Towards a Future with Inclusive Mobile Manipulators

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https://charliekemp.com

Associate Professor, Department of Biomedical Engineering

Co-founder & CTO, Hello Robot Inc.

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Charlie’s Conflict of Interest Statement

Dr. Kemp is both an associate professor at Georgia Tech and the chief technology officer (CTO) of Hello Robot Inc. where he works part time. **He owns equity** in Hello Robot Inc. and is an inventor of Georgia Tech intellectual property (IP) licensed by Hello Robot Inc. Consequently, **he receives royalties** through Georgia Tech for sales made by Hello Robot Inc. He also benefits from increases in the value of Hello Robot Inc.

Summary: If Hello Robot does well, Charlie does well.

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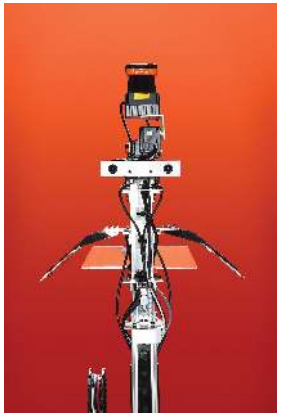
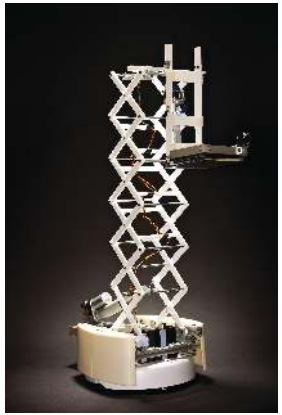
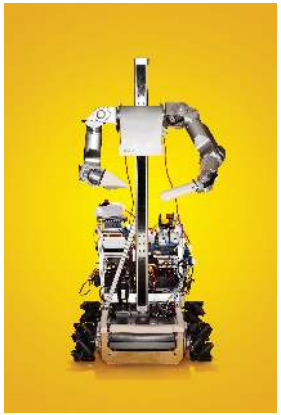
Mobile Manipulators

- Can assist people with disabilities
- Are becoming commercially viable
- Require research to realize their potential


Photos by
Josh Meister

Commercial Assistive Robots

JACO by Kinova

- On your wheelchair
- On a table or desk
- On your body

DynamicArm by Ottobock

My Spoon by SECOM

Myomo by Myomo Inc.

Advantages of Mobile Manipulators

- Operate independently from the user
- No don/doff
- Assist diverse users
- Potential for mass market product

Prices for Emerging Technologies

All prices inflation adjusted to 2020-2021 US dollars

Google Spreadsheet Used to Generate Graphs

Computers

DEC PDP-8

DEC PDP-11

Apple II

IBM PC

Apple IIe

Price

$160,000
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$0

1965
1970
1975
1980

Year

Mobile Phones

Motorola DynaTAC

Nokia 1011

Treo 650

iPhone

Price

$11,000
$10,000
$9,000
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$0

1980
1985
1990
1995
2000
2005

Year

Not All Emerging Technologies Become Personal

1903,The Wright Flyer
https://en.wikipedia.org/wiki/Wright_Flyer

Only 16 years!

1919 - Today
https://en.wikipedia.org/wiki/Airliner

2018 - Today, Volocopter 2X
https://en.wikipedia.org/wiki/Volocopter_2X

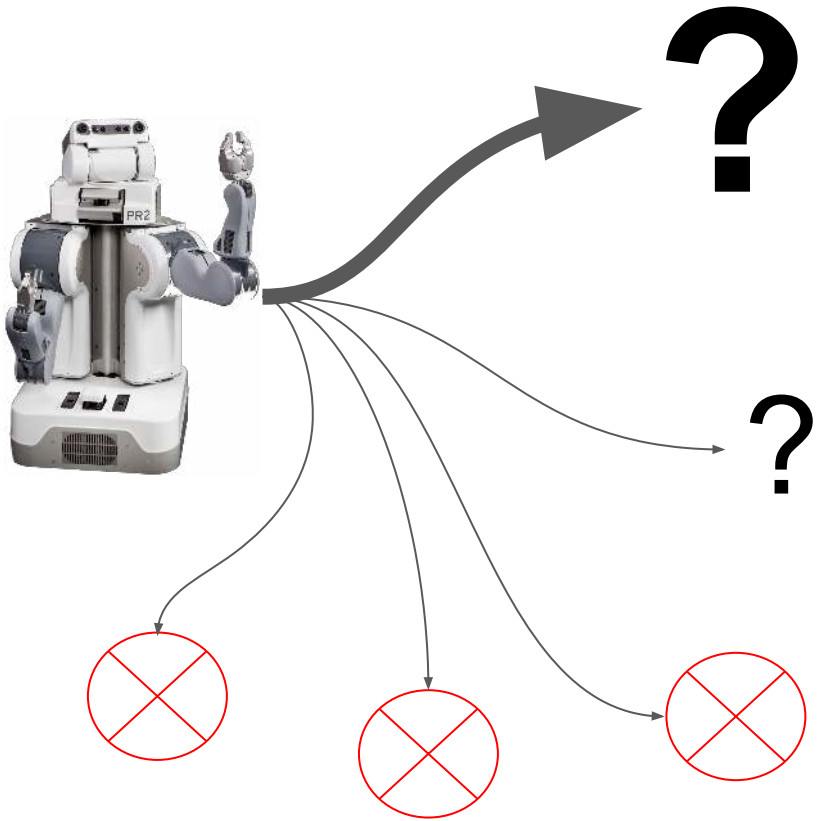
1940, Jess Dixon's flying automobile
https://en.wikipedia.org/wiki/Flying_car

1947, Convair Model 118
https://en.wikipedia.org/wiki/Convair_Model_118

1973, AVE Mizar
https://en.wikipedia.org/wiki/AVE_Mizar

https://en.wikipedia.org/wiki/Flying_car
https://en.wikipedia.org/wiki/The_Jetsons

Society has to Discover Where An Emerging Technology Fits In



Mobile Manipulators

PR2

Fetch

PAL Tiago

Stretch

Price

$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0

2010
2012
2014
2016
2018
2020

Year

Mobile Manipulators

- Versatile and complex emerging technology
- Opportunity to assist diverse people with disabilities
- Broad spectrum of research needed
- What happens in 10 years depends on today





The Story of Stretch

The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments,
Charles C. Kemp, Aaron Edsinger, Henry M. Clever and Blaine Matulevich, arXiv, 2021.

