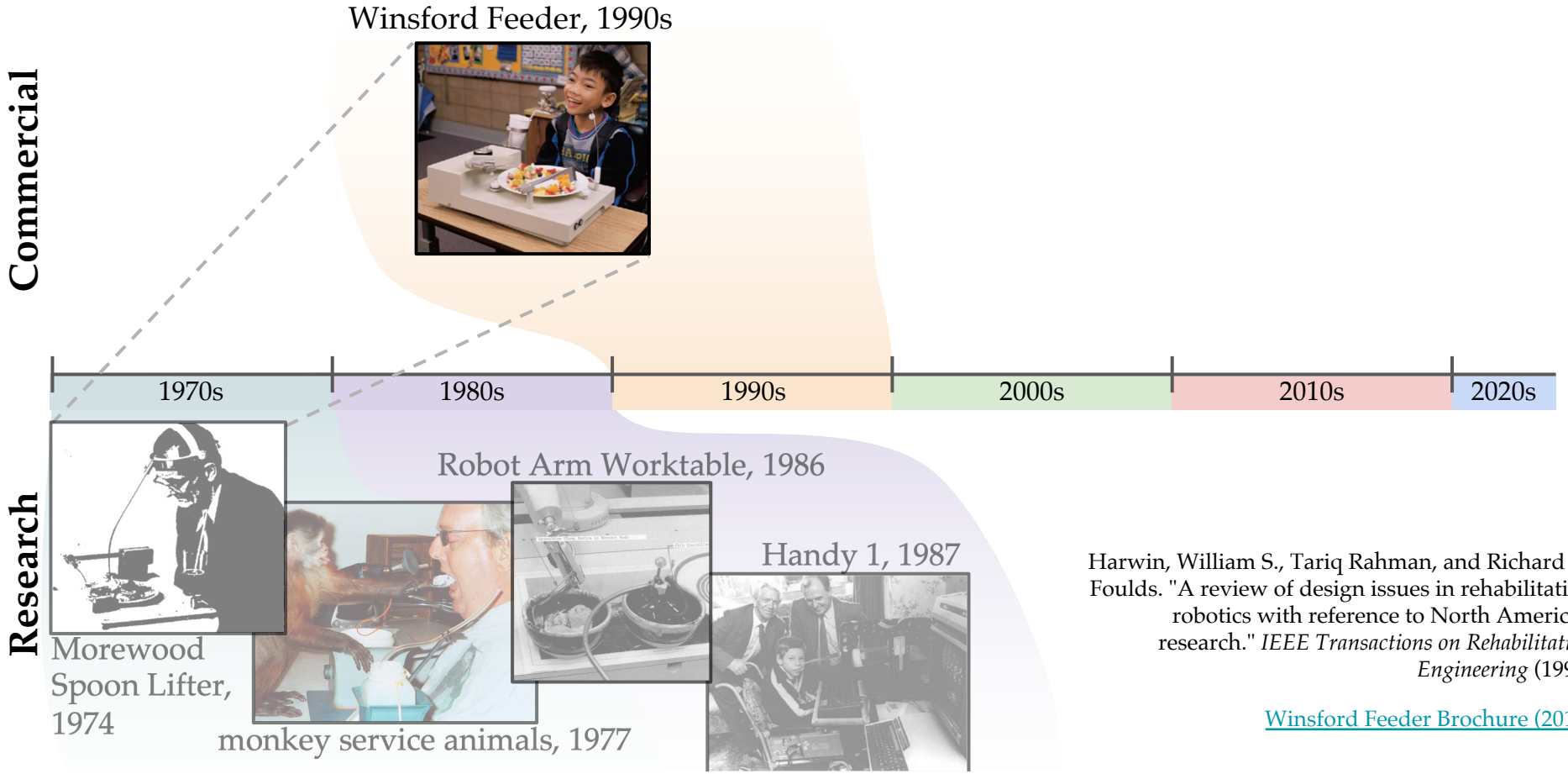
Robot Arm Worktable (1980s):

- 20 people with quadriplegia
- Environments: family home, nursing home, hospital
- As long as 1 year of use

Seamone, W., and G. Schmeisser. "Early clinical evaluation of a robot arm/worktable system for spinal-cord-injured persons." *Journal of rehabilitation research and development* (1985)

Philips, G. N. "Feasibility Study for Assistive Feeder". *Southwest Research Institute*. (1986)

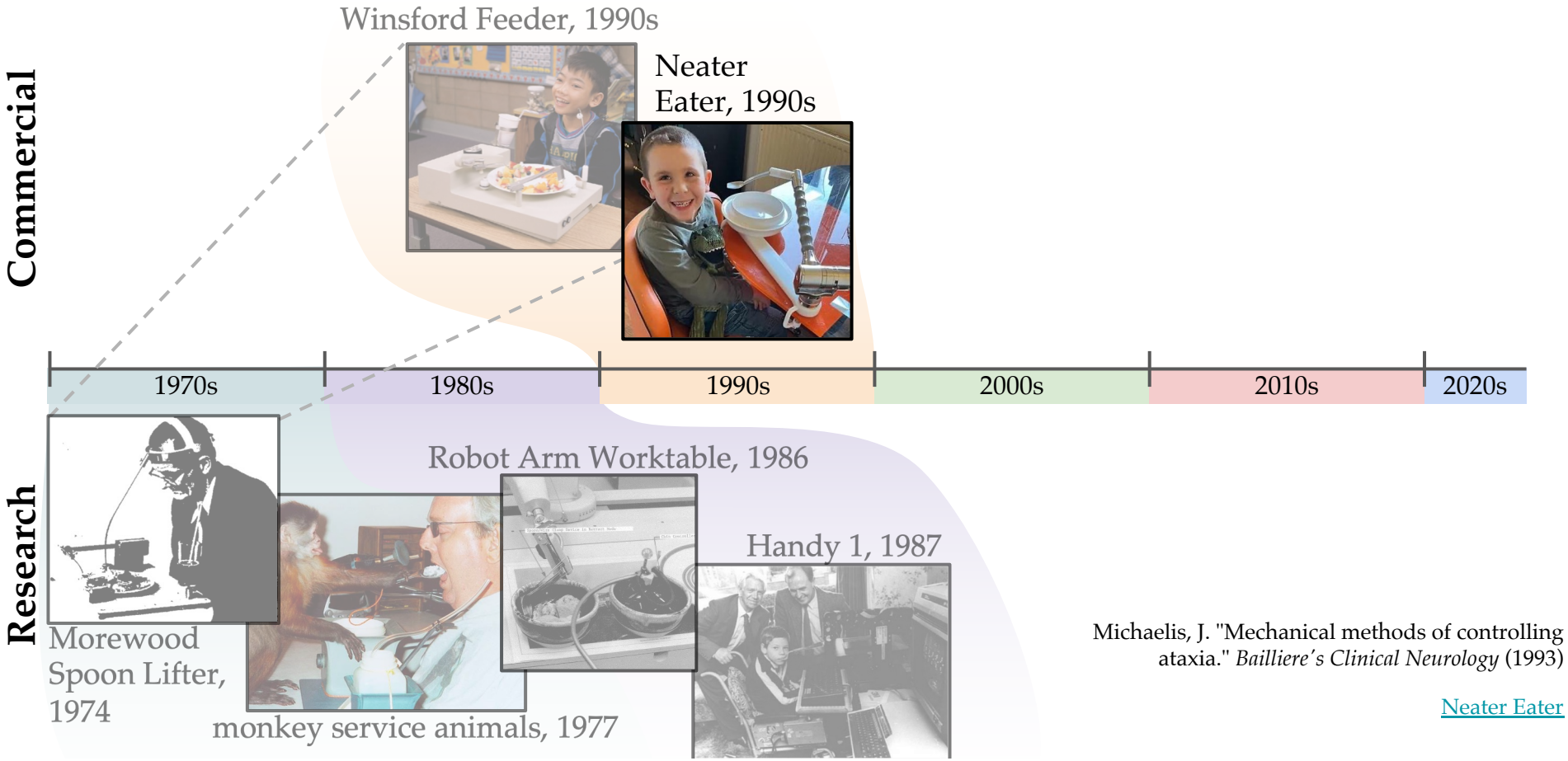
Commercial translation in 1990s-2000s



Harwin, William S., Tariq Rahman, and Richard A. Foulds. "A review of design issues in rehabilitation robotics with reference to North American research." *IEEE Transactions on Rehabilitation Engineering* (1995)

Winsford Feeder Brochure (2011)

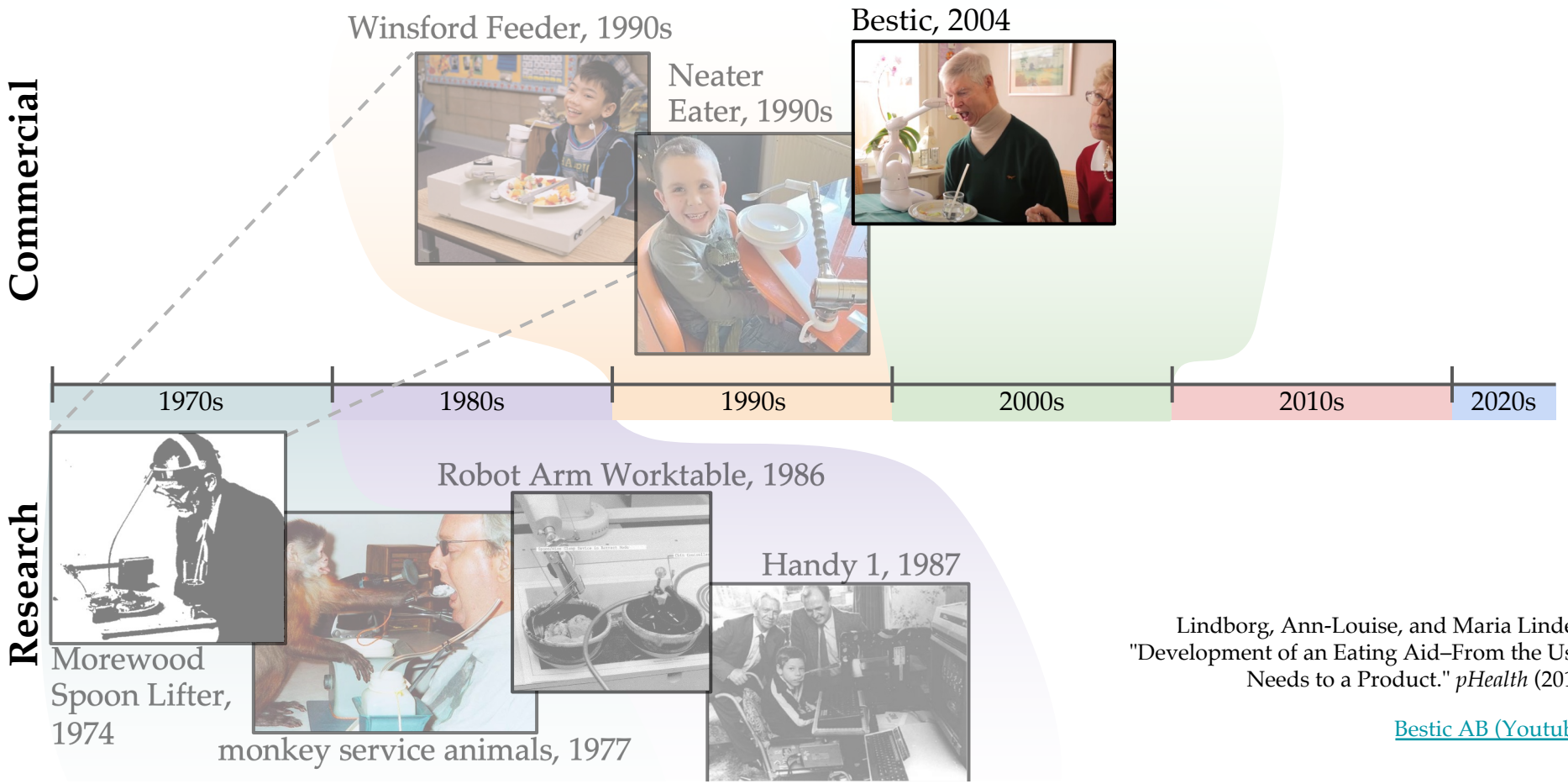
Commercial translation in 1990s-2000s



Michaelis, J. "Mechanical methods of controlling ataxia." *Bailliere's Clinical Neurology* (1993)

Neater Eater

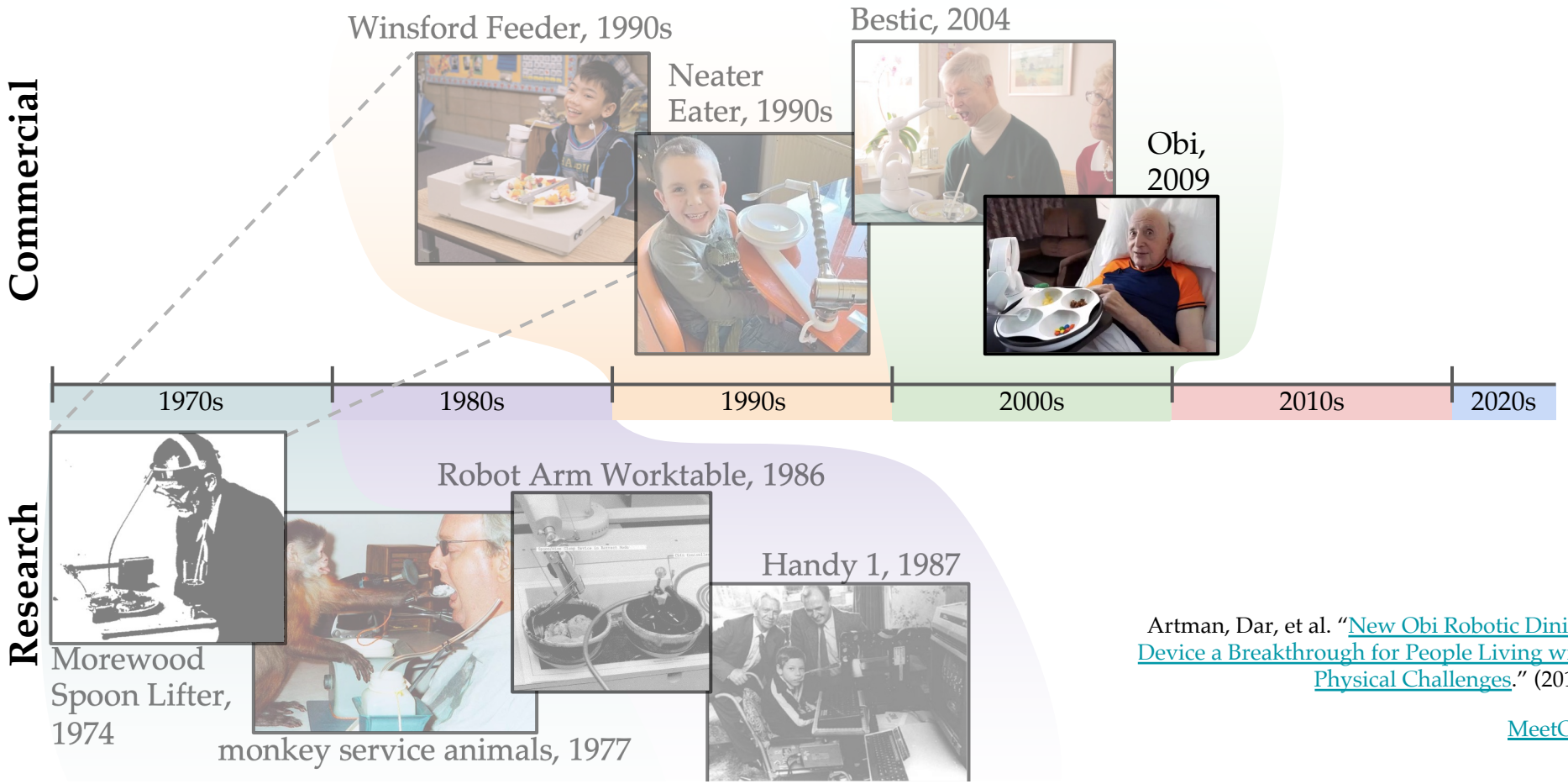
Commercial translation in 1990s-2000s



Lindborg, Ann-Louise, and Maria Lindén. "Development of an Eating Aid–From the User Needs to a Product." *pHealth* (2015)

Bestic AB (Youtube)

Commercial translation in 1990s-2000s



Artman, Dar, et al. "New Obi Robotic Dining Device a Breakthrough for People Living with Physical Challenges." (2016)