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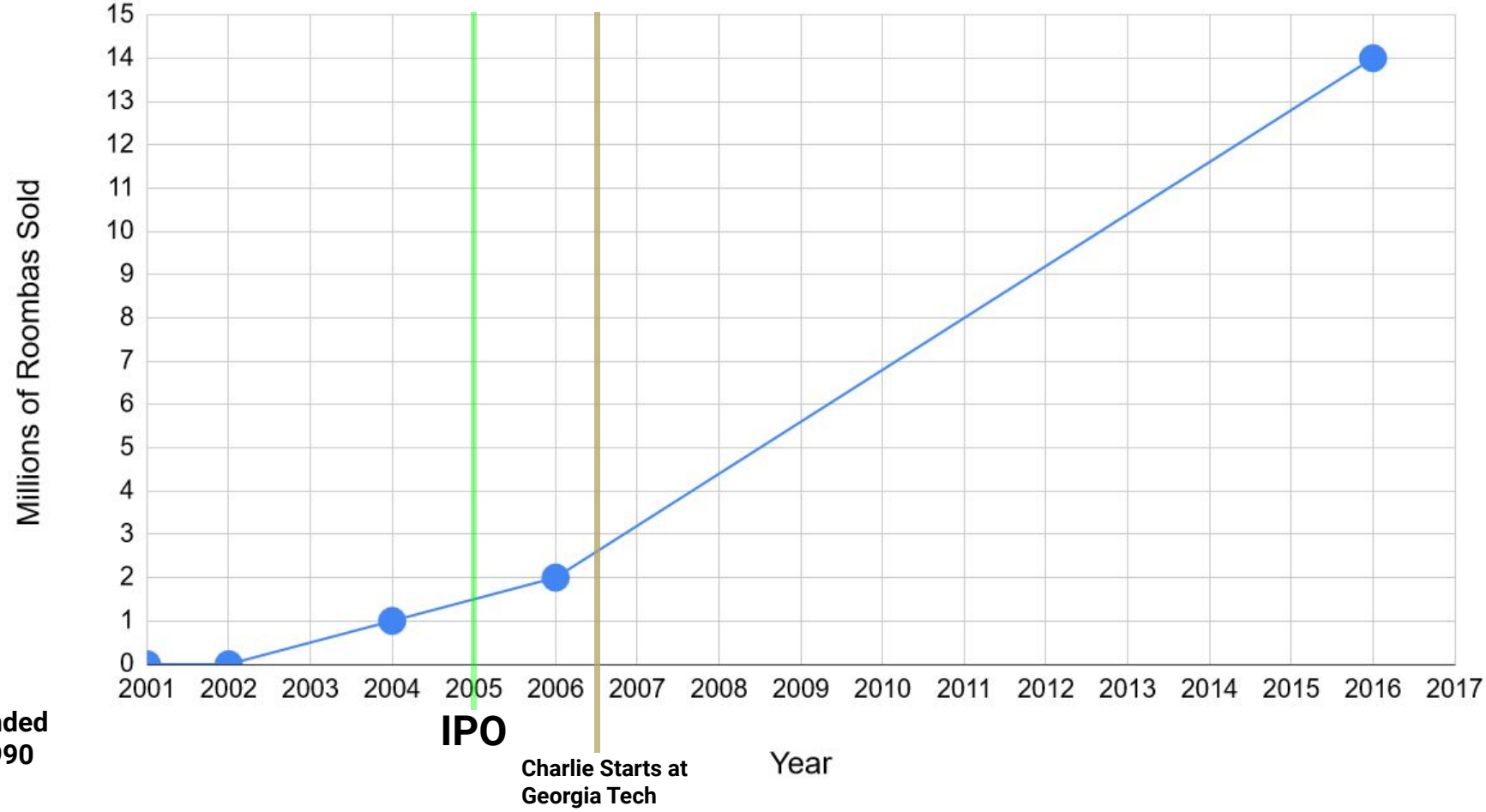
Photo Credit: Peter Menzel/Science Source
from https://robots.ieee.org/robots/cog/

Rodney A. Brooks, "How To Build Complete Creatures Rather Than Isolated Cognitive Simulators", Architectures for Intelligence, K. VanLehn (ed), Erlbaum, Hillsdale, NJ, Fall 1989, pp. 225–239.

The first Roomba from 2002.
Almost 20 years ago!

Millions of Roombas Sold vs. Year



Bodies and Brains Working Together

- Body matched to ecological niche
  - Small footprint
  - Circular and flat
  - Giant contact sensor
  - Easy for people to pick up and move
- Brain matched to the body
  - Haptic sensing as primary modality
  - Change direction on contact
  - Wall following
  - Spiraling

“Viewed as a geometric figure, the ant’s path is irregular, complex, and hard to describe. But its complexity is really a complexity in the surface of the beach, not the complexity in the ant.”

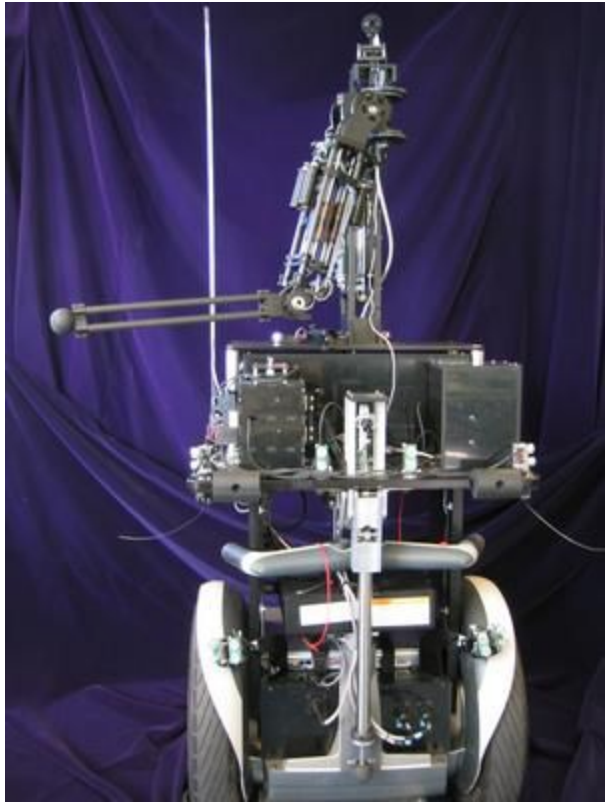
Herbert Simon,
The Sciences of the Artificial, 1969

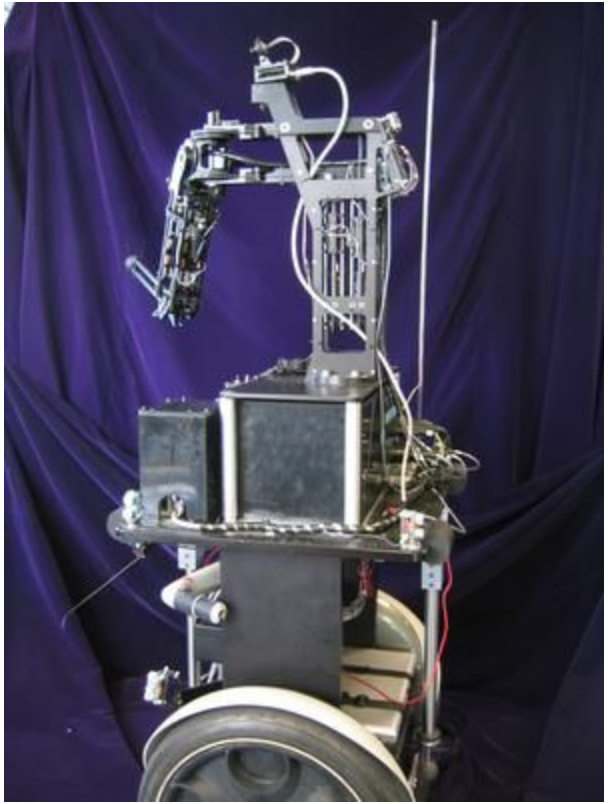
Photo Credit:
Andreas Dantz
Roomba, first attempt
Taken on April 14, 2013
https://www.flickr.com/photos/szene/8649326807/in/pool-roomba/

What is the Roomba of mobile manipulation?

What body for **indoor** mobile manipulation in homes and workplaces?

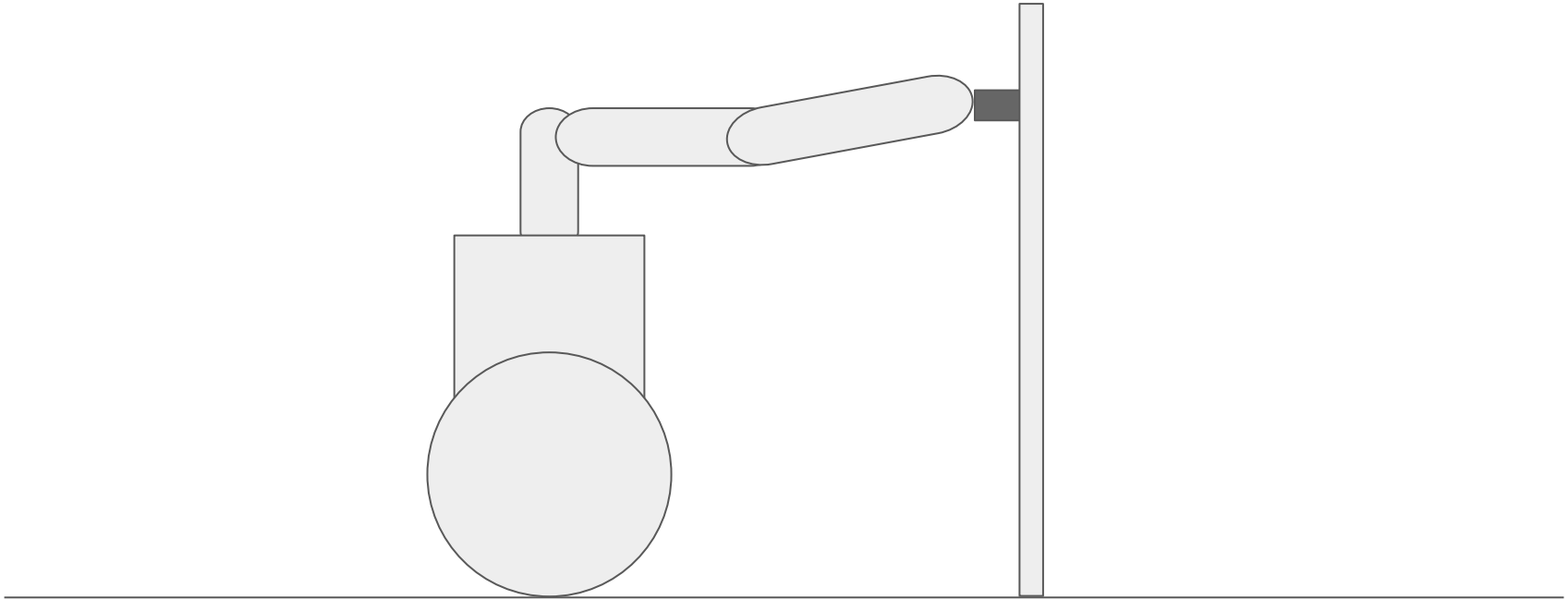
- Flat smooth surfaces
- Visible from human head height
- Reachable by human arms
- Children, older adults, and pets



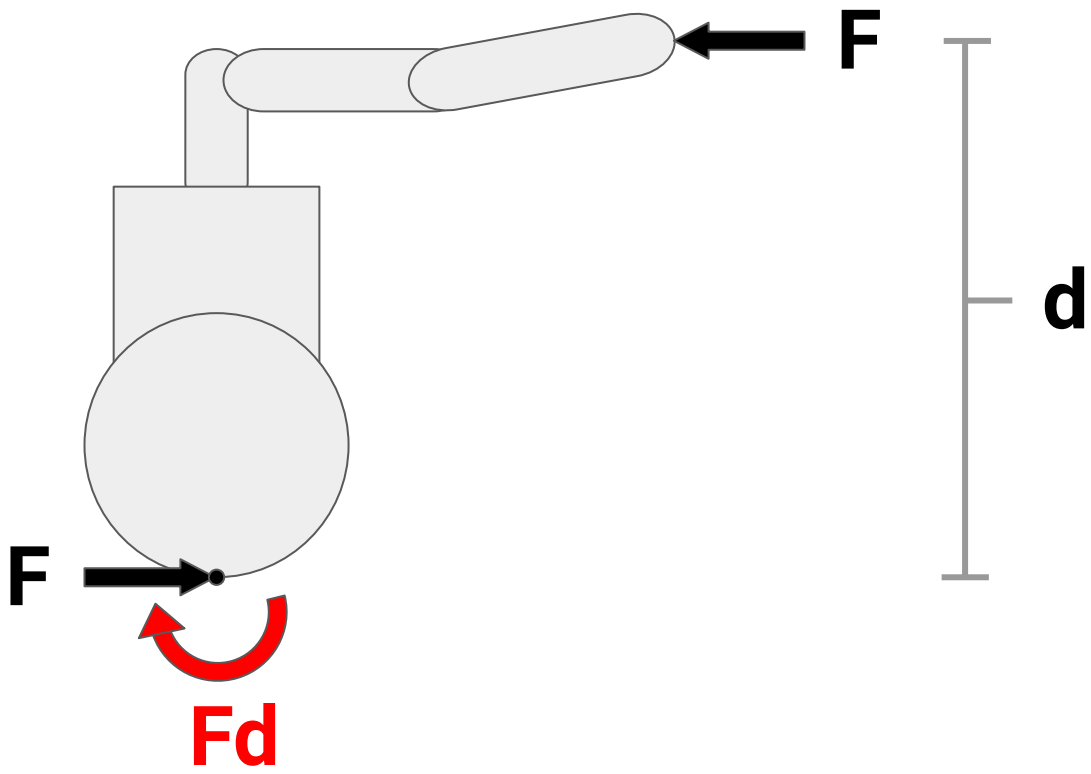


Sensing and Manipulating Built-for-Human Environments, **Rodney A. Brooks**, Lijin Aryananda, **Aaron Edsinger**, Paul M. Fitzpatrick, **Charles C. Kemp**, Una-May O'Reilly, Eduardo Torres-Jara, Paulina Varshavskaya and Jeff Weber. International Journal of Humanoid Robotics, Vol 1, Number 1, pages 1-28, 2004.

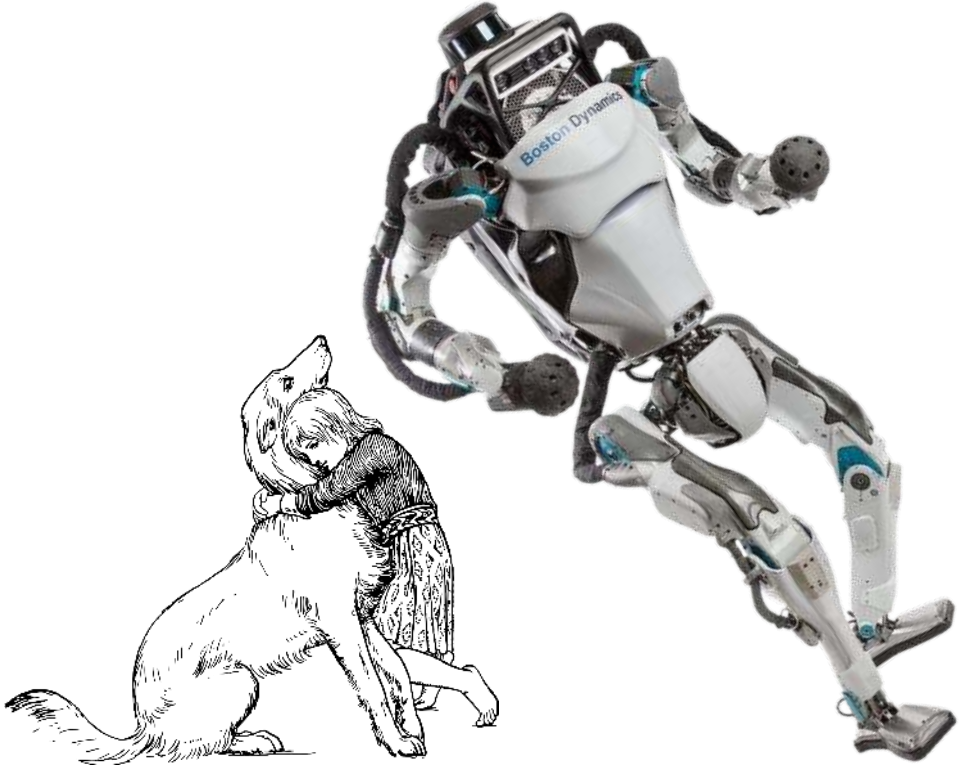
Momentary Problem when Balancing on Wheels



Momentary Problem when Balancing on Wheels



It Just Takes One Fall



Images from
https://openclipart.org/detail/314874/little-girl-hugging-dog
https://ozrobotics.com/tag/humanoid-robot/