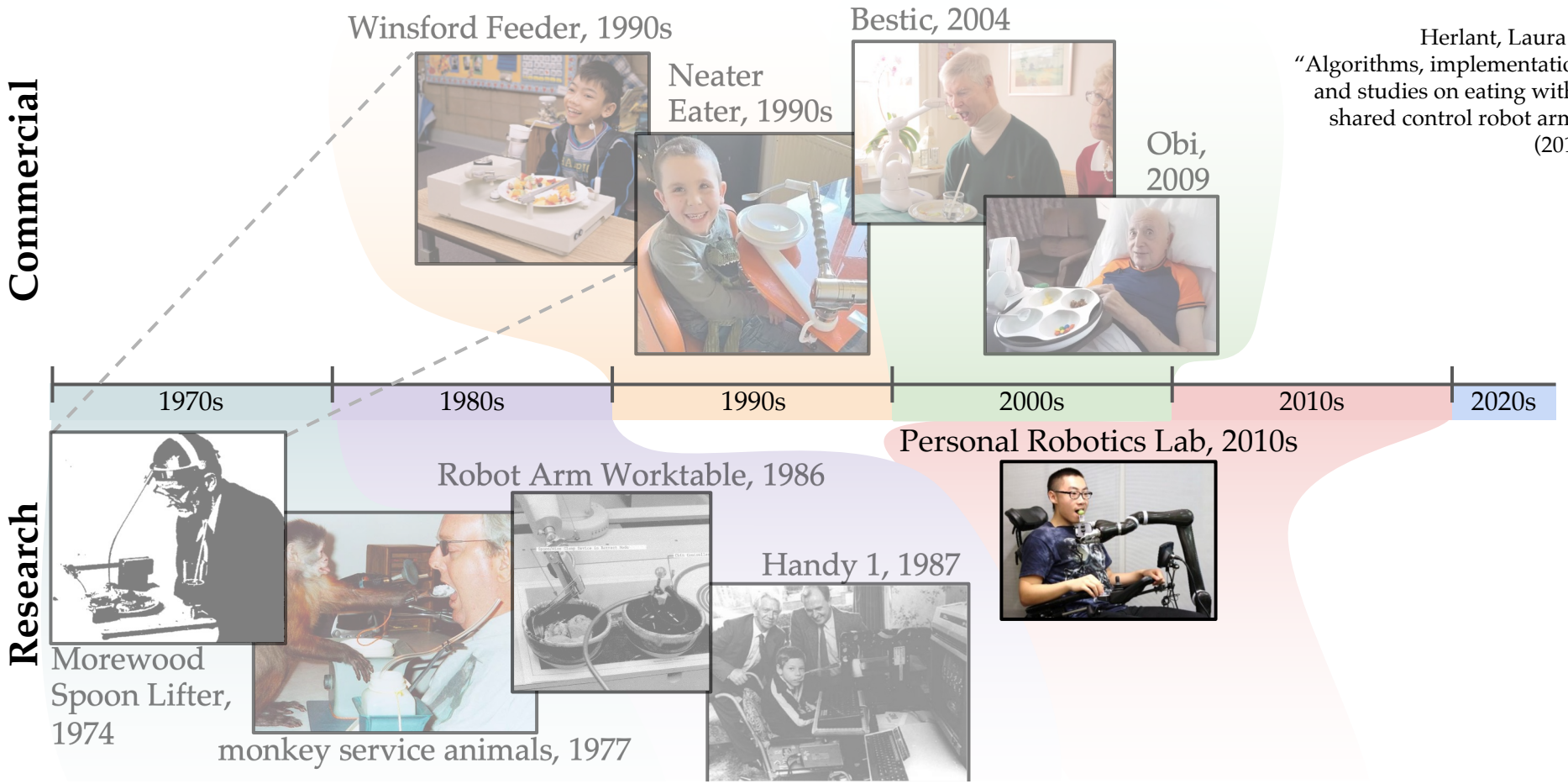
MeetObi

1990s-2000s: Is Robot-Assisted Feeding Solved?

- Strengths of Commercial Systems*:
  - Independently eating a full meal
  - Increased feelings of confidence
  - Improved posture
- Shortcomings of Commercial Systems*:
  - Only able to acquire limited foods
  - Acquiring too little food
  - Dropping food
  - Requiring users to hold head in stationary position
- All but Obi and Neater Eater have been discontinued 😢

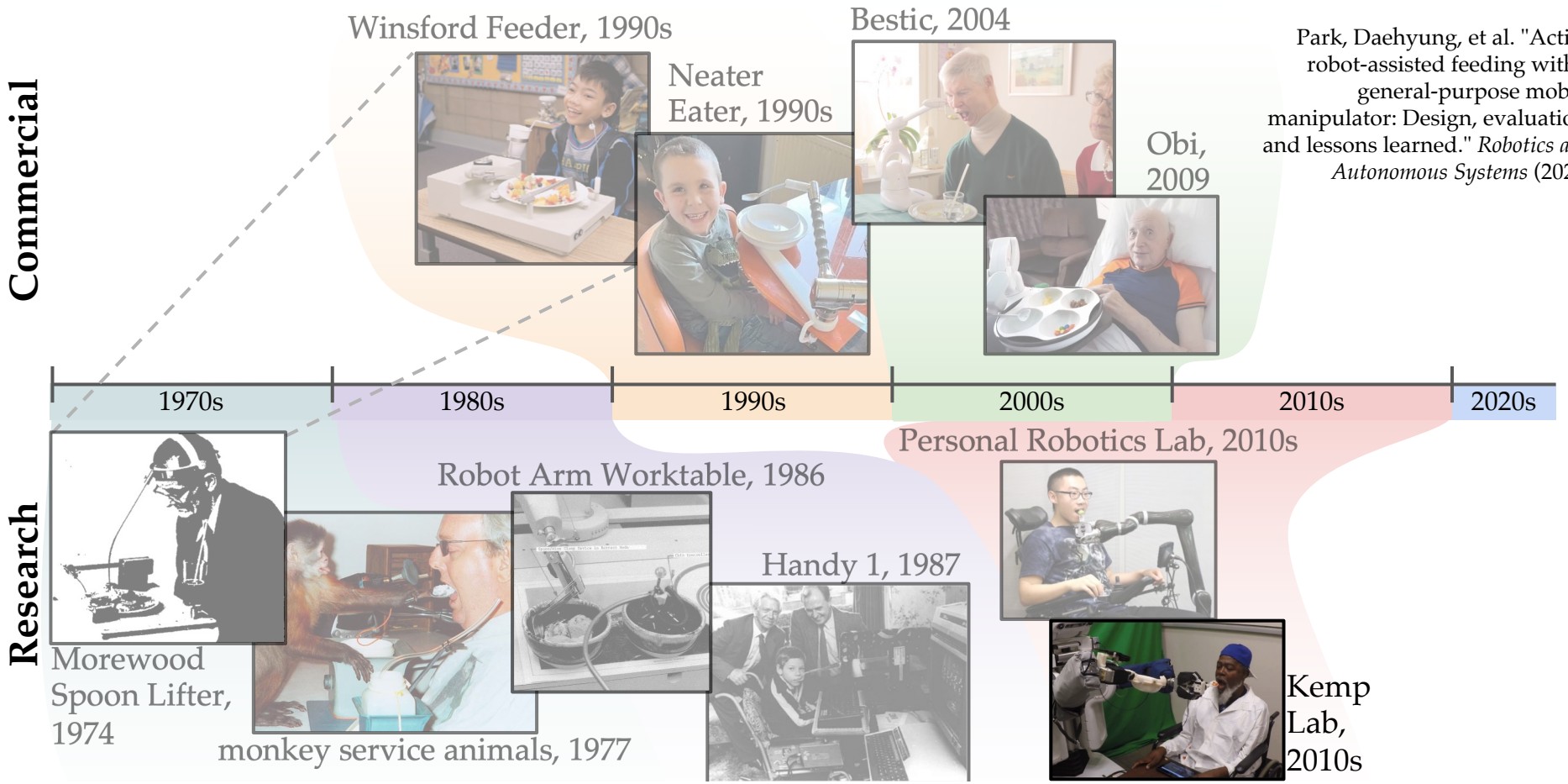
* citations in General exam document

Modern Robot-assisted Feeding Research, 2010s-



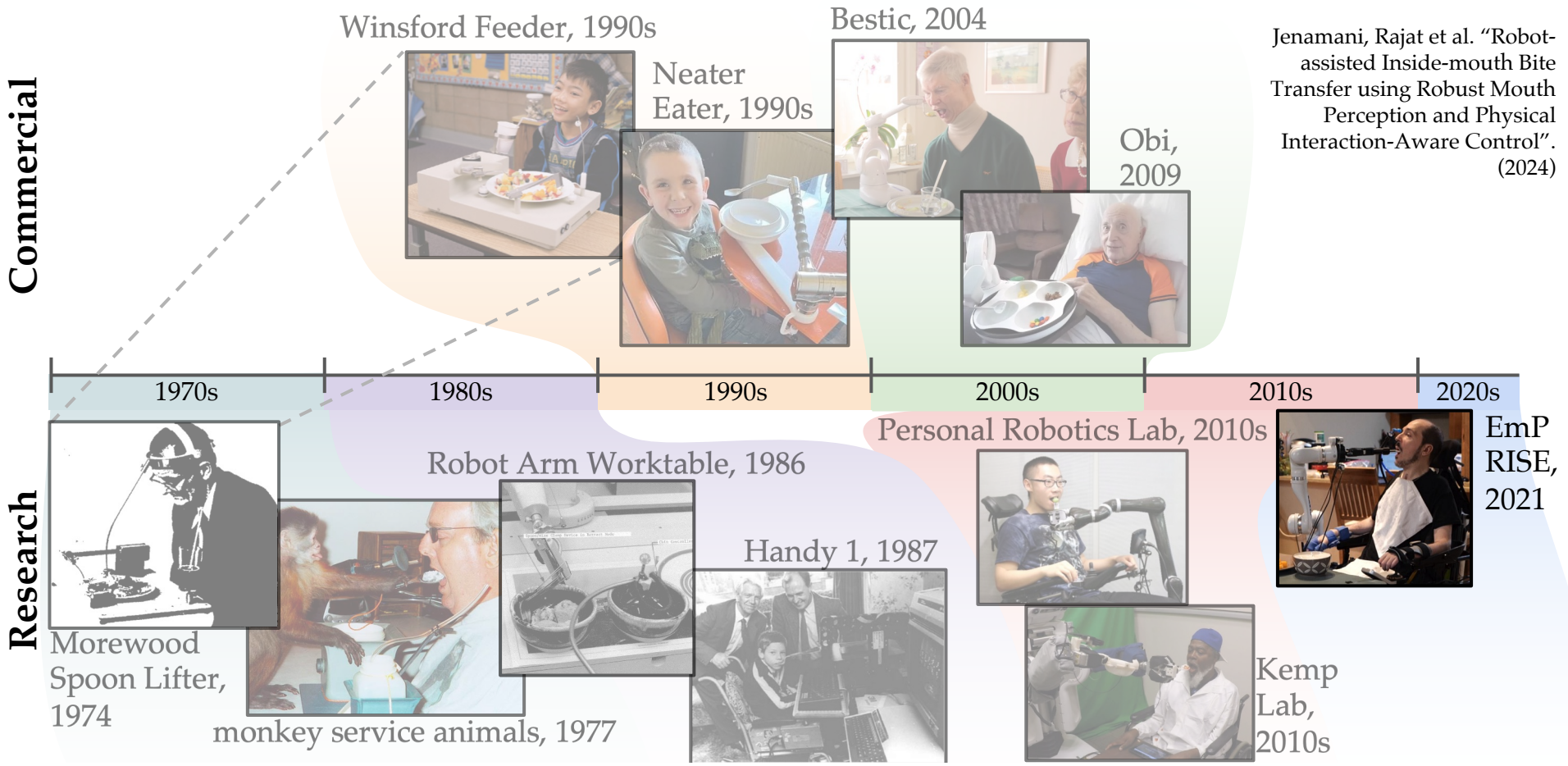
Herlant, Laura V. "Algorithms, implementation, and studies on eating with a shared control robot arm". (2016)

Modern Robot-assisted Feeding Research, 2010s-



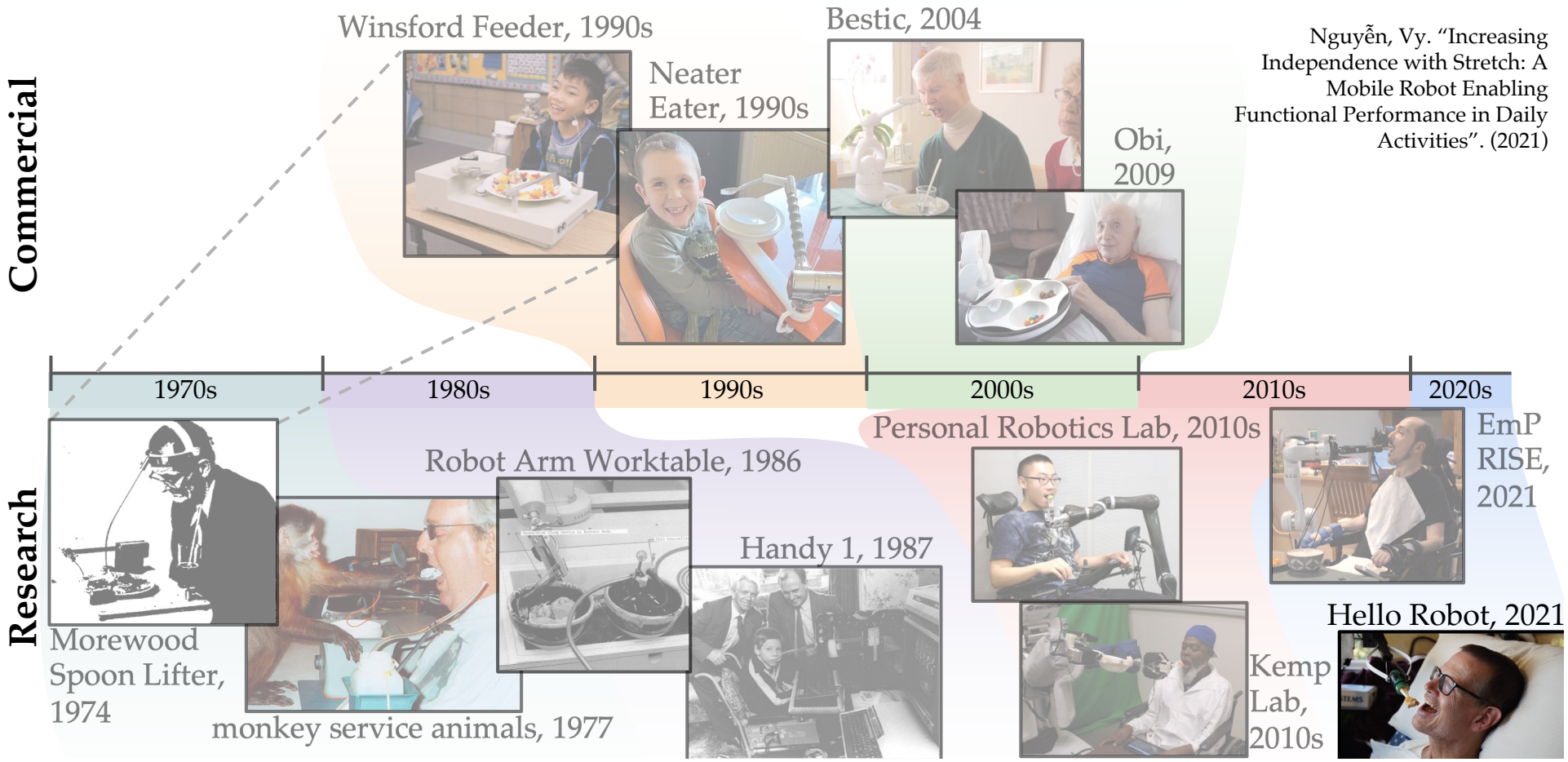
Park, Daehyung, et al. "Active robot-assisted feeding with a general-purpose mobile manipulator: Design, evaluation, and lessons learned." *Robotics and Autonomous Systems* (2020)

Modern Robot-assisted Feeding Research, 2010s-



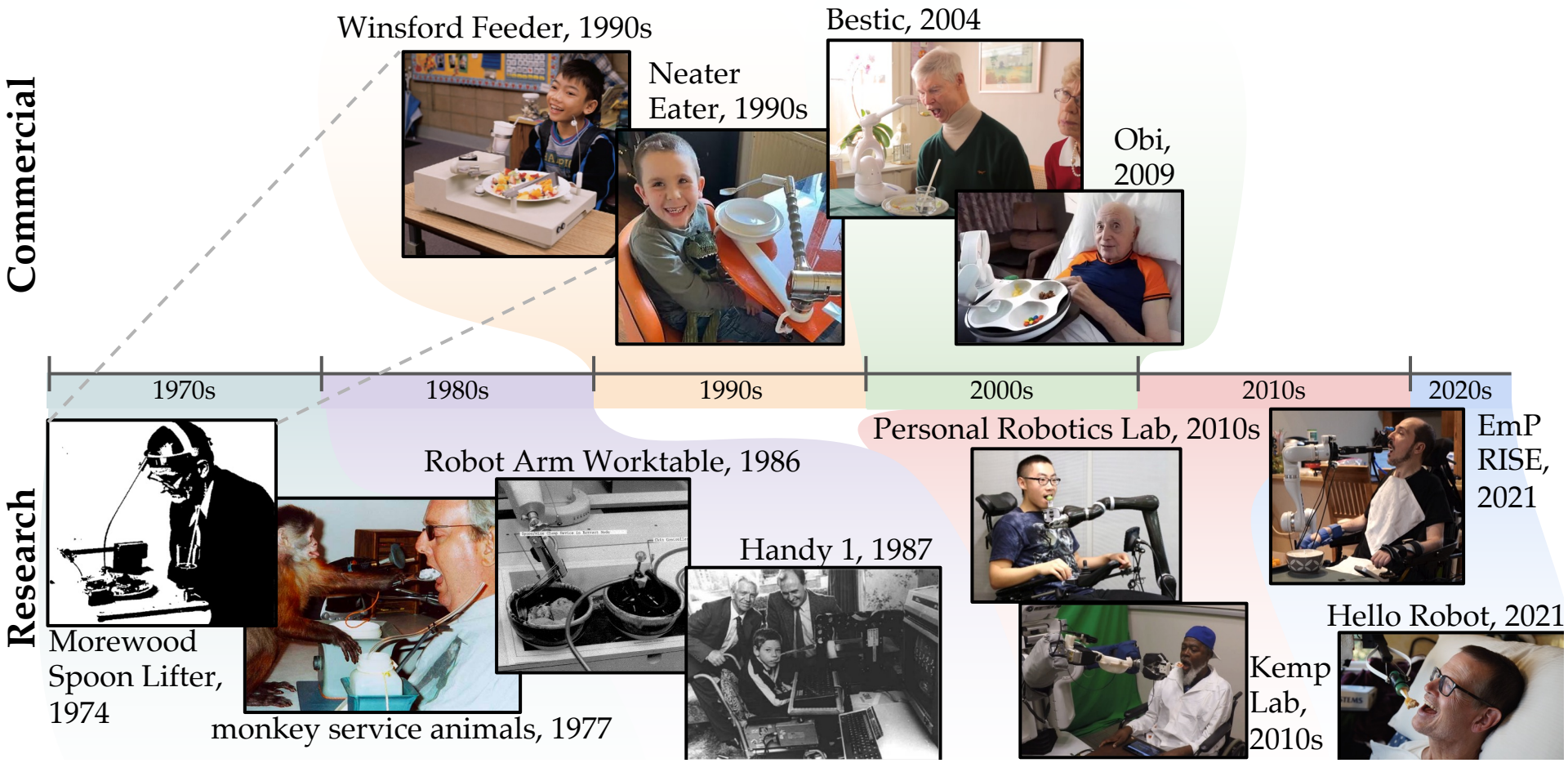
Jenamani, Rajat et al. "Robot-assisted Inside-mouth Bite Transfer using Robust Mouth Perception and Physical Interaction-Aware Control". (2024)

Modern Robot-assisted Feeding Research, 2010s-



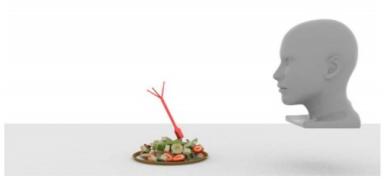
Nguyễn, Vy. "Increasing Independence with Stretch: A Mobile Robot Enabling Functional Performance in Daily Activities". (2021)

Modern Robot-assisted Feeding Research, 2010s-

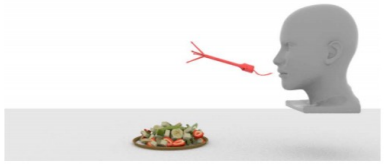


Our Robot-Assisted Feeding System

Bite Acquisition



Bite Transfer



Community-Based Participatory Research (CBPR)

Tyler Schrenk

- Entire research process is grounded in and accountable to community needs and priorities
- **Community Researchers**: equal team members throughout the process, from ideation to dissemination
- Academic & community researchers each bring unique skills, expertise, and **lived experience** to the table
- Learn from each other
- Long-term partnership

Israel, B. A., Schulz, A. J., Parker, E. A., & Becker, A. B. "Review of community-based research: assessing partnership approaches to improve public health". *Annual review of public health*. (1998)

Jonathan Ko

Roadmap

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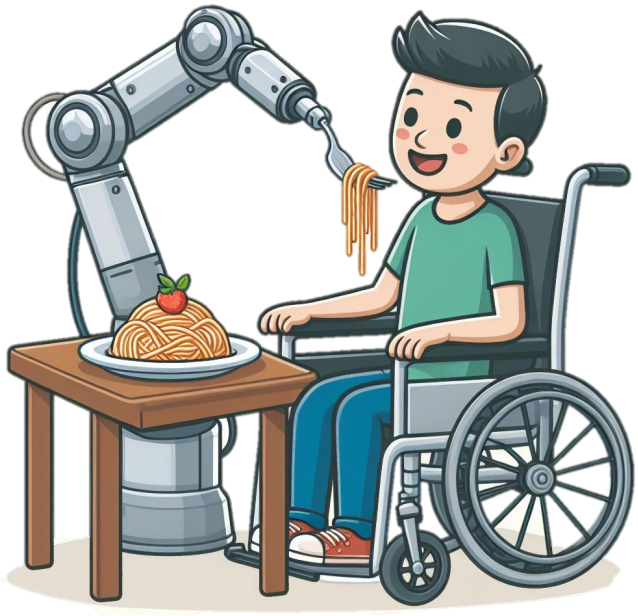
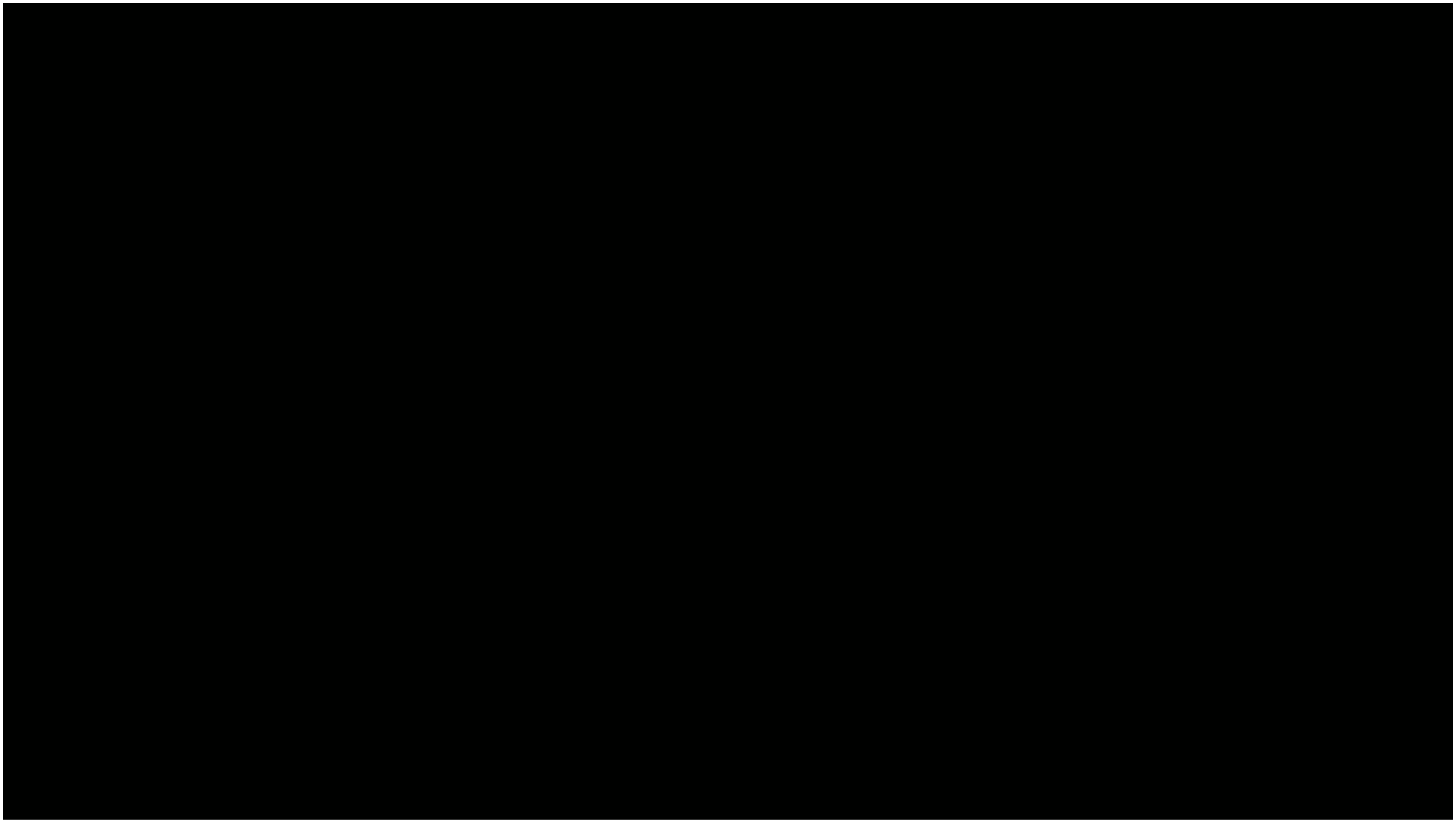


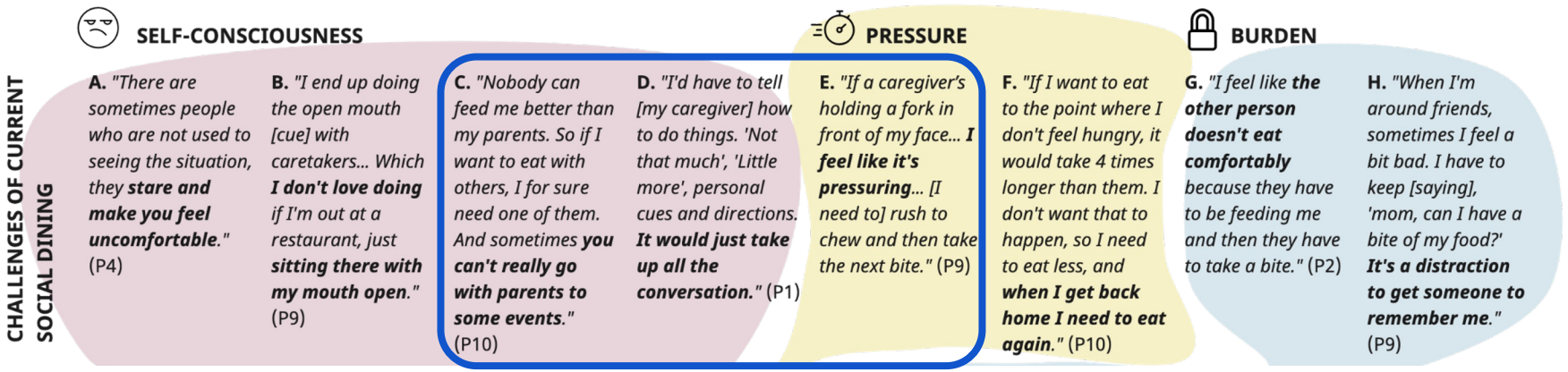
RQ1: What challenges do users face during (social) dining, and how can a robot-assisted feeding system address them?

Nanavati, Amal*, Alves-Oliveira, Patrícia*, et al. "Design principles for robot-assisted feeding in social contexts." *HRI*. (2023)

Method

- Remote, semi-structured interviews led by community researcher
- n=10 participants
- Study stages:
  - Discuss current dining routines
  - Watch social dining videos showcasing various robot features
  - Discuss participants' thoughts
- Thematically analyzed participant quotes





Caregiver Variability

Caregivers feed differently (e.g., bite size, eating pace, etc.)

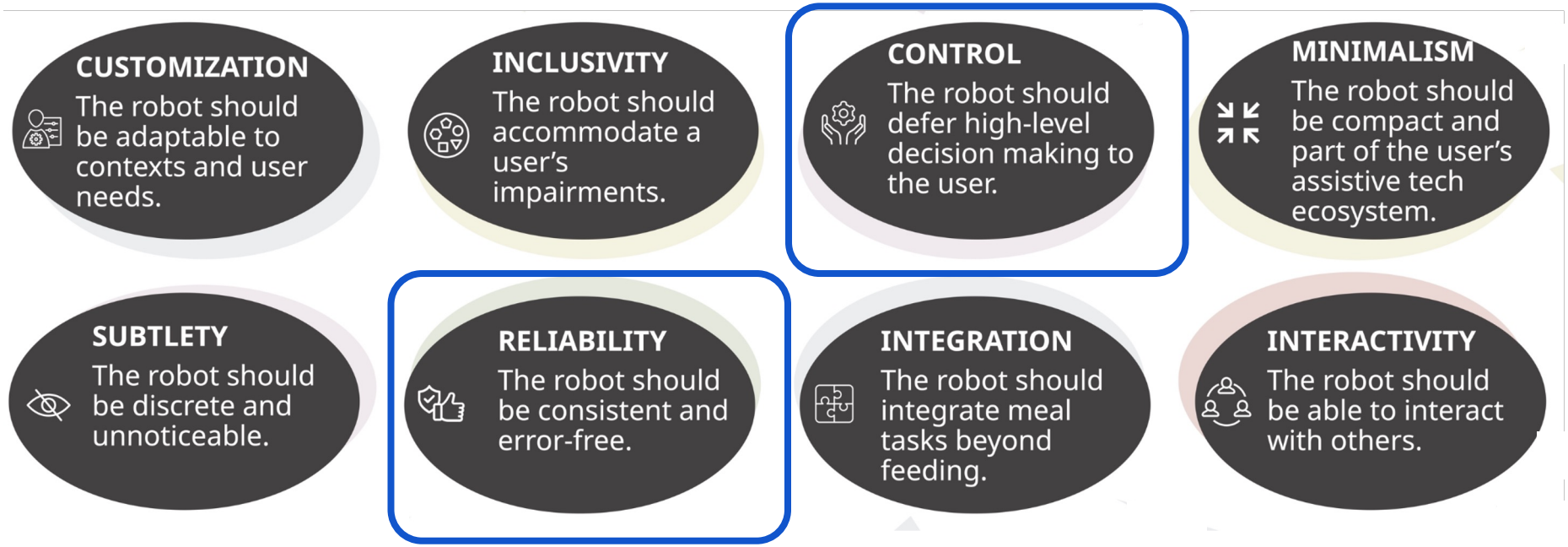
Participants feel self-conscious about interrupting a conversation to instruct their caregiver

Participants don't feel comfortable bringing some caregivers to some social interactions.

Participants want

consistent customization

Design Principles



Nanavati, Amal*, Alves-Oliveira, Patrícia*, et al. "Design principles for robot-assisted feeding in social contexts." *HRI*. (2023)

Design Principles: **Reliability**

A.

"If it can't get it on the first try, it's still on the plate, **[the food's] not on me**. If it drops it on the way that would be worse." (P1)

B.

"If it was at a soccer game where [my wife] was sitting next to me, the side-resting position could **be in her way, in front of her face**." (P8)

C.

"I want everyone to just see me, not **see me behind a feeding device**." (P9)

RELIABILITY

The robot should be consistent and error-free.

Design Principles: **Control**

D.

“When it's something as delicate as 'if this messes up I can get impaled,' it would be good to have a **backup safety mechanism**.” (P8)

E.

“I'm not too fond of [automatic bite initiation]. It's restrictive. By giving the robot the command, **you are controlling the robot**.” (P6)

F.

“For me, I don't mind the robot doing a lot of the thinking, with the exception of **selecting what food I eat**.” (CR)

CONTROL

The robot should defer high-level decision making to the user.

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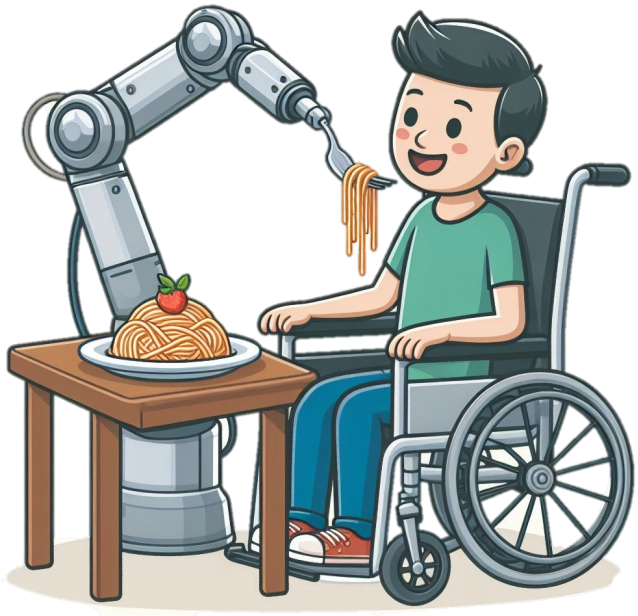


generalize across users

usable without researcher intervention

generalize across environments

How can we develop a deployable robot-assisted feeding system that can feed any* user, in any* environment, a meal of their choice†, while aligning with their preferences?