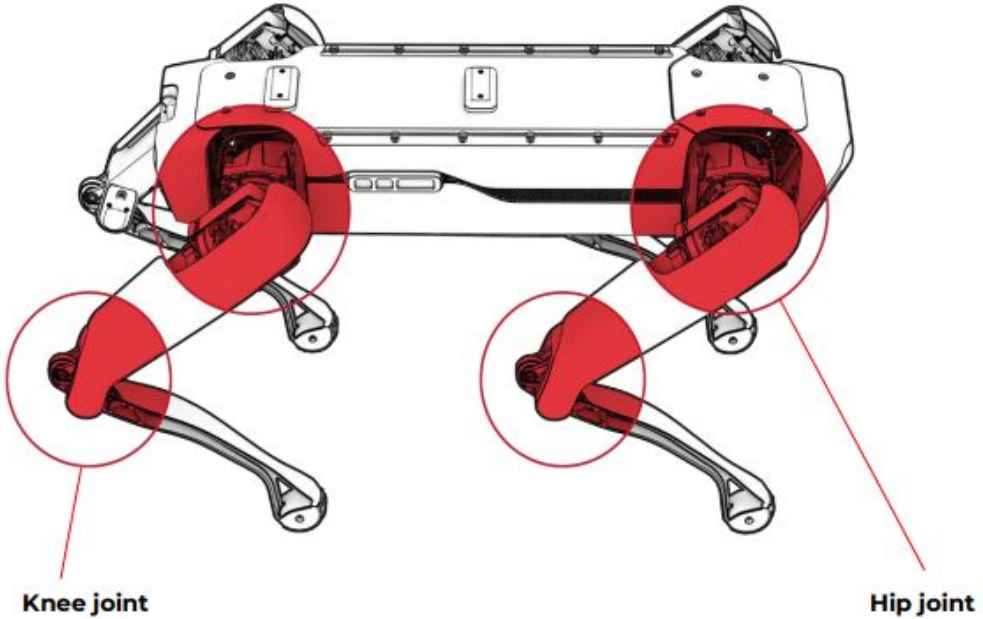
CSAIL

What about quadrupeds?

Image from
https://www.bostondynamics.com/spot

Pinch Points

Spot's joints can pinch fingers and other body parts and entangle loose clothing, long hair, and jewelry.



BostonDynamics

SPOT INFORMATION FOR USE

V1.0 - Original Instructions

https://www.bostondynamics.com/sites/default/files/inline-files/spot-information-for-use-en.pdf

Dynamic Stability Risks

Spot will always try to keep balance. This may result in high-acceleration motion of the legs

Failure in locomotion could happen unexpectedly and could result in de-energization of the robot's actuators.

A failure event may cause loss of stability and potential hazards associated with a fall or tipping over.

Always keep a separation distance of 2 m

BostonDynamics

SPOT INFORMATION FOR USE

V1.0 - Original Instructions

https://www.bostondynamics.com/sites/default/files/inline-files/spot-information-for-use-en.pdf

What is the Roomba of mobile manipulation?

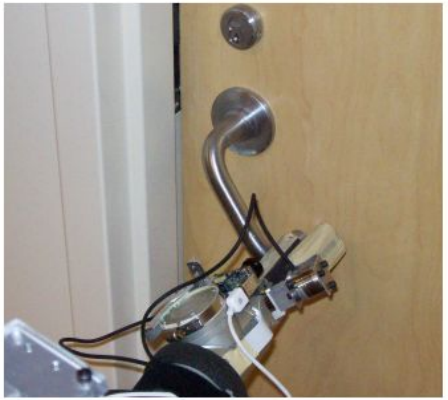
Stretch’s Ancestor

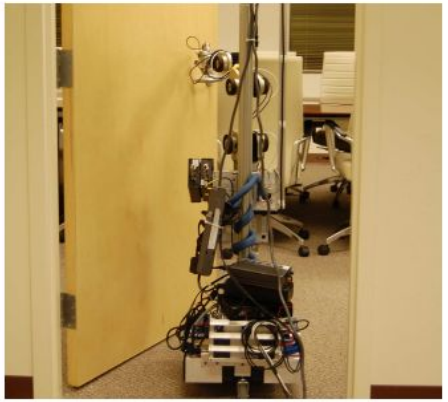
EL-E from 2008

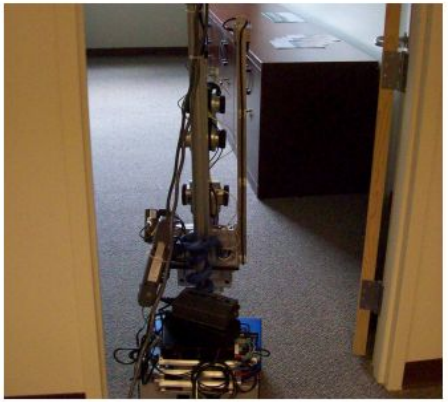
- Statically stable
- Small footprint
- Lightweight
- Cameras high
- Reach flat surfaces

A Point-and-Click Interface for the Real World: Laser Designation of Objects for Mobile Manipulation, Charles C. Kemp, Cressel Anderson, Hai Nguyen, Alex Trevor, and Zhe Xu, 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2008







Behaviors for Robust Door Opening and Doorway Traversal with a Force-Sensing Mobile Manipulator, Advait Jain and Charles C. Kemp, RSS Manipulation Workshop: Intelligence in Human Environments, 2008.