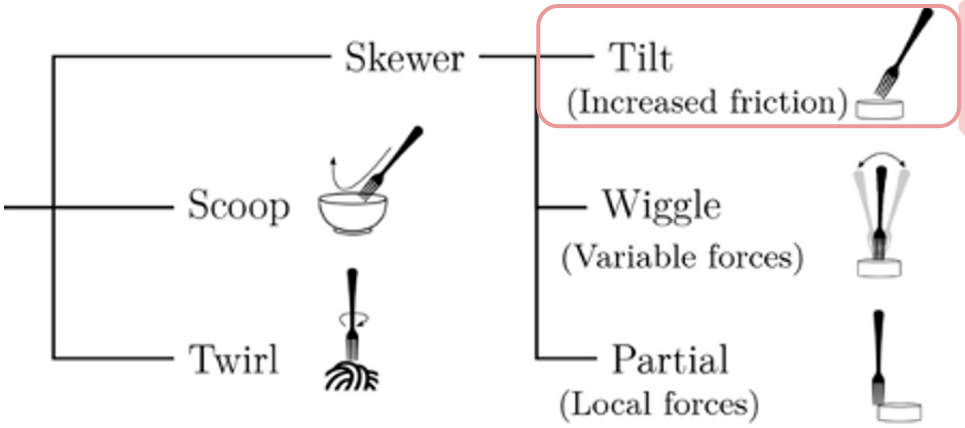
customized

generalize across foods

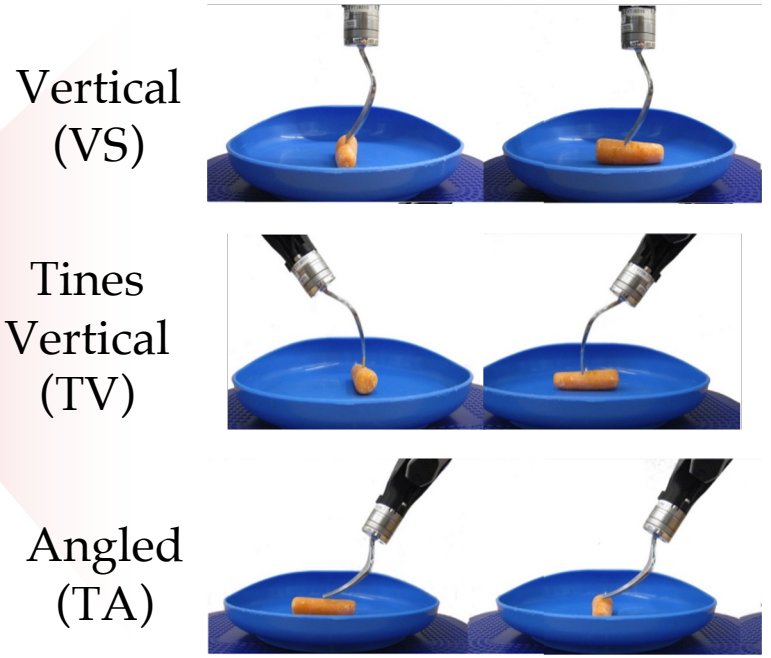
RQ2: How can a robot-assisted feeding system acquire the large variety of food items users may want to eat?

Gordon, Ethan K*, **Nanavati, Amal***, et al. "Towards General Single-Utensil Food Acquisition with Human-Informed Actions." *Conference on Robot Learning*. (2023)

Bite Acquisition: Past Work



Bhattacharjee, Tapomayukh, et al. "Towards robotic feeding: Role of haptics in fork-based food manipulation." *IEEE Robotics and Automation Letters* (2019)



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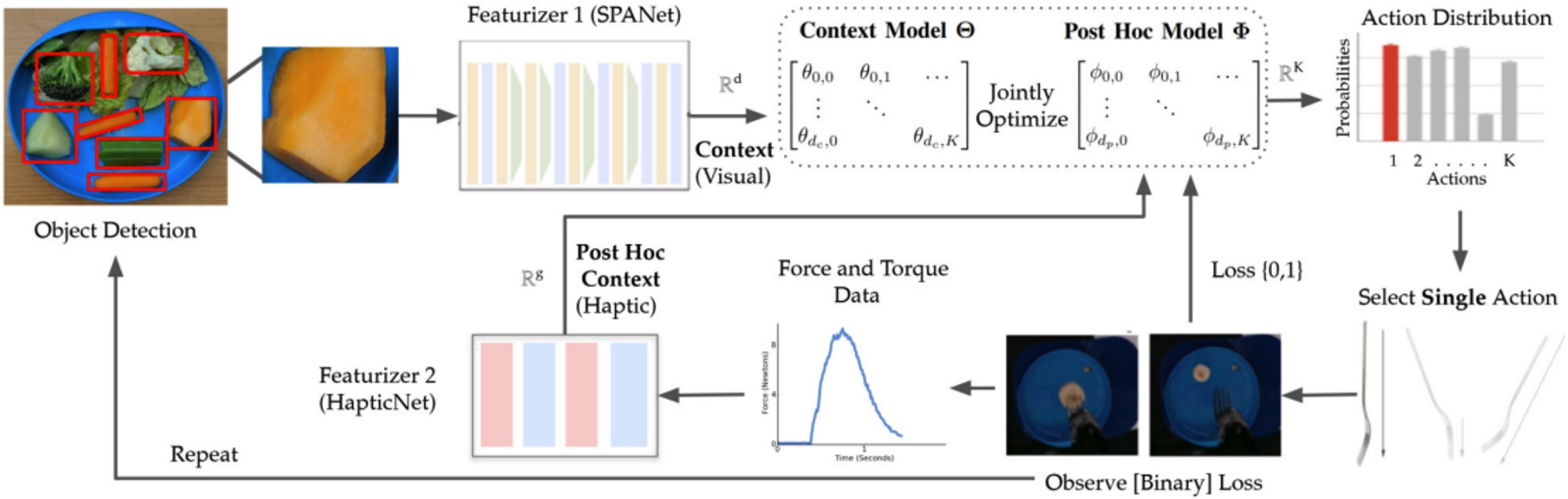
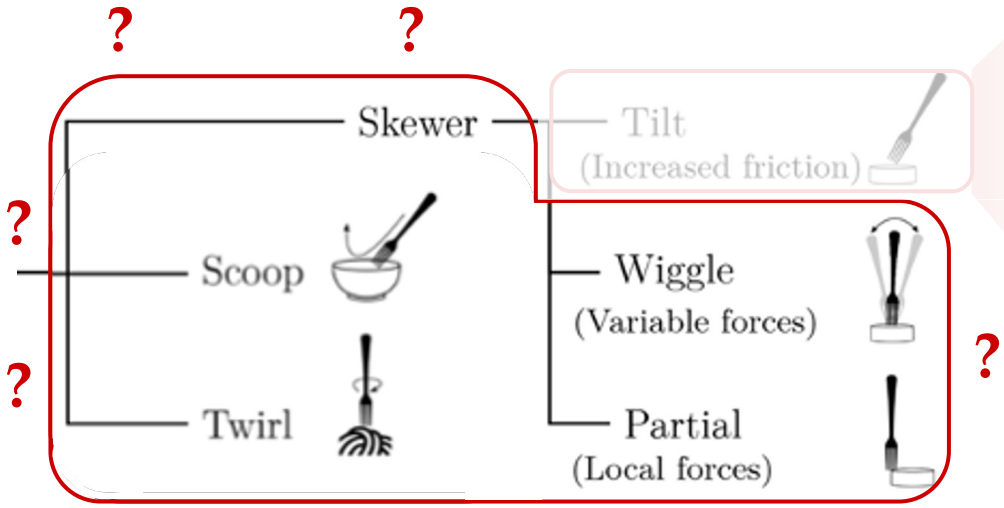
Bite Acquisition: Past Work



Gordon, Ethan K., et al. "Leveraging post hoc context for faster learning in bandit settings with applications in robot-assisted feeding." *IEEE International Conference on Robotics and Automation (ICRA)*. (2021)

Bite Acquisition: Past Work

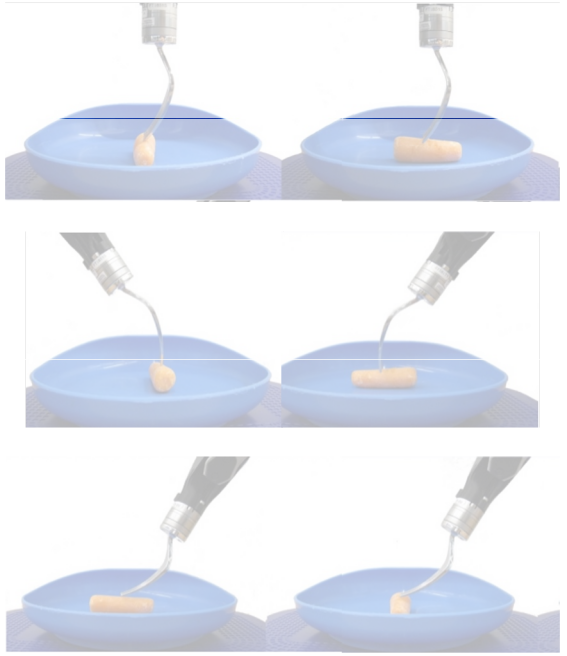


Bhattacharjee, Tapomayukh, et al. "Towards robotic feeding: Role of haptics in fork-based food manipulation." *IEEE Robotics and Automation Letters* (2019)

Vertical (VS)

Tines Vertical (TV)

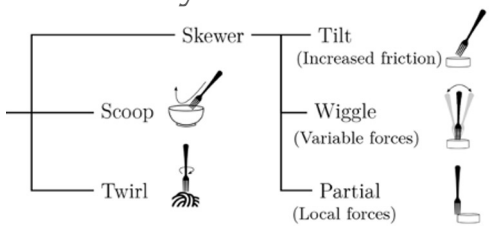
Angled (TA)

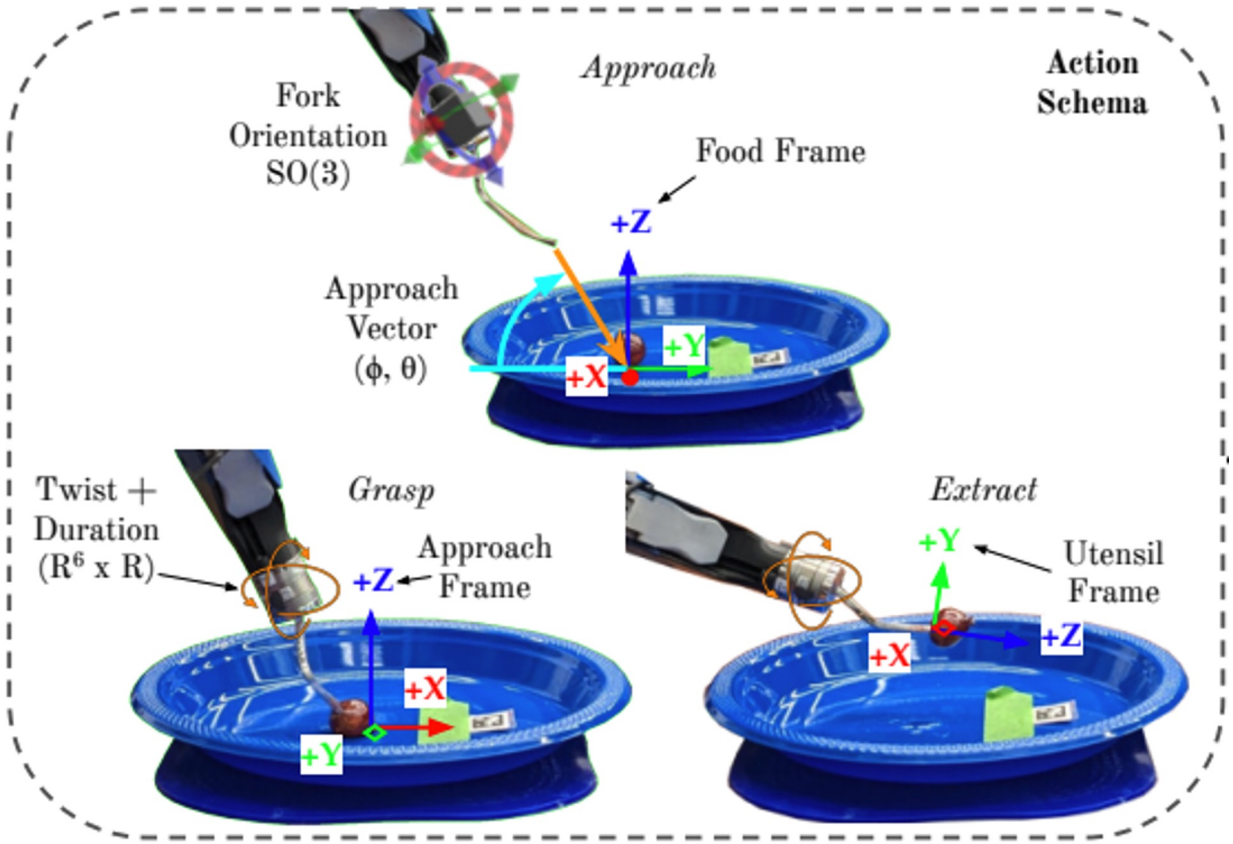


Feng, Ryan, et al. "Robot-assisted feeding: Generalizing skewering strategies across food items on a plate." *The International Symposium of Robotics Research*. (2019)

Representing Actions: Acquisition Schema

- 3 steps: Approach, Grasp, Extract
- 26 continuous parameters
- Encompasses entire taxonomy