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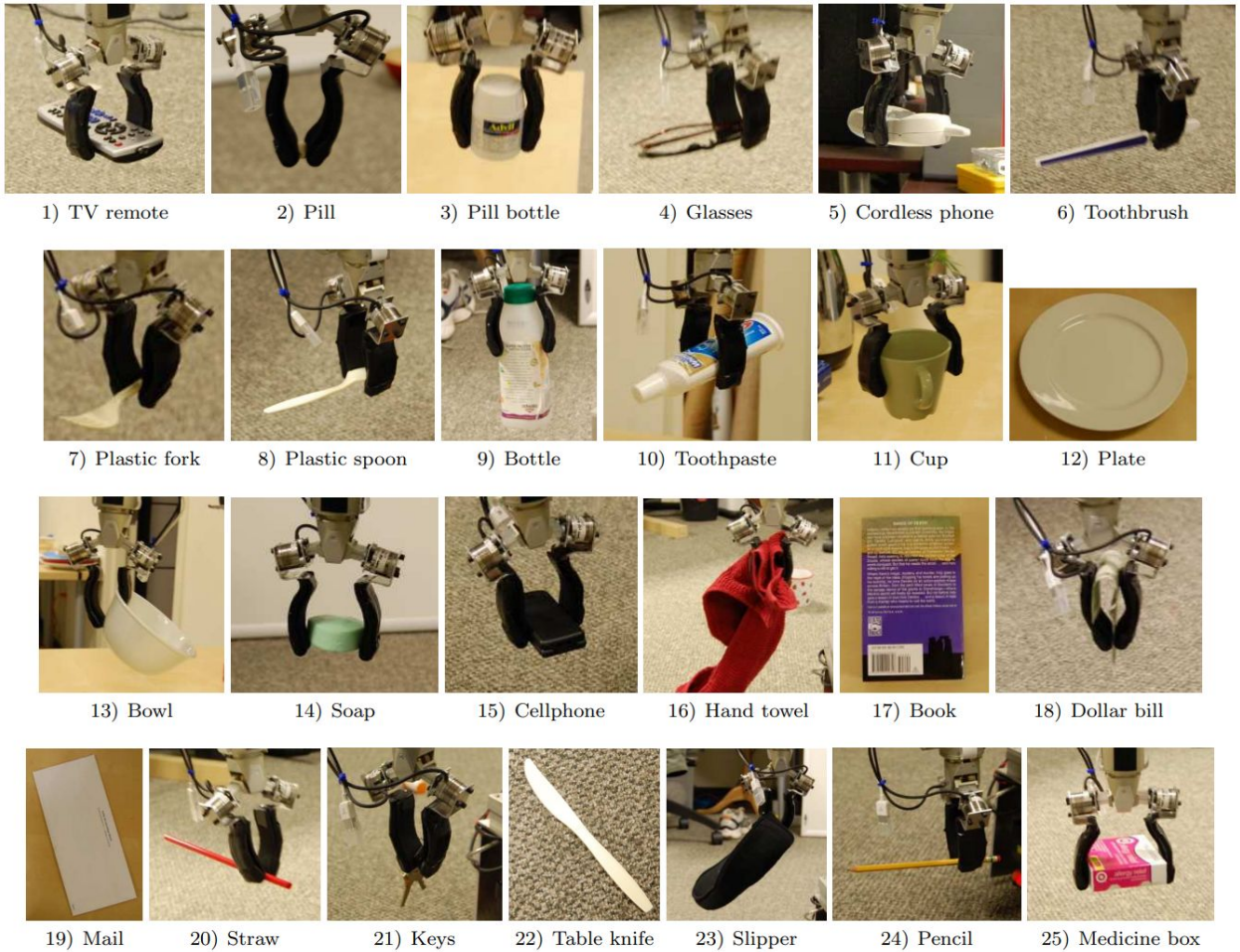
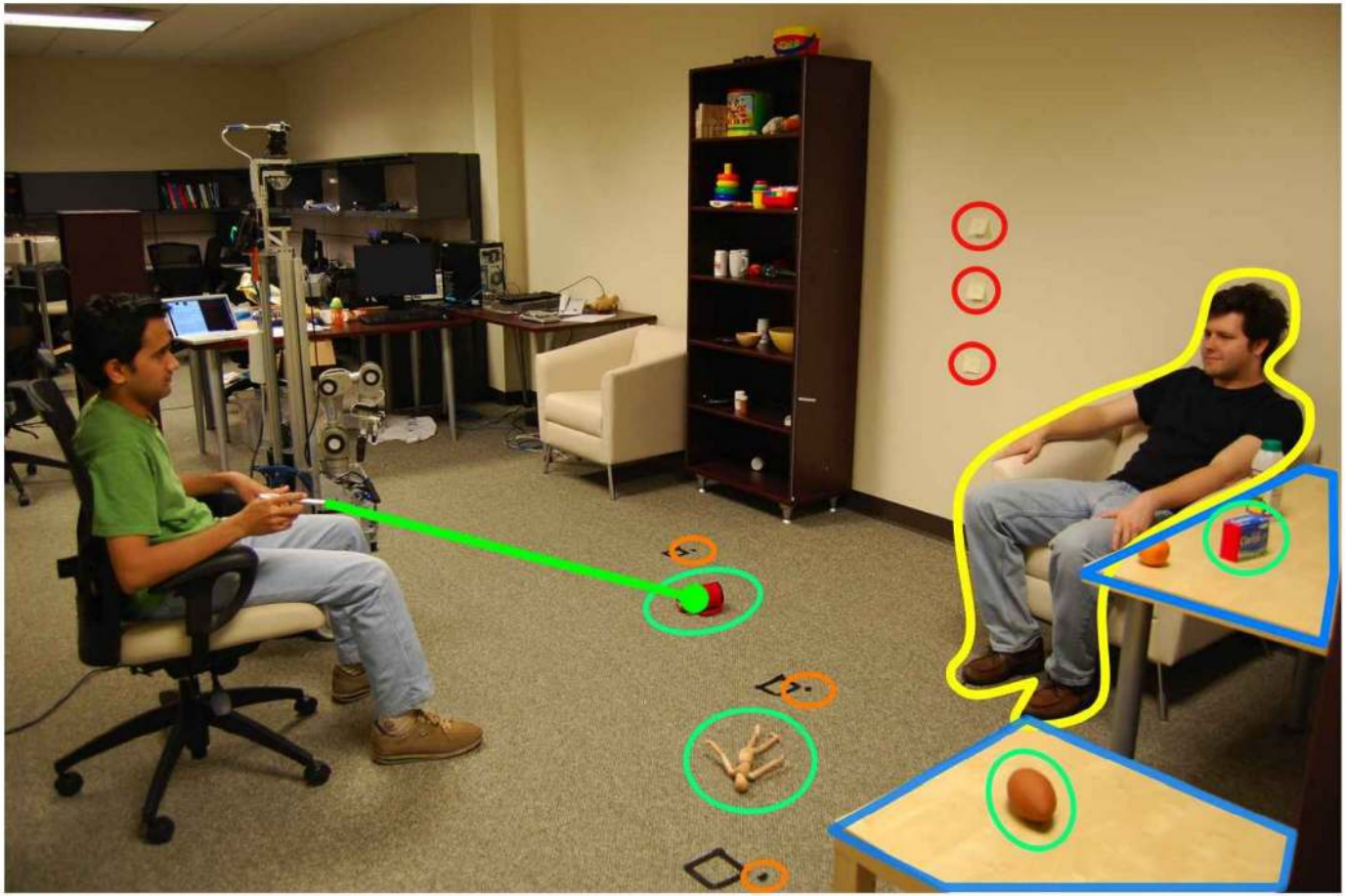


EL-E: An Assistive Mobile Manipulator that Autonomously Fetches Objects from Flat Surfaces, Advait Jain and Charles C. Kemp, Autonomous Robots, 2010

Georgia Tech

PPS-Tags: Physical Perceptual and Semantic Tags for Autonomous Mobile Manipulation, Hai Nguyen, Travis Deyle, Matt Reynolds, and Charles C. Kemp, IROS 2009 workshop: Semantic Perception for Mobile Manipulation, 2009.

Georgia Tech

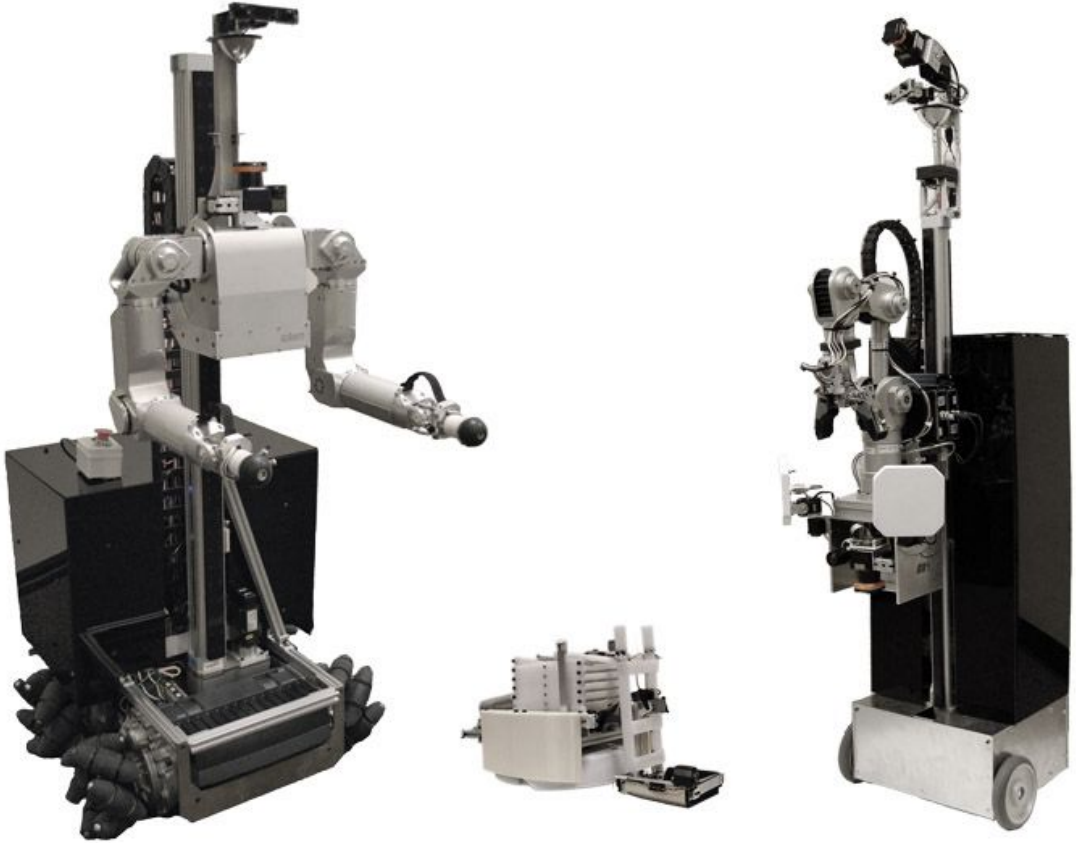


A Clickable World: Behavior Selection Through Pointing and Context for Mobile Manipulation, Hai Nguyen, Advait Jain, Cressel Anderson, and Charles C. Kemp, IEEE/RJS International Conference on Intelligent Robots and Systems (IROS), 2008.

Georgia Tech

Hand It Over or Set It Down: A User Study of Object Delivery with an Assistive Mobile Manipulator, Young Sang Choi, Tiffany L. Chen, Advait Jain, Cressel Anderson, Jonathan D. Glass, and Charles C. Kemp, IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2009.

Georgia Tech



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In 2010 the World Changed

Image from
https://www.roboticstoday.com/institutions/willow-garage

Photo from
https://www.flickr.com/photos/willowgarage/4675655695/

Domestic robots for older adults: Attitudes, preferences, and potential, Cory-Ann Smarr, Tracy L. Mitzner, Jenay M. Beer, Akanksha Prakash, Tiffany L. Chen, Charles C. Kemp, and Wendy A. Rogers. International Journal of Social Robotics, 6(2):229–247, 2014.

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Photo from
https://www.flickr.com/photos/willowgarage/4648144203/

Mobile Manipulators Can Provide Meaningful Assistance






research from the Healthcare Robotics Lab (healthcare-robotics.com) at Georgia Tech

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Mobile Manipulators Can Provide Meaningful Assistance

research from the Healthcare Robotics Lab (healthcare-robotics.com) at Georgia Tech

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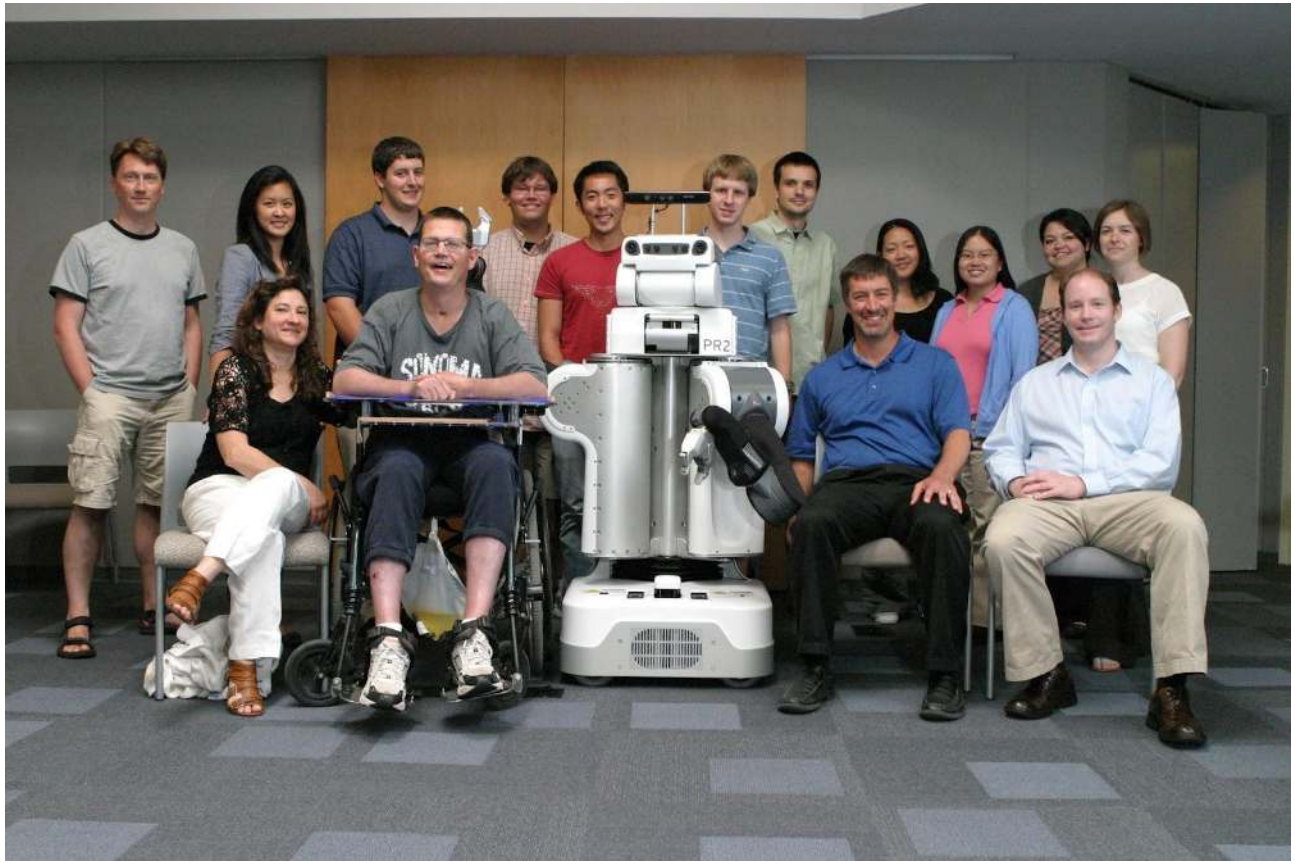
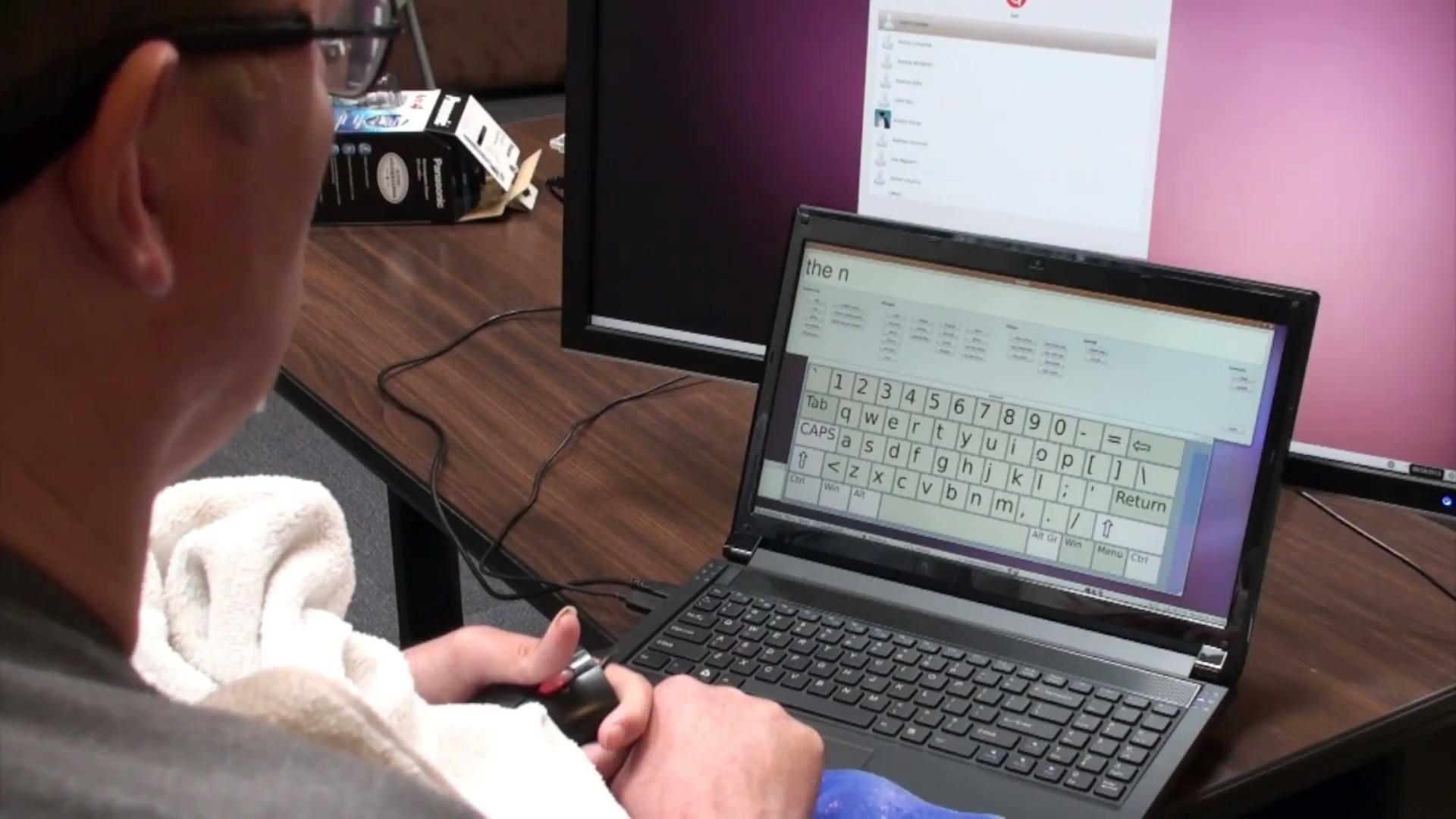
The Robots for Humanity Project