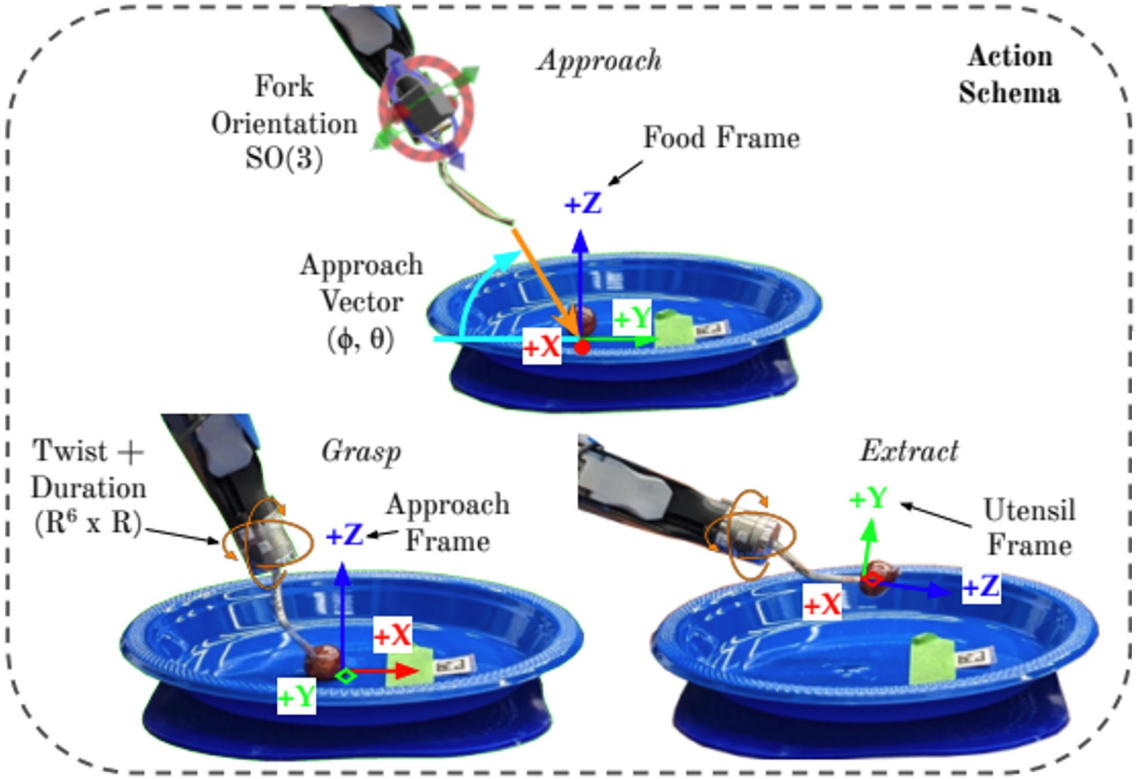




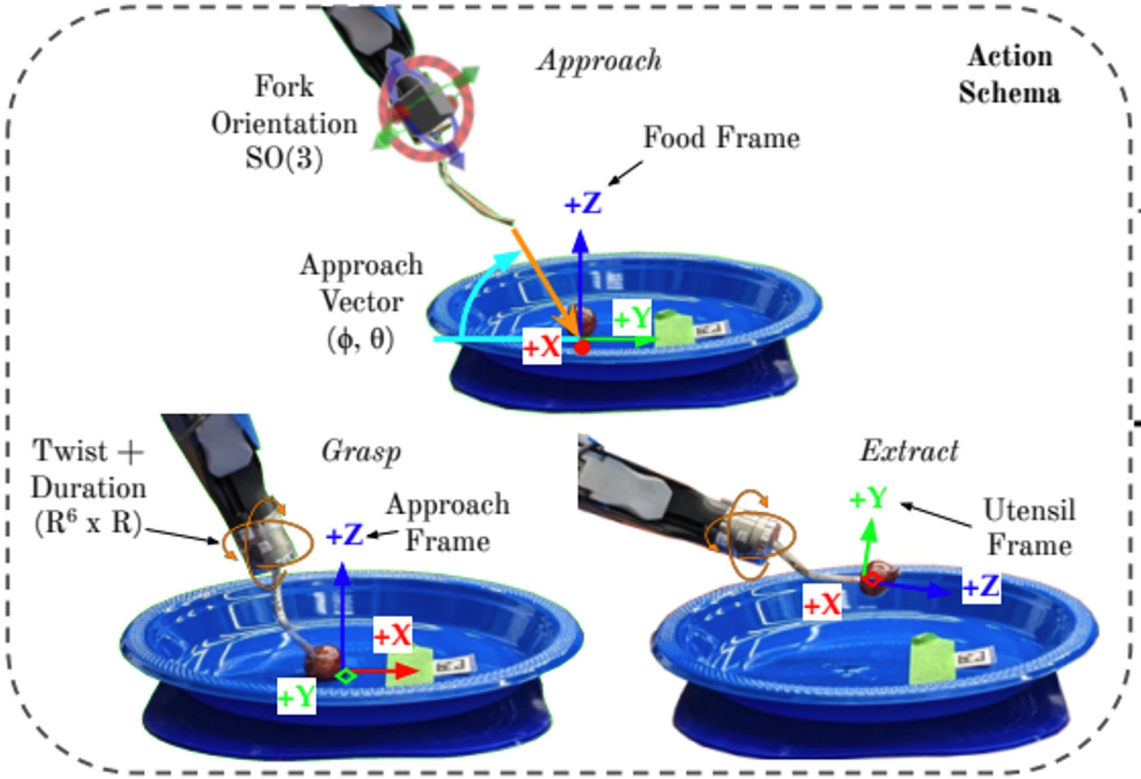
Learning Actions: From Human Data

- Users acquire 13 food items
    - e.g., mashed potatoes, chicken tenders, sandwich bites, jello, noodles, etc.
    - Foods a community researcher ate in a week.
- Capture motion & haptic data
- 496 acquisition trials

Learning Actions: From Human Data



Learning Actions: From Human Data



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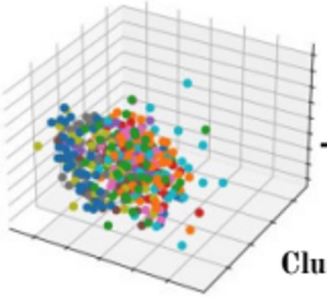
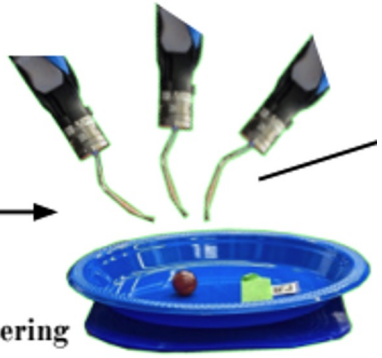
Schema Mapping



Discrete Action Space



k-medoids

Discrete Actions: Emergent Behavior

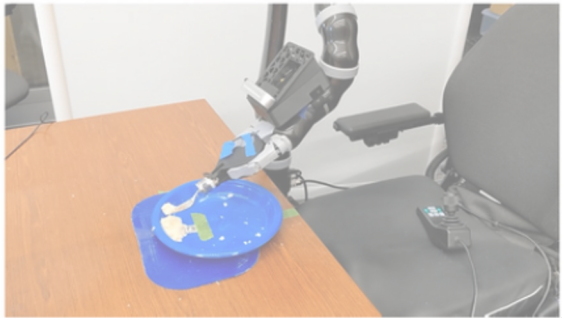
Scooping

Action 6; Potato

Discrete Actions: Emergent Behavior

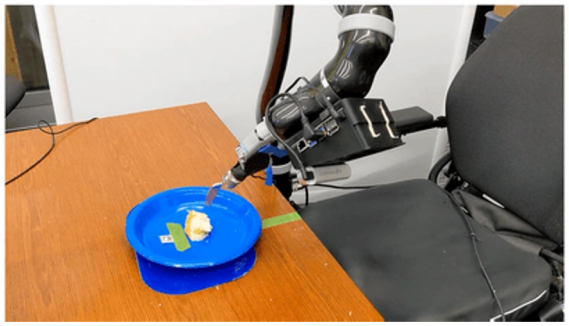
Scooping

Action 6; Potato



Tilted Tines for Higher Pressure

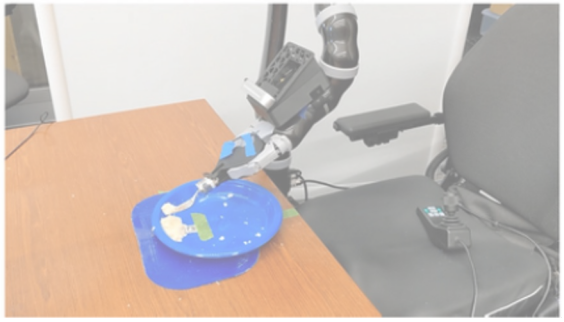
Action 10; Sandwich



Discrete Actions: Emergent Behavior

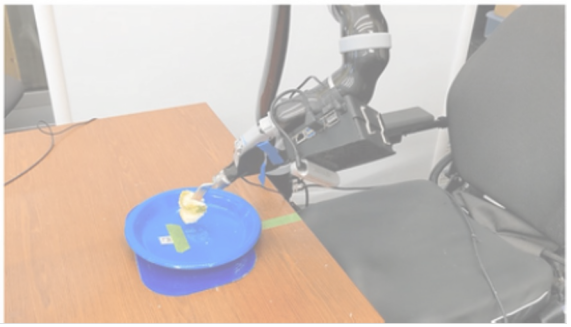
Scooping

Action 6; Potato



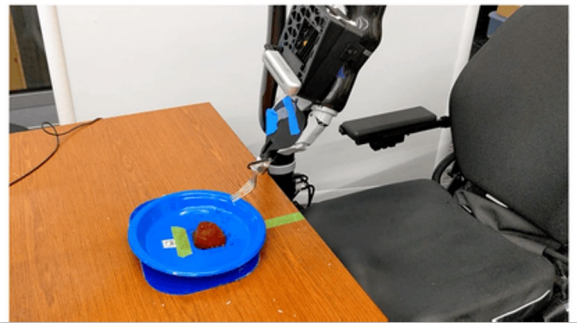
Tilted Tines for Higher Pressure

Action 10; Sandwich



Tilted Extraction

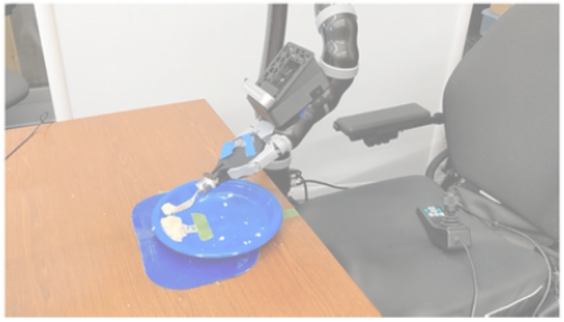
Action 8; Jello



Evaluating Actions

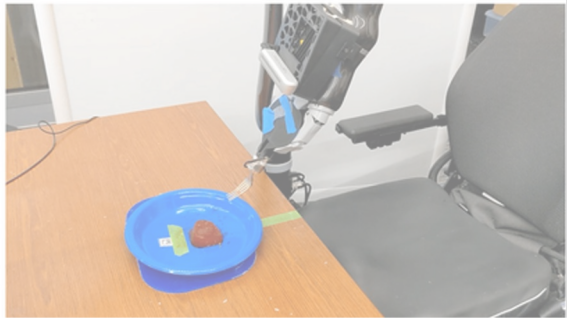
Action 6; Potato

Scooping



Action 8; Jello

Tilted Extraction

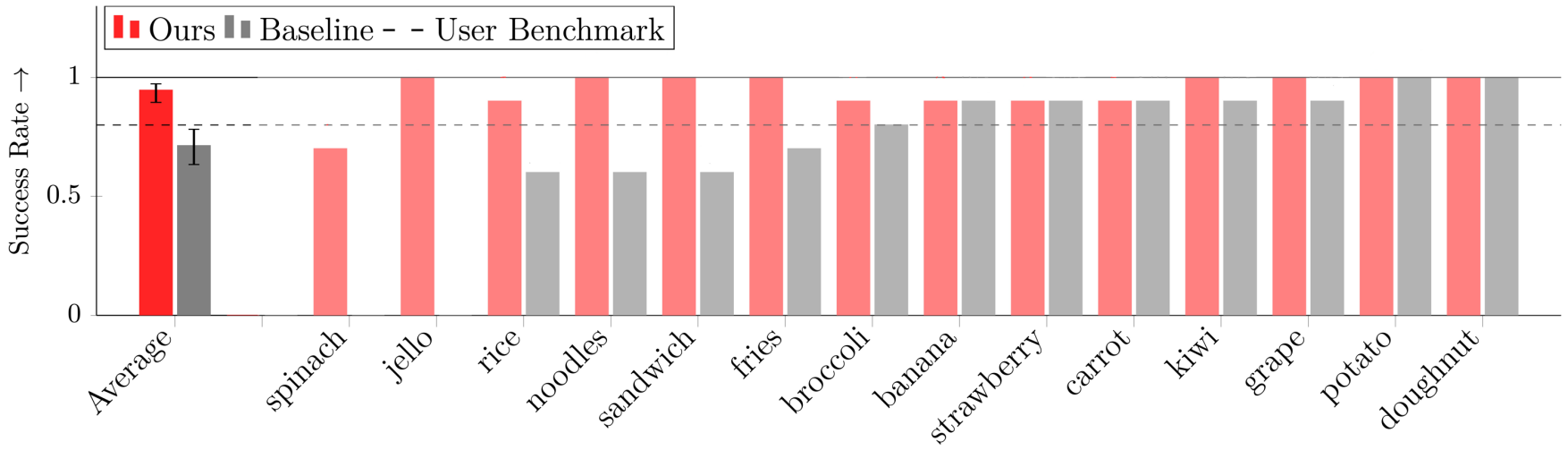


1. **Coverage**

2. **Learnability**

14 food items (9 unseen)

Evaluating Actions: Coverage

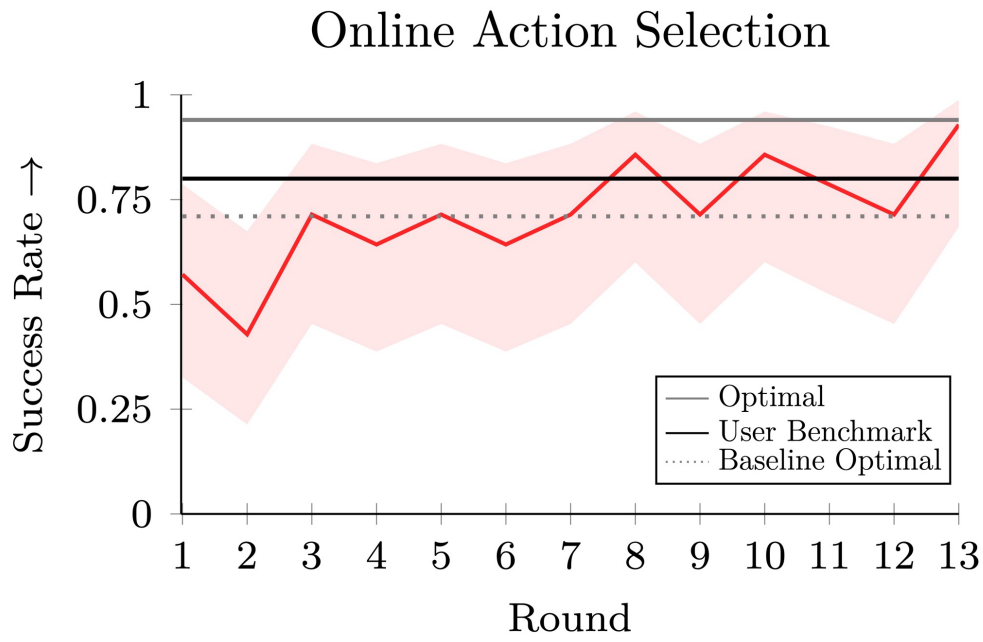


Coverage

For every food item, there exists an action that can acquire it with ≥ 80% success.

Bhattacharjee, Tapomayukh, et al. "Is more autonomy always better? exploring preferences of users with mobility impairments in robot-assisted feeding." *HRI*. (2020)

Evaluating Actions: Learnability



Error Bars: Wilson 95% confidence intervals

~30s / acquisition → learn optimal action in ~4m of pre-meal training!

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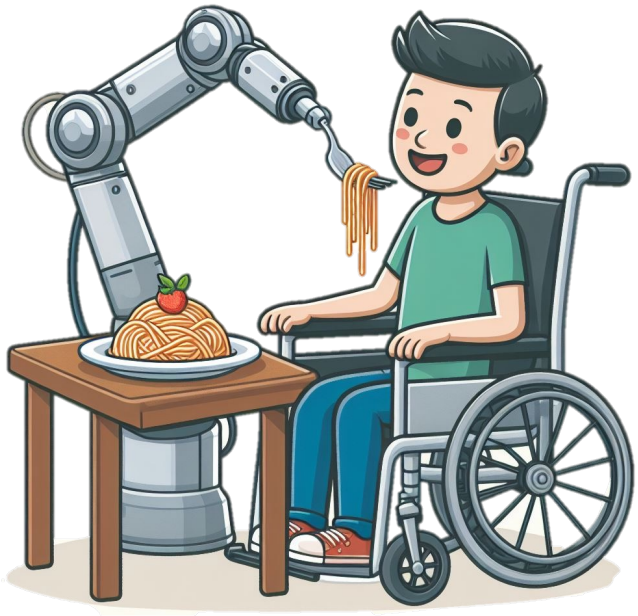


generalize across users

usable without researcher intervention

generalize across environments

How can we develop a deployable robot-assisted feeding system that can feed any* user, in any* environment, a meal of their choice†, while aligning with their preferences?

customized

generalize across foods

RQ3: How can we take a functional robot-assisted feeding system and make it deployable?

Why is “deployable” challenging?

Nominal Scenario:

everything – user, robot, and environment – proceeds according to plan.

Off-Nominal Scenario:

something – user, robot, or environment – does not proceed according to plan.

Firesmith, Donald. “The need to specify requirements for off-nominal behavior”. *CMU Software Engineering Institute Blog*. (2012)

Off-Nominals Scenarios in Robot-Assisted Feeding

User	Robot	Environment
User no longer wants bite	Robot collides with object	Food falls off the fork
User cannot eat (e.g., is coughing)	Robot fails to perceive bite	Plate moves (e.g., caregiver serves food)
User takes a partial bite	Robot fails to acquire bite	Local area network fails
User clicks unintended button	Robot stops far from face	Device running web app fails
…	…	…

The multitude & diversity of off-nominals makes it challenging to develop a deployable robot feeding system.

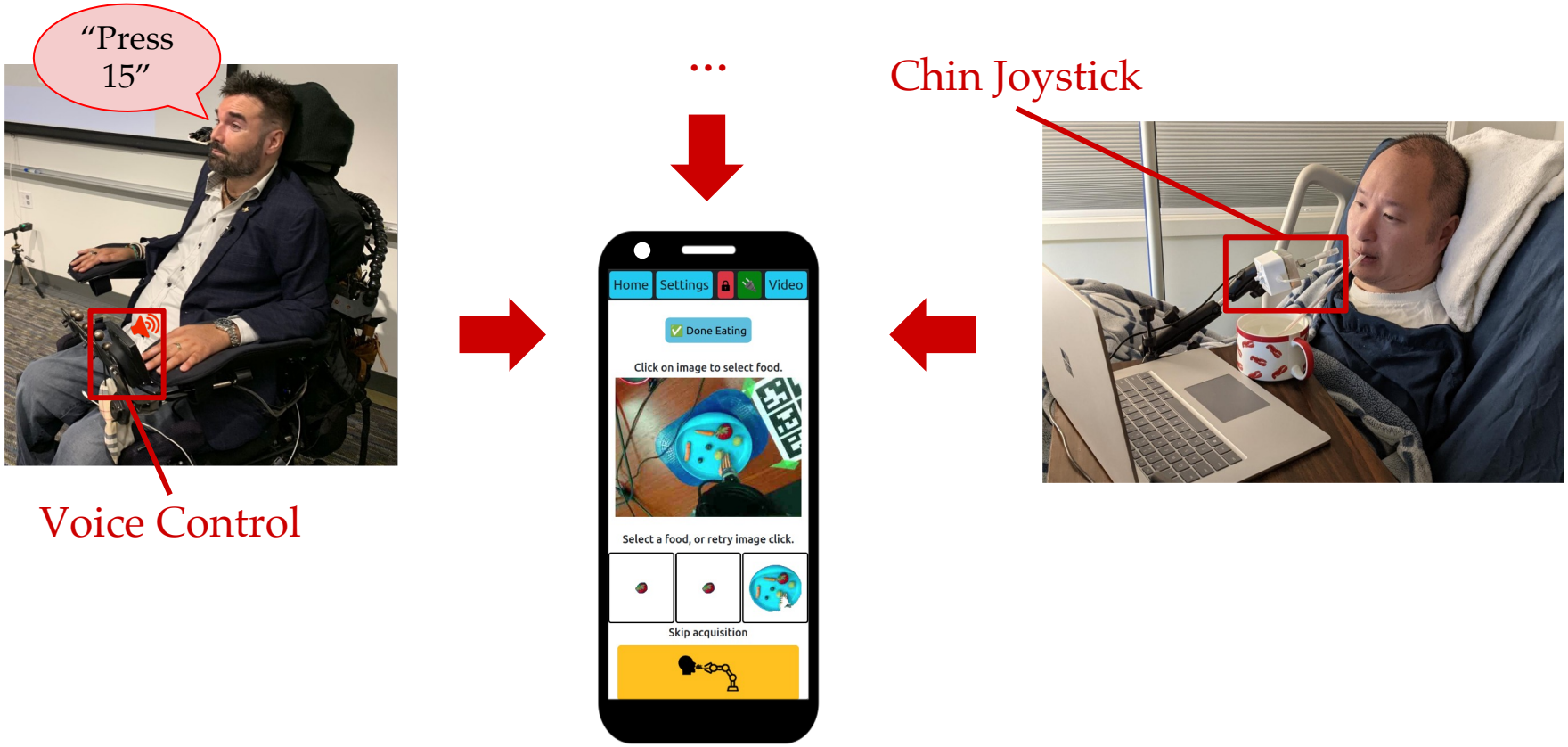
Key Observation:

Users' goal fully aligns with the robot, they are co-located with the robot, and they desire control over their robot.

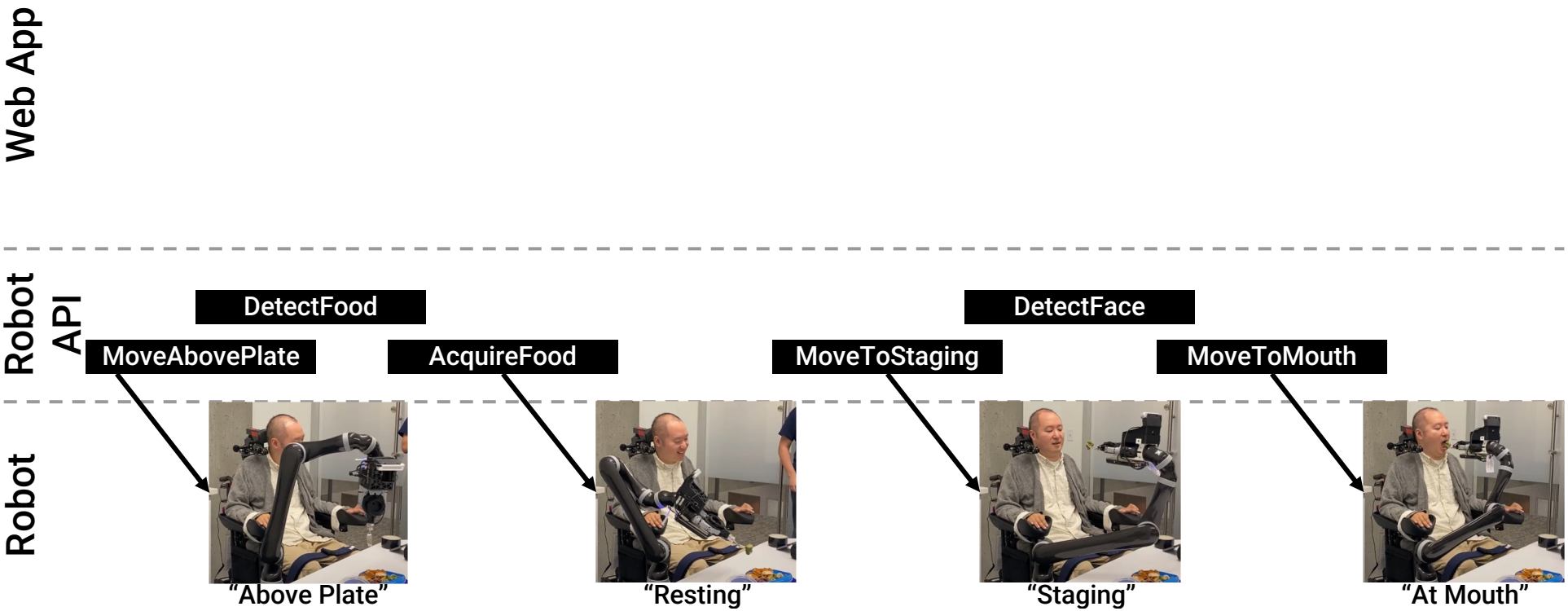
Insight #1:

Users can resolve off-nominals, given control and transparency.

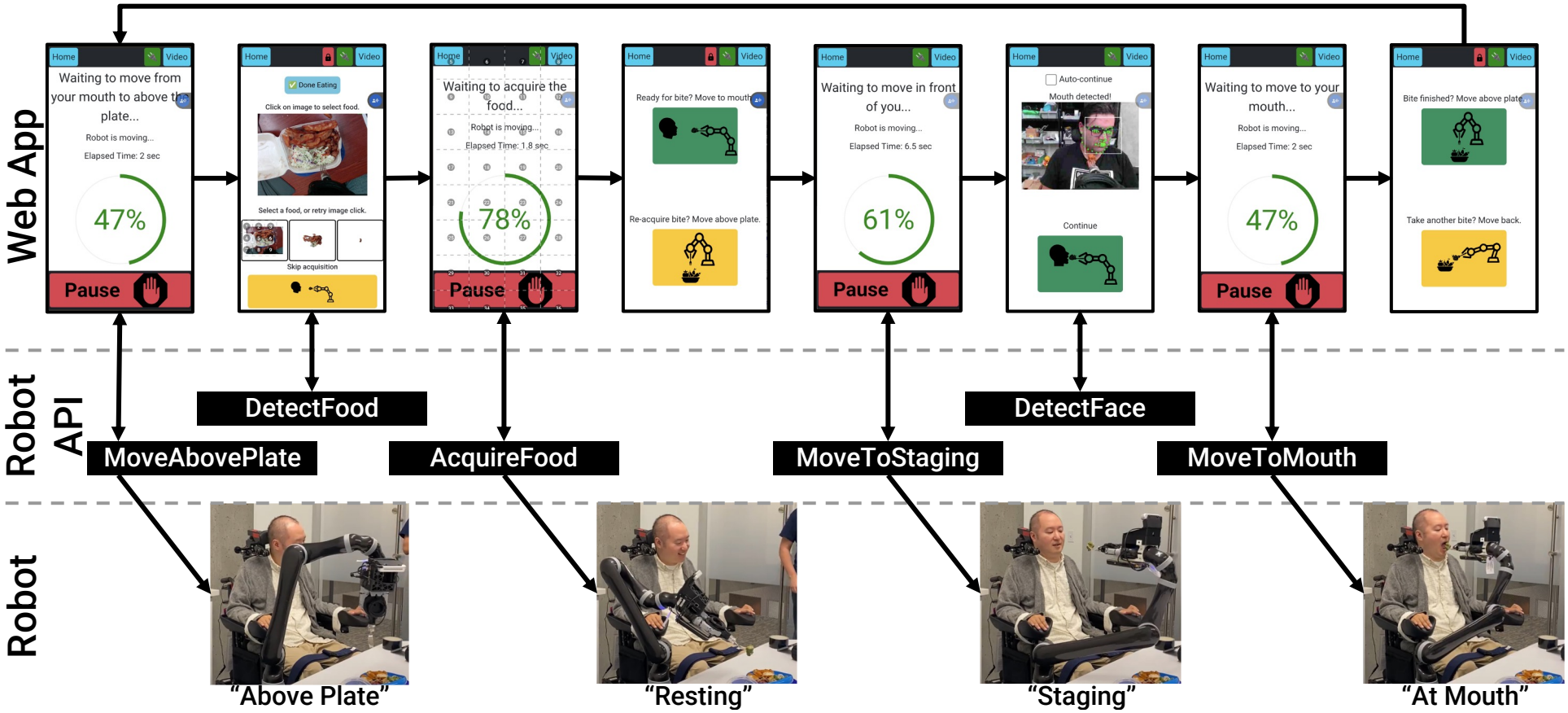
User Interface: **Web App**



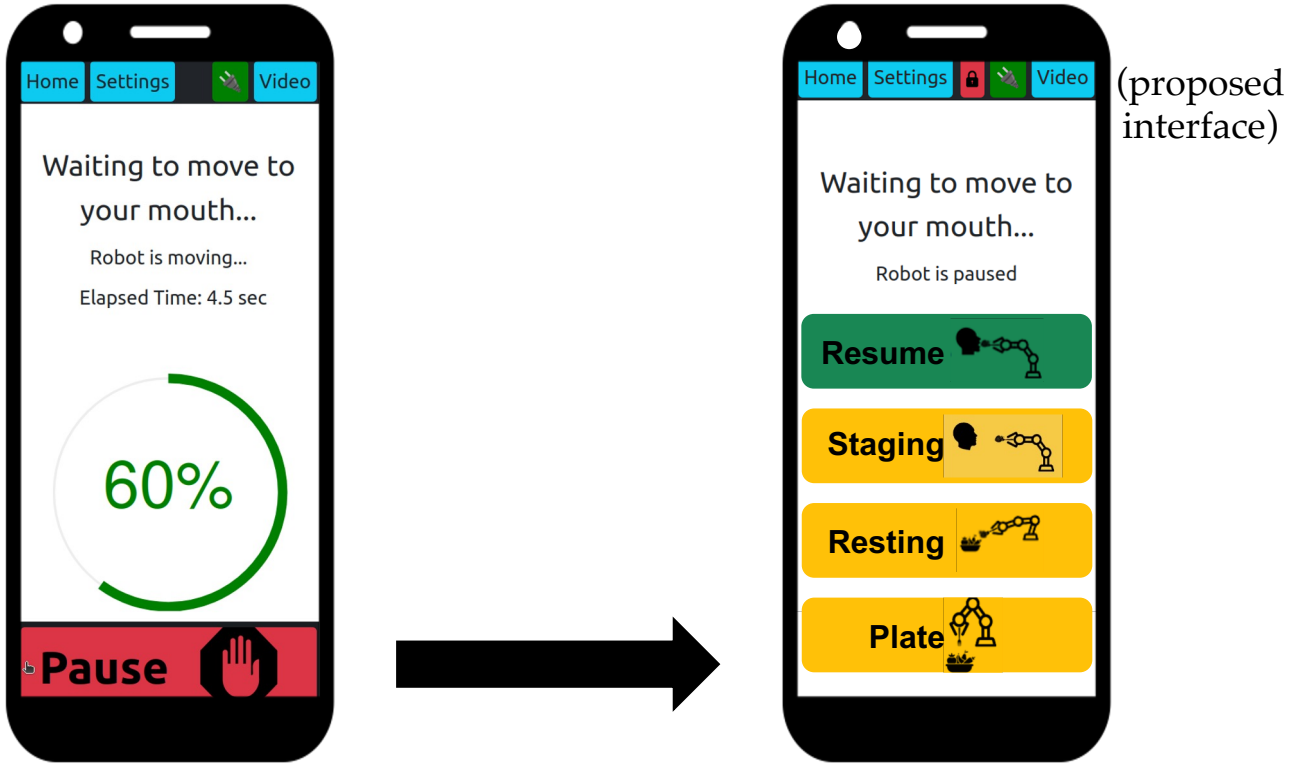
Software Architecture: **App Controls Execution**!



Software Architecture: **App Controls Execution!**

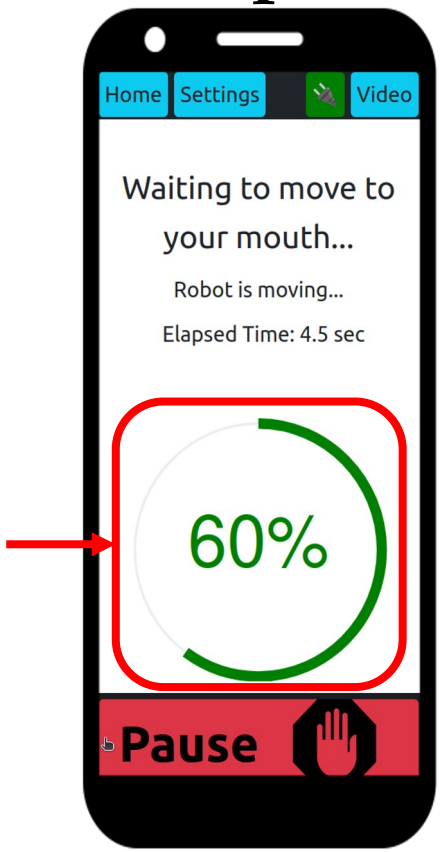


Web App Design Principle: **User Control**

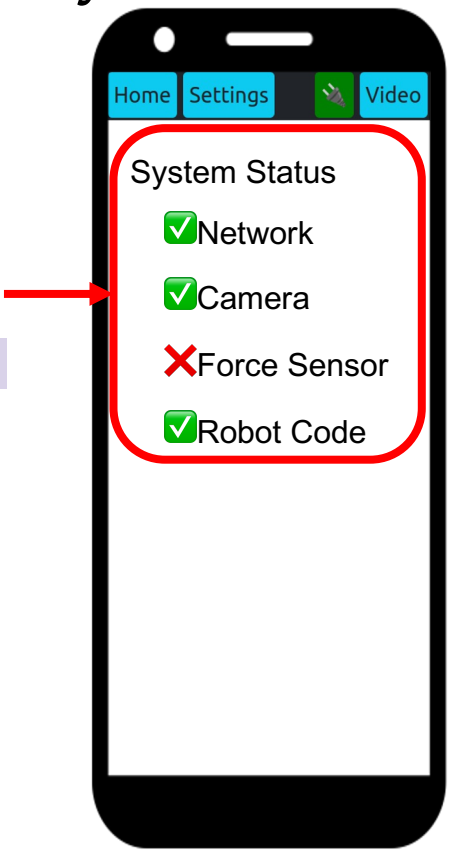


(proposed interface)

Transparency is necessary to resolve system issues



Transparency and control are two sides of the same coin when it comes to empower users to resolve off-nominal scenarios.