Robots for humanity: using assistive robotics to empower people with disabilities, Tiffany L. Chen, Matei Ciocarlie, Steve Cousins, Phillip Grice, Kelsey Hawkins, Kaijen Hsiao, **Charles C. Kemp**, Chih-Hung King, Daniel A. Lazewatsky, Adam Leeper, Hai Nguyen, Andreas Paepcke, Caroline Pantofaru, William D. Smart, and Leila Takayama, IEEE Robotics & Automation Magazine, 2013

Photo taken on June 16, 2011 at Willow Garage. Image from https://www.flickr.com/photos/willowgarage/5941309642 .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Return
Panasonic

Assistive Mobile Manipulation for Self-Care Tasks Around the Head, Kelsey Hawkins, Phillip M. Grice, Tiffany L. Chen, Chih-Hung King, and Charles C. Kemp, 2014 IEEE Symposium on Computational Intelligence in Robotic Rehabilitation and Assistive Technologies, 2014.

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Assistive Mobile Manipulation for Self-Care Tasks Around the Head, Kelsey Hawkins, Phillip M. Grice, Tiffany L. Chen, Chih-Hung King, and Charles C. Kemp, 2014 IEEE Symposium on Computational Intelligence in Robotic Rehabilitation and Assistive Technologies, 2014.

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In-home and remote use of robotic body surrogates by people with profound motor deficits, Phillip M. Grice and Charles C. Kemp, PLoS ONE 14(3), 2019.

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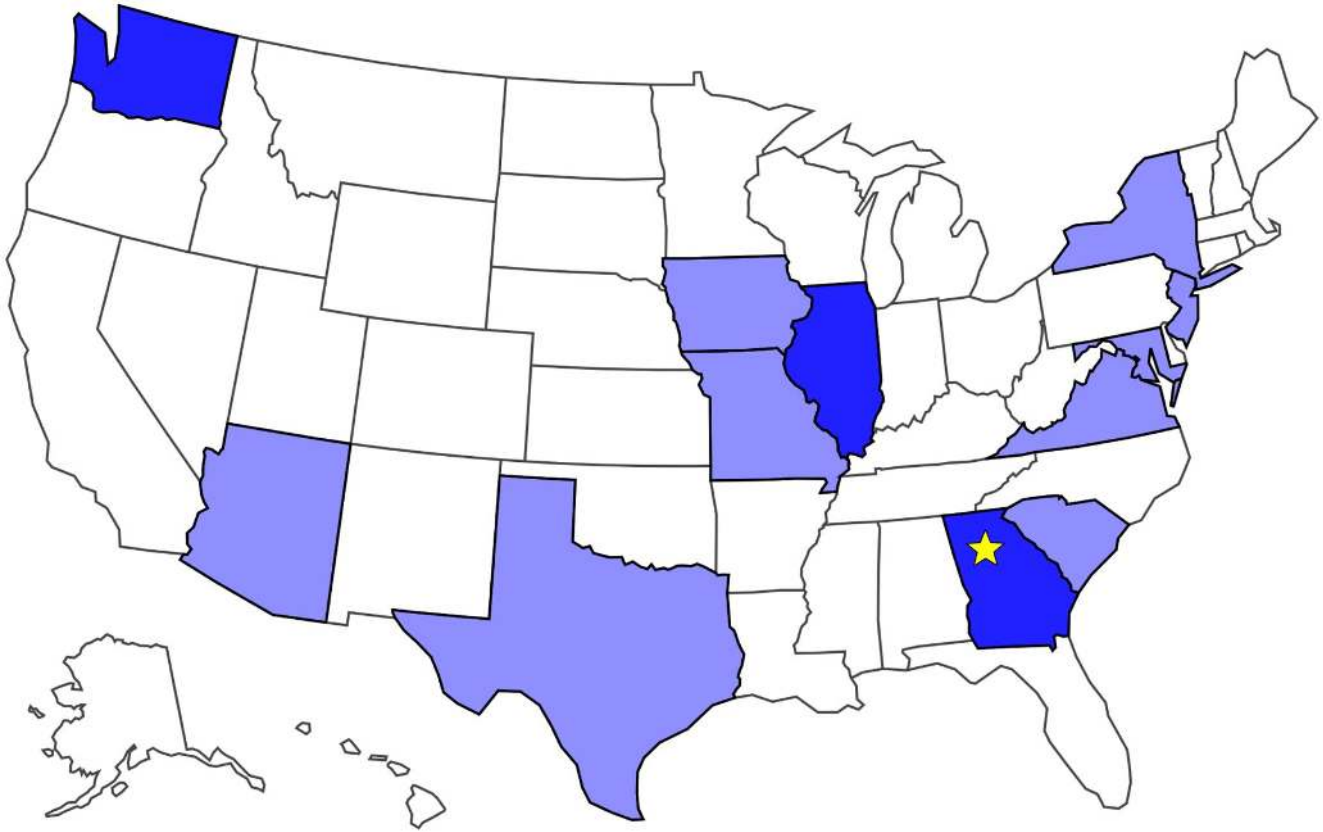
Control Interface
Phillip
monty1wan.bme.gatech.edu:8008/assistive_teleop/vci.html
Main Menu
Look
Spine
Left Hand
Right Hand
Drive
Controls
Step Size
XS
S
M
L
Position/Rotation
Hand Position
Wrist Rotation
3D Peek
Move Aside
Move to Setup
Re-zero Skin
Gripper
4x


Realtime

15 Participants



In-home and remote use of robotic body surrogates by people with profound motor deficits, Phillip M. Grice and Charles C. Kemp, PLoS ONE 14(3), 2019.