(proposed interface)

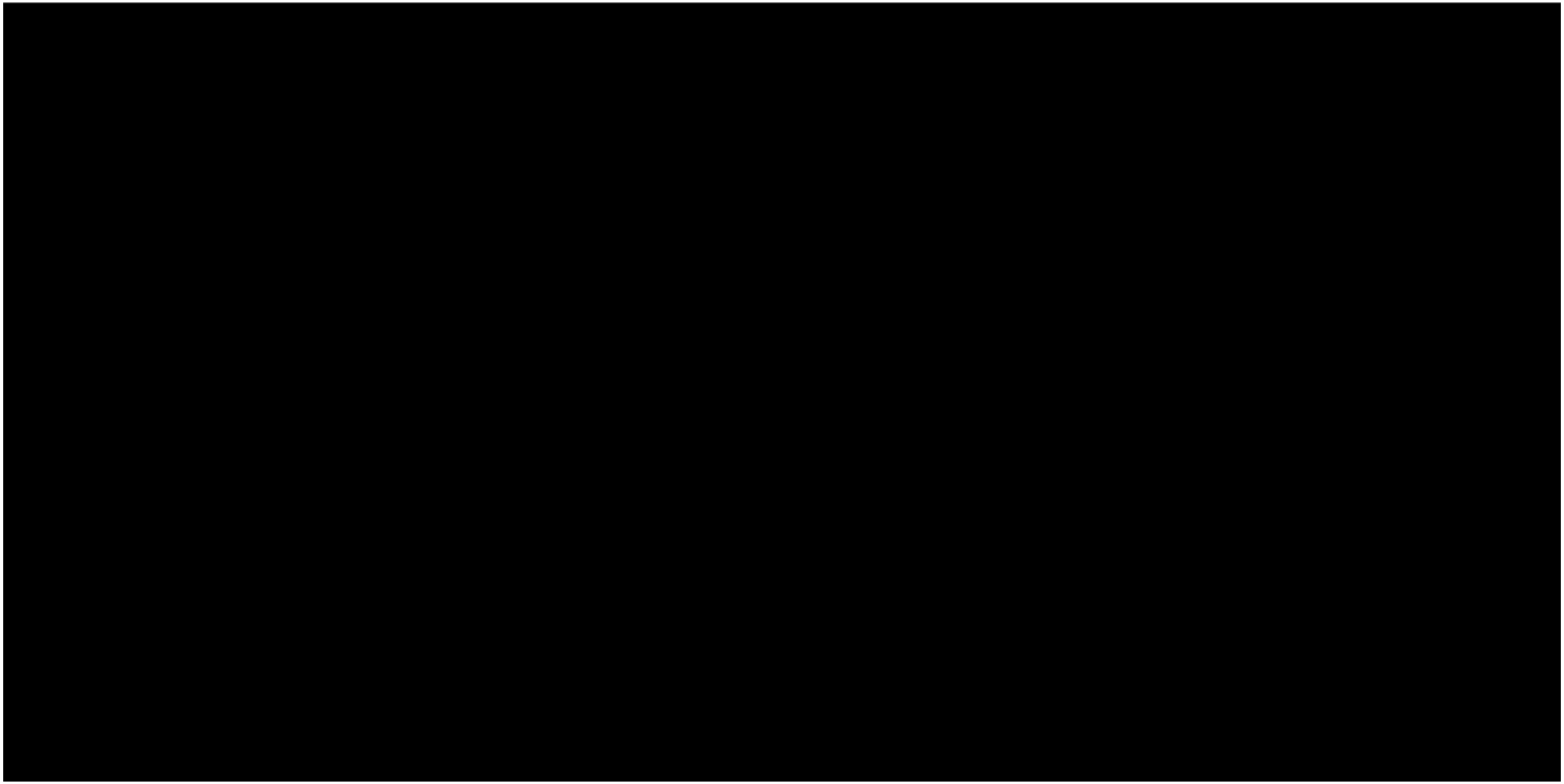
Key System Design Considerations for Deployability

Insight #1: Users can resolve off-nominals, given control & transparency

Insight #2: Safety in all levels of the system

Insight #3: Portability is key

In-Lab Test from Last Month



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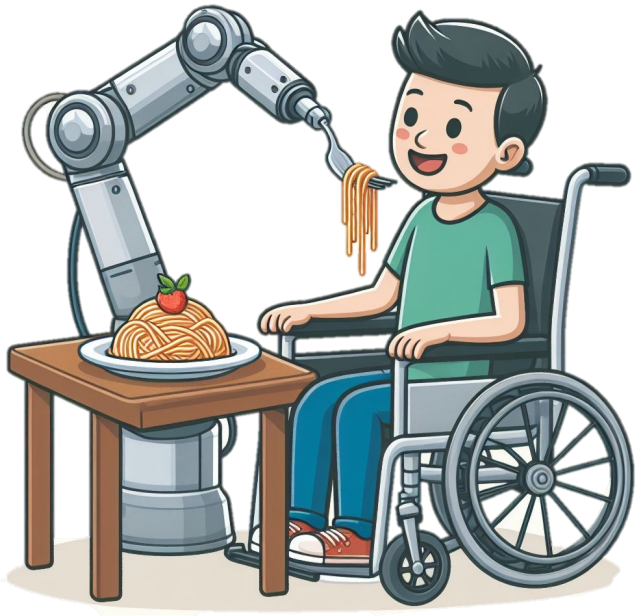

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How can we develop a deployable robot-assisted feeding system that can feed any* user, in any* environment, a meal of their choice†, while aligning with their preferences?

customized

generalize across foods

RQ4: How can a robot-assisted feeding system customize to users' needs and environments?

Why Customize?

Needs

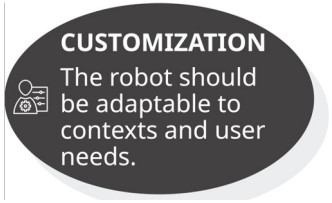
User can only move their head a certain distance to the fork

User must be fed from one side of their mouth

User needs small bites to prevent choking

…

Nanavati, Amal*, Alves-Oliveira, Patrícia*, et al. "Design principles for robot-assisted feeding in social contexts." *HRI*. (2023)



Why Customize?

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User can only move their head a certain distance to the fork

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User wants the robot to not occupy their visual field

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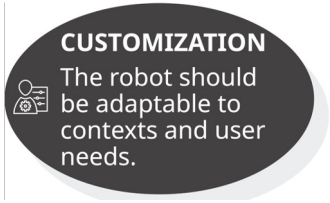
Nanavati, Amal*, Alves-Oliveira, Patrícia*, et al. "Design principles for robot-assisted feeding in social contexts." *HRI*. (2023)



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…

Preferences

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User wants the robot to automatically move to their mouth

…

Environment

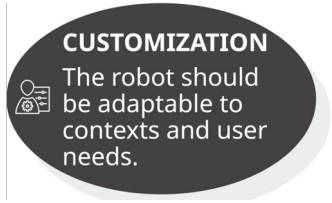
User wheelchair is angled relative to the table/plate

User is being fed in-bed, a different relative position to the robot

User wants the robot to not block their TV or social companion

…

Nanavati, Amal*, Alves-Oliveira, Patrícia*, et al. "Design principles for robot-assisted feeding in social contexts." *HRI*. (2023)



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Needs	**Preferences**	**Environment**
User can only move their head a certain distance to the fork	User wants the robot to not occupy their visual field	User wheelchair is angled relative to the table/plate
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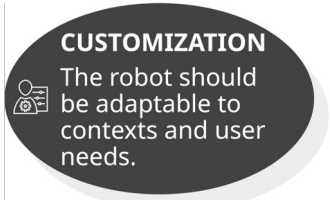
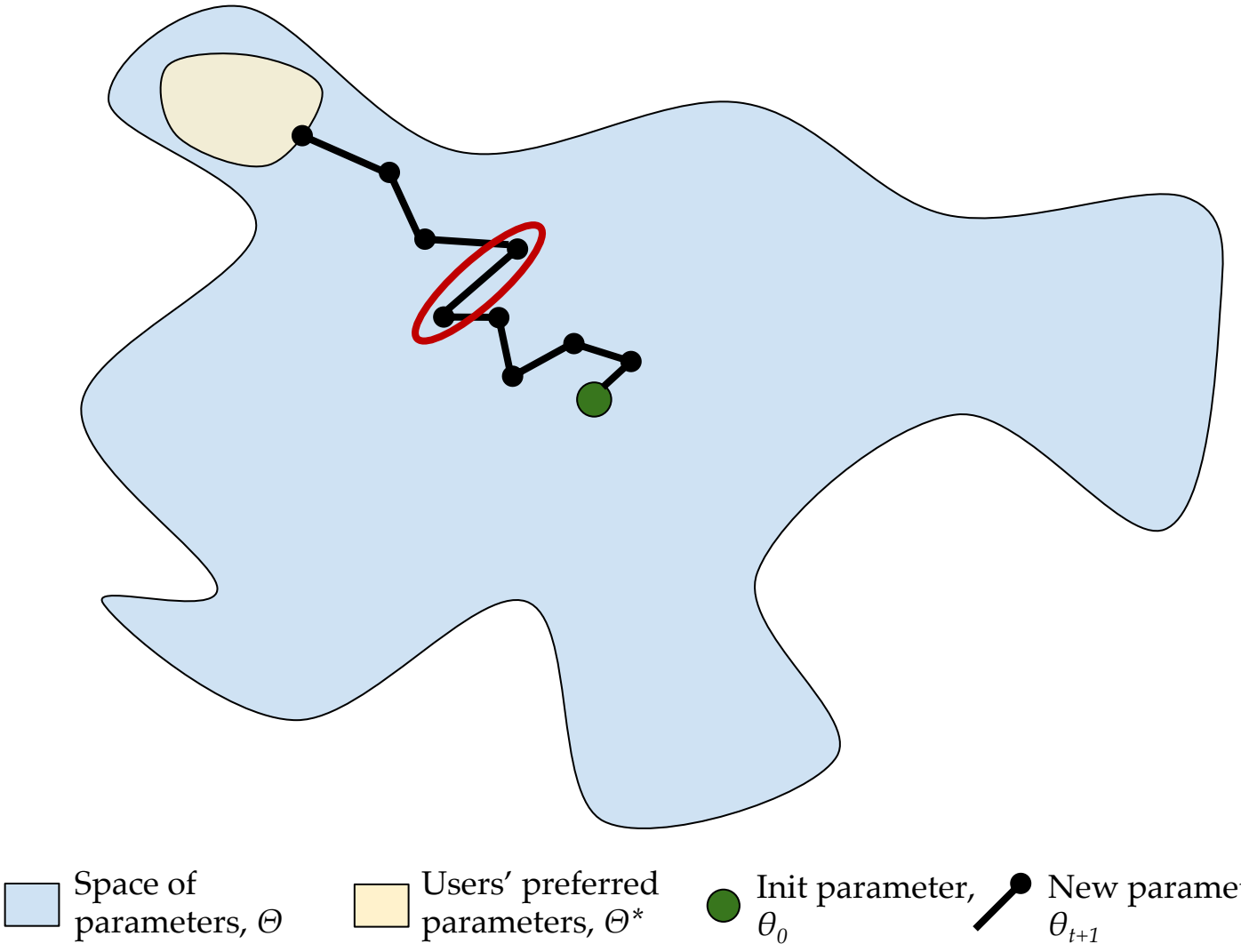




Formalization

parameter
$\theta \in \Theta$

program
$f_\theta \in F$

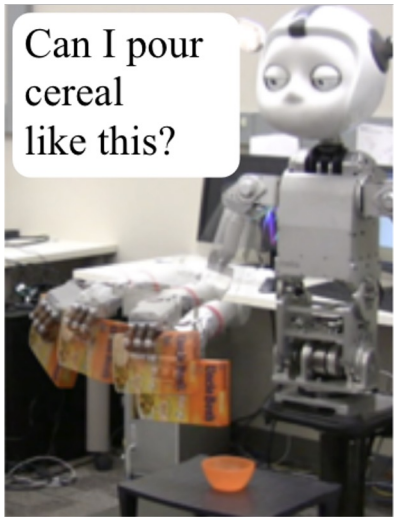
user preferences
$h : F \to \mathbb{R}$

user preferred programs
$\Theta^* = \{\theta | h(f_\theta) \geq \eta\}$

Goal: find some
$\theta^* \in \Theta^*$

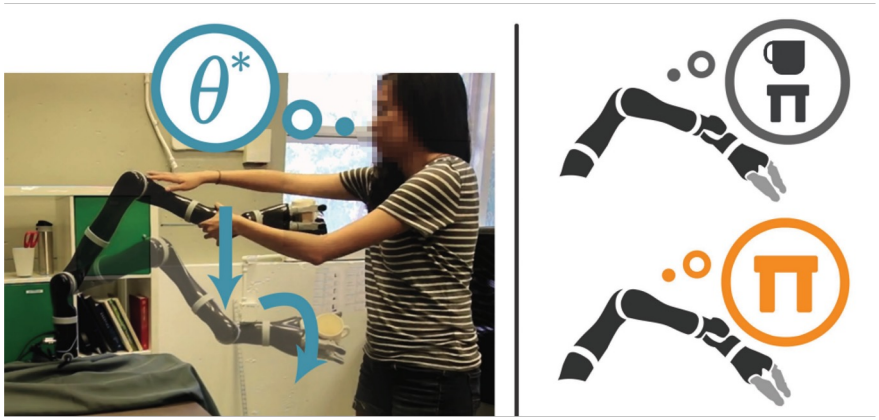
(often done iteratively)
$\theta_0 \cdots \theta_t \to \theta_{t+1} \cdots \theta^*$

One Approach: "Robot-Driven Customization"



Active Learning

Cakmak, Maya, and Andrea L. Thomaz. "Designing robot learners that ask good questions." *HRI*. (2012).



Learning from Corrections

Bajcsy, Andrea, et al. "Learning from physical human corrections, one feature at a time." *HRI*. (2018)

typically requires an ***explicit*** model of user preferences:

$$h(f_\theta|w) = w \cdot \Phi(f_\theta)$$

including the features users care about: $\Phi(f_\theta)$

One Approach: "Robot-Driven Customization"

Pro: It works well across many tasks.

Con: User frustration due to insufficient control and transparency.

Amershi, Saleema, et al. "Power to the people: The role of humans in interactive machine learning." *Ai Magazine* 35.4 (2014)

questions." *HRI*. (2012).

es:

$$h(f_\theta|w) = w \cdot \Phi(f_\theta)$$

including the features users care about: $\Phi(f_\theta)$

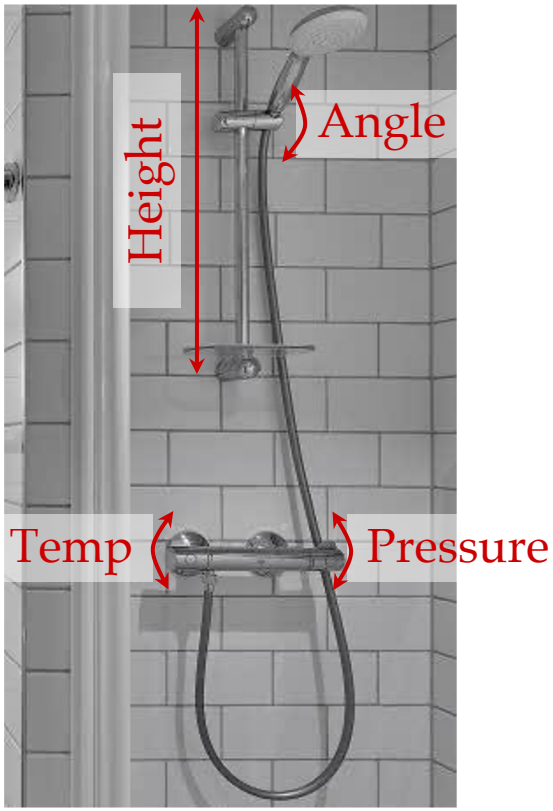
Key Observation:

Users are experts at what they want.

Key Insight:

By providing intuitive knobs, we can empower users to directly customize their robot.

(User-Driven) Customization Everywhere!

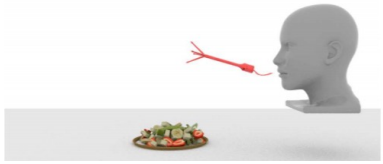


Proposed Work:

1. Design user-driven customization for the robot-assisted feeding system.
2. Run a user study investigating users' perceived tradeoffs between user-driven and robot-driven customization.

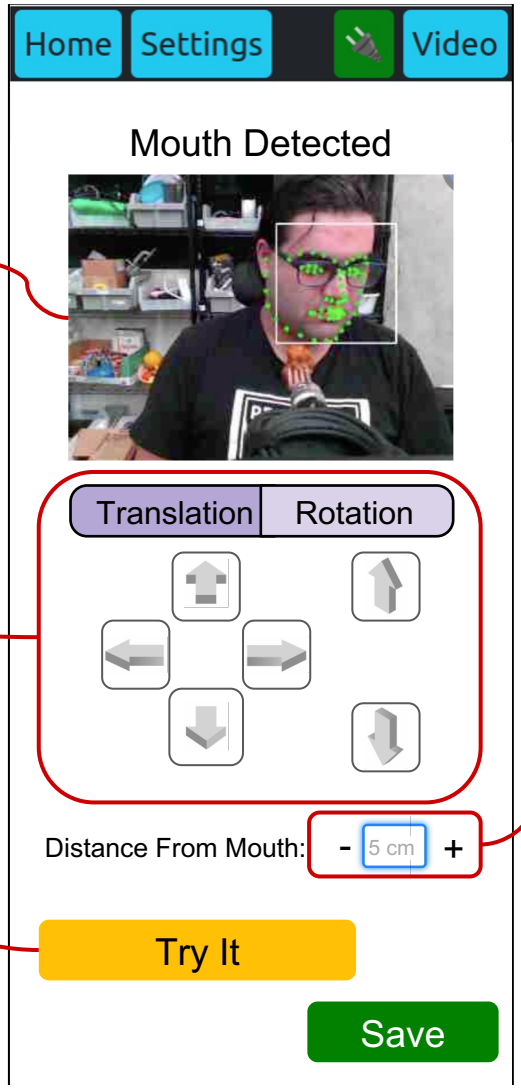
What to Customize?

Needs	**Preferences**	**Environment**
User can only move their head a certain distance to the fork	User wants the robot to not occupy their visual field	User wheelchair is angled relative to the table/plate
User must be fed from one side of their mouth	User wants the robot to take human-like arm configurations	User is being fed in-bed, a different relative position to the robot
User needs small bites to prevent choking	User wants the robot to automatically move to their mouth	User wants the robot to not block their TV or social companion
…	…	…



Bite Transfer: staging configuration (6D) + distance to mouth (1D)

User-Driven Customization



(proposed interface)

Transparently expose technical constraints to user

Give users free control to tune the parameter(s)

Allow users to immediately try robot behavior with the set parameter(s)

Accessible interface

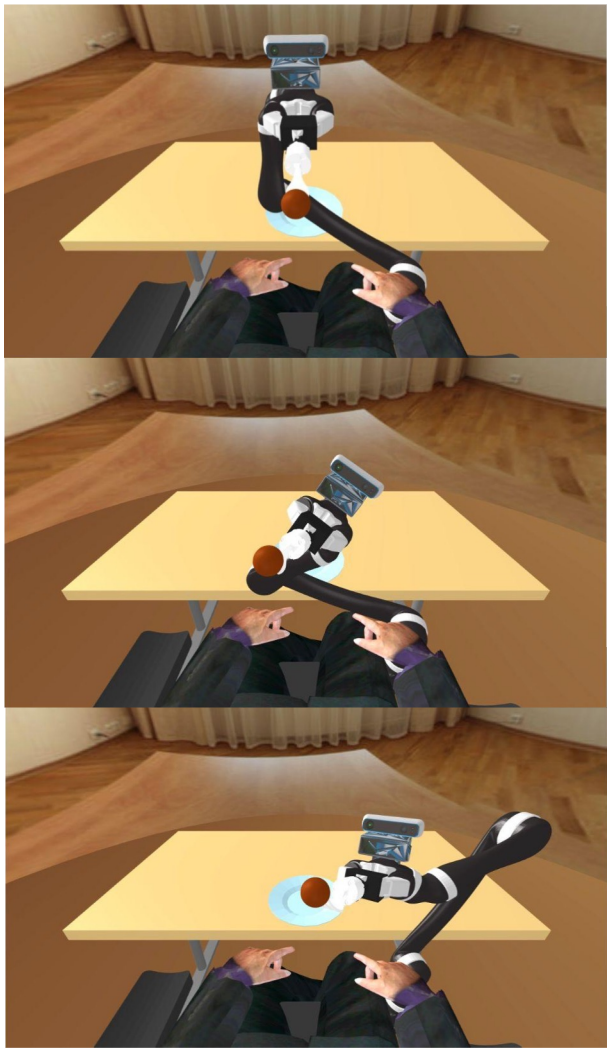
Resnick, Mitchel, and Eric Rosenbaum. "Designing for tinkerability." *Design, make, play: Growing the next generation of STEM innovators* (2013)

Robot-Driven Customization

Features $\Phi(f_\theta)$: fork centering, robot height, visual occlusion, zig-zagginess, etc.

User Preferences:

$$h(f_\theta|w) = w \cdot \Phi(f_\theta)$$



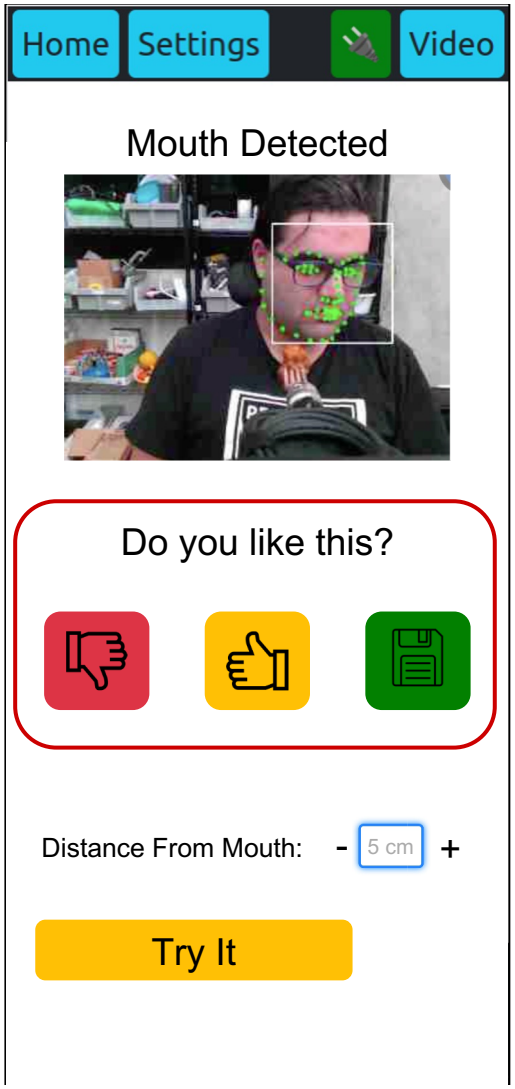
Robot-Driven Customization

Features $\Phi(f_\theta)$: fork centering, robot height, visual occlusion, zig-zagginess, etc.

User Preferences:

$$h(f_\theta | w) = w \cdot \Phi(f_\theta)$$

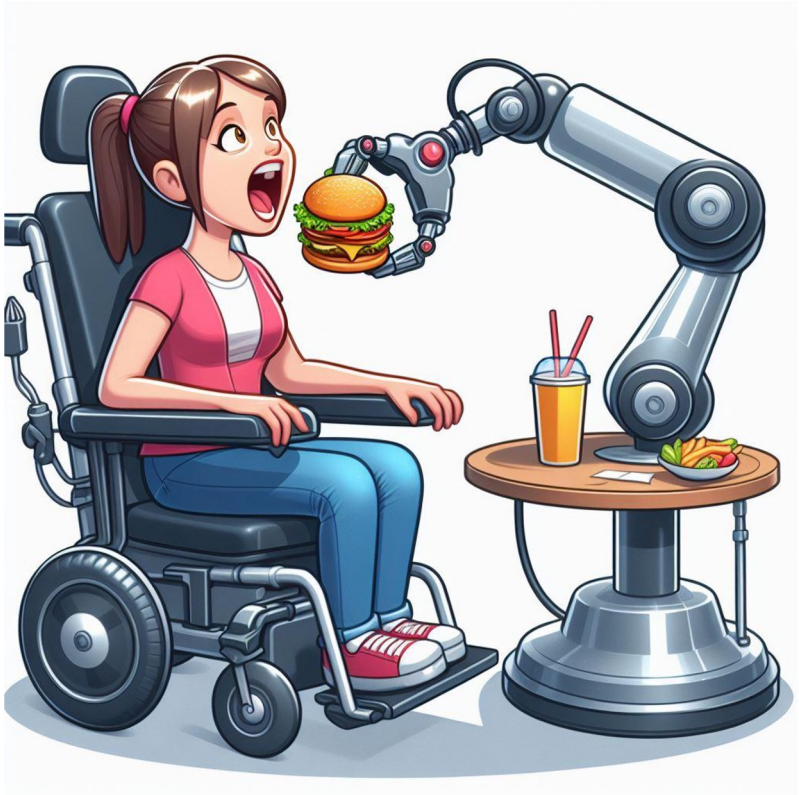
- Robot samples staging configuration.
- Users provide binary feedback.
- Robot uses feedback to generate another sample.
- **Algorithm (Bayesian Optimization)**: Thompson Sampling + Laplace Approximation



(proposed interface)

Proposed Study

- Users try both user-driven and robot-driven customization (within-subjects)
- Objective Metrics:
  - Time to customize (sec)
- Subjective Metrics:
  - Feeling of customization (5-point Likert)
  - Cognitive Workload & Frustration (NASA-TLX)
  - Preferred customization experience (force-choice)
- Hypotheses:
  - **User-driven customization**: shorter time-to-customize and higher feelings of customization.
  - **Robot-driven customization**: lower cognitive workload but higher frustration.



The Power of Customizing Arm Configurations

Needs	**Preferences**	**Environment**
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…	…	…

Bonus: Customizing to relative positioning of user/robot/plate.

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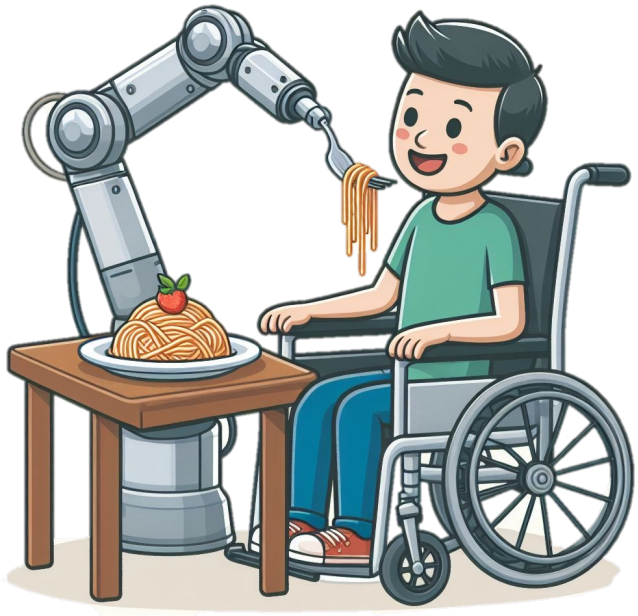


generalize across users

usable without researcher intervention

generalize across environments

How can we develop a deployable robot-assisted feeding system that can feed any* user, in any* environment, a meal of their choice†, while aligning with their preferences?

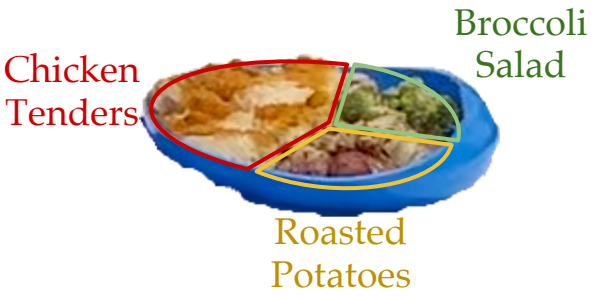
customized

generalize across foods

* "any" = North Star.
Demonstrate it with "multiple"

† that can be acquired with a single arm using a fork

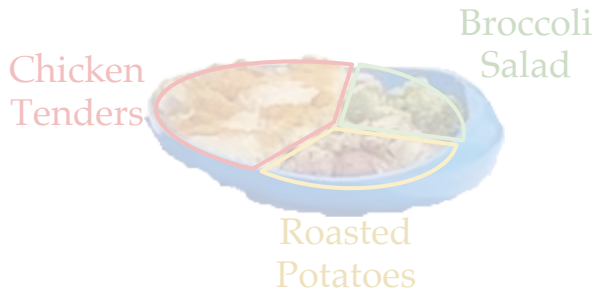
Pilot Single-Meal Deployment (3 weeks ago)



Hot off the QFC (supermarket) shelf!

~ 1m30s per bite
(and we'll make it faster 🙂)

Pilot Single-Meal Deployment (3 weeks ago)



Hot off the QFC (supermarket) shelf!

~ 1m30s per bite
(and we'll make it faster 🙂)

What Remains? (Proposed Work)

- Customization
- Transparency & control to resolve system errors
- Testing in less structured environments

Evaluations

- n=5 single-meal deployments
  - conference room, atrium, cafeteria, etc.
  - a meal of their choice
  - **Metrics**: # researcher interventions, time per bite, cognitive workload (NASA-TLX), usability (SUS)
- n=1 in-home deployment
  - one week, e.g., 10 lunches & dinners
  - n-of-1 experimental design*
  - alternate caregiver-fed and robot-fed meals
  - **Metrics**: meal length, stress levels, feelings of self-efficacy, caregiver time
  - (perhaps) bed-side feeding?

*Tate, Robyn L., and Michael Perdices. "N-of-1 trials in the behavioral sciences." *The essential guide to N-of-1 trials in health* (2015)

Timeline

Research Question(s)	**End Quarter**	**Milestone(s)**
Needs Assessment (RQ1) & Acquisition (RQ2)	Autumn 2023	Pilot Single-Meal Deployment: 1 user
Customizability (RQ4) & Deployability (RQ3)	Winter 2024	Single-Meal Deployments: 5 users
Deployability (RQ3)	Spring 2024	In-Home Deployment & Bed-side Feeding
Potential Internship	*Summer 2024*	*N/A*
Customizability (RQ4)	Autumn 2024	RQ4 Study
(RQ-Thesis)	Winter 2025	Dissertation & Defense

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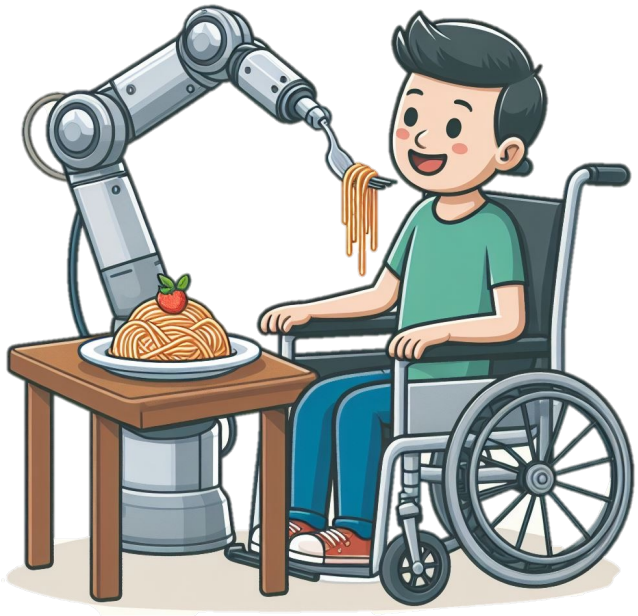
6. RQ4: Customizing to Users and Environments [Proposed]
7. Evaluations & Timeline



Community Researchers

Tyler Schrenk
Jonathan Ko

Co-Advisors

Maya Cakmak
Siddhartha Srinivasa

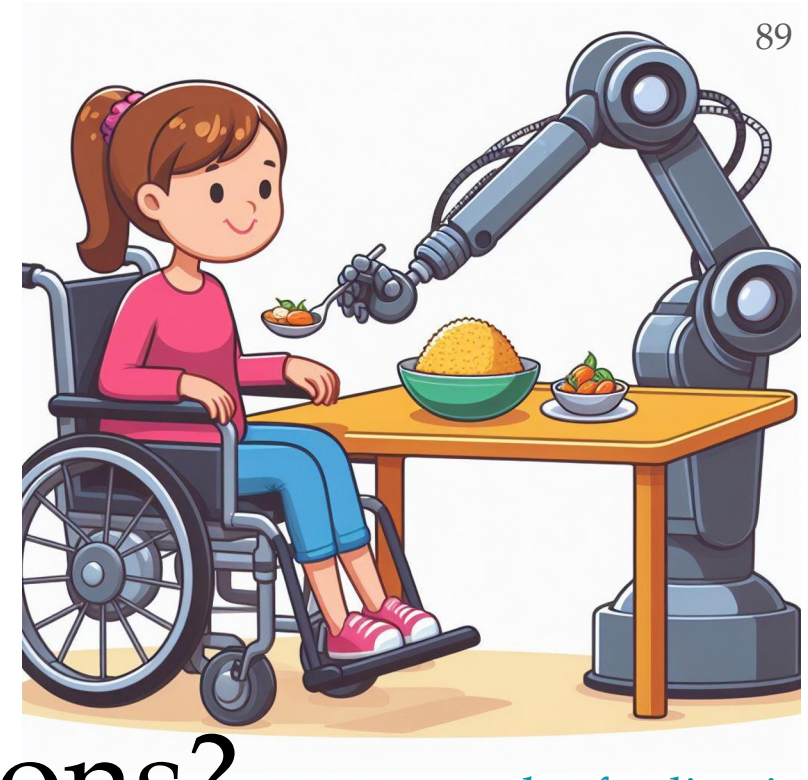
Collaborators

Ethan Gordon
Taylor Kessler Faulkner
Patrícia Alves-Oliveira
Vinitha Ranganeni
Bernie Zhu
Atharva Kashyap
Raida Karim
Haya Bolotski
Nick Walker
Chris Mavrogiannis
Tapo Bhattacharjee
Leila Takayama

Committee

Anat Caspi
Henny Admoni
Kim Ingraham

Thank You
Any Questions?



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