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Causes of Motor Impairment

6 Spinal Muscular Atrophy (SMA)

3 Muscular Dystrophy (Duchenne/Becker)

3 Spinal Cord Injury

1 Amyotrophic Lateral Sclerosis (ALS)

1 Arthrogryposis

1 Dejerine-Sottas

ARAT Threshold: 9/57 with best arm

Computer Access Devices

4 – Trackball

3 – Touchpad

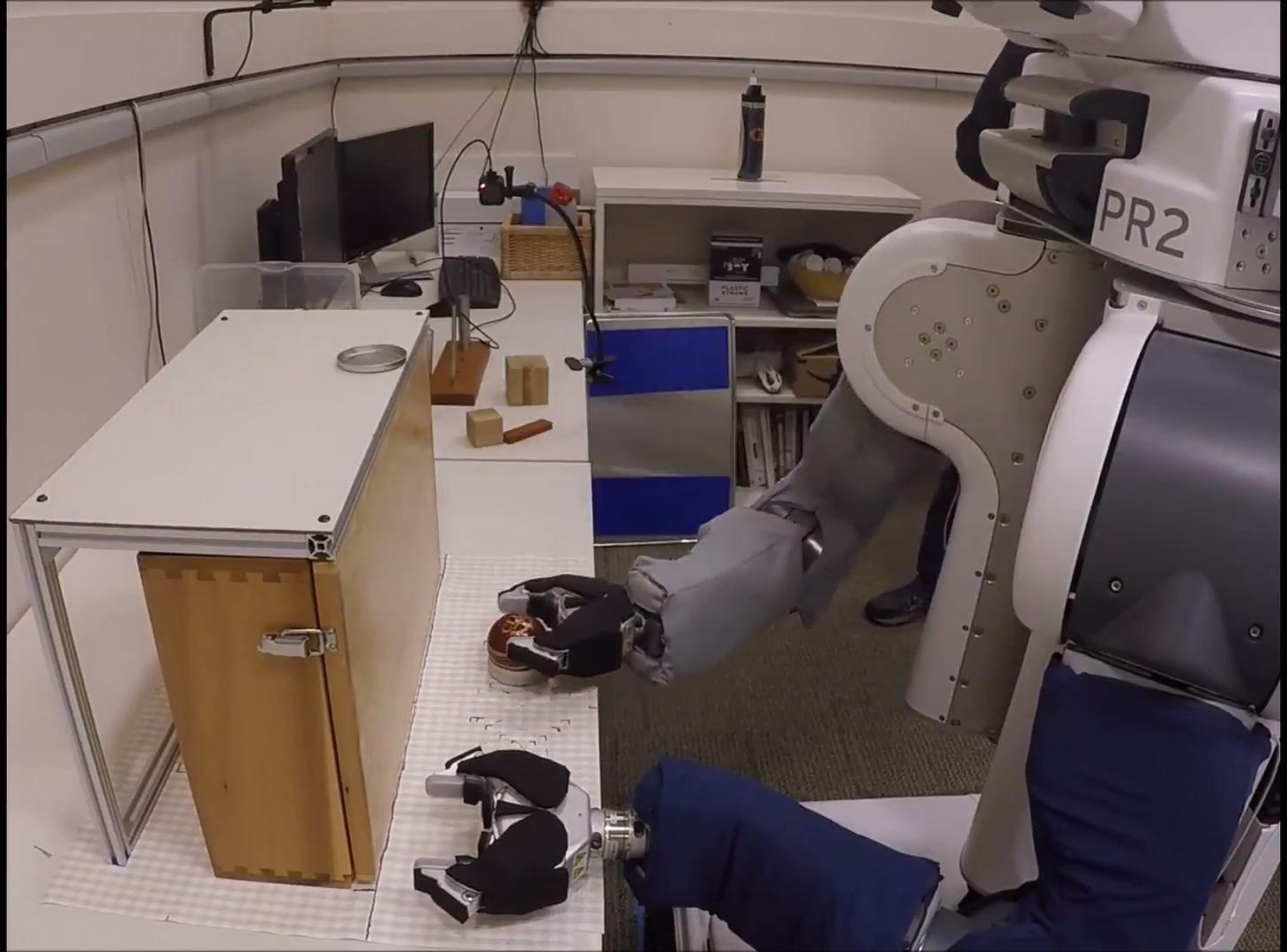
3 – Head-mouse (TrackerPro, 2x HeadMouse Extreme)

2 – Standard mouse

1 – Eye-gaze (Tobii)

1 – Touchpad w/Stylus held in mouth

1 – Speech (Dragon MouseGrid)


40x
PR2
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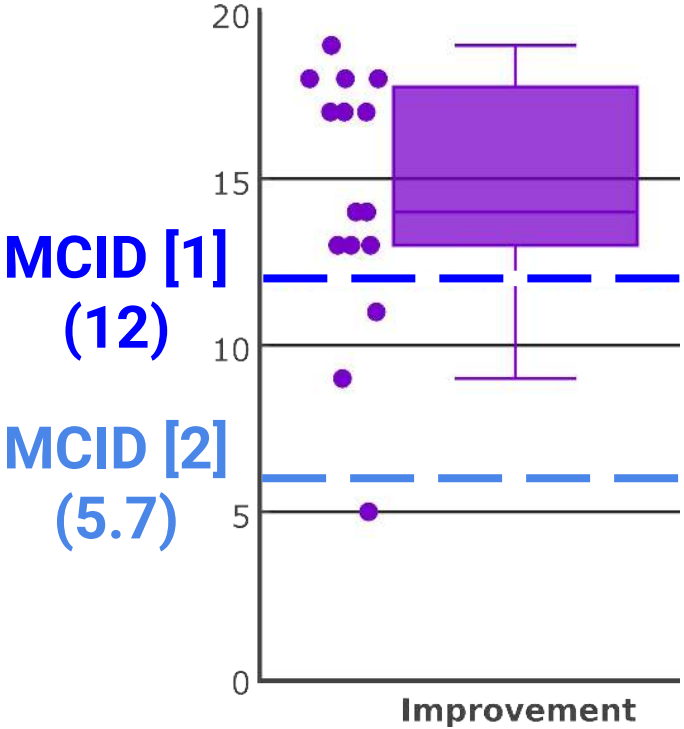
Improvement Exceeded Conservative Minimal Clinically Important Difference (MCID)

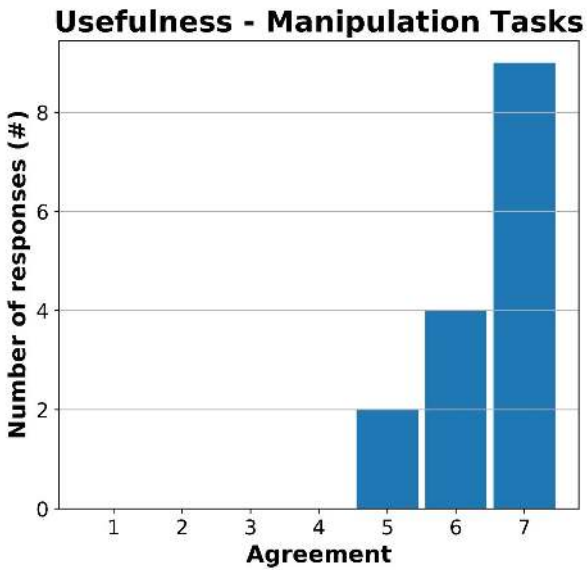


[1] C. E. Lang, D. F. Edwards, R. L. Birkenmeier, and A. W. Dromerick, **"Estimating minimal clinically important differences of upper-extremity measures early after stroke,"** Archives of physical medicine and rehabilitation, vol. 89, no. 9, pp. 1693– 1700, 2008.

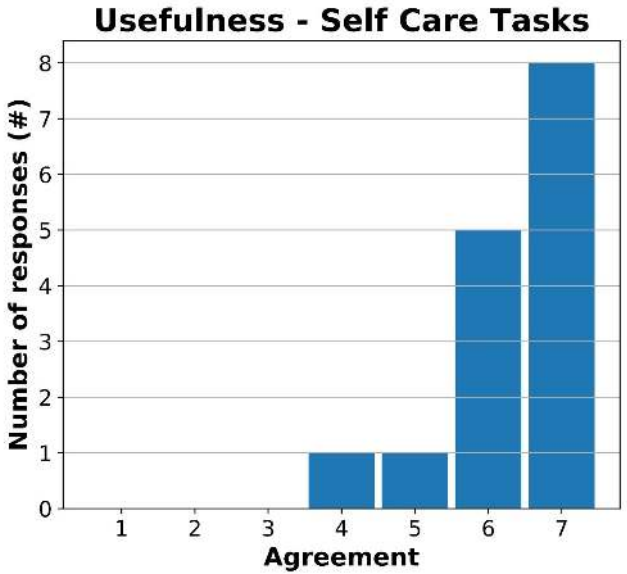
[2] J. H. Van der Lee, V. De Groot, H. Beckerman, R. C. Wagenaar, G. J. Lankhorst, and L. M. Bouter, **"The intra-and interrater reliability of the action research arm test: A practical test of upper extremity function in patients with stroke,"** Archives of physical medicine and rehabilitation, vol. 82, no. 1, pp. 14–19, 2001.

1-tailed Wilcoxon signed-rank test vs MCID: W=96, **p=.021**

Perceived Usefulness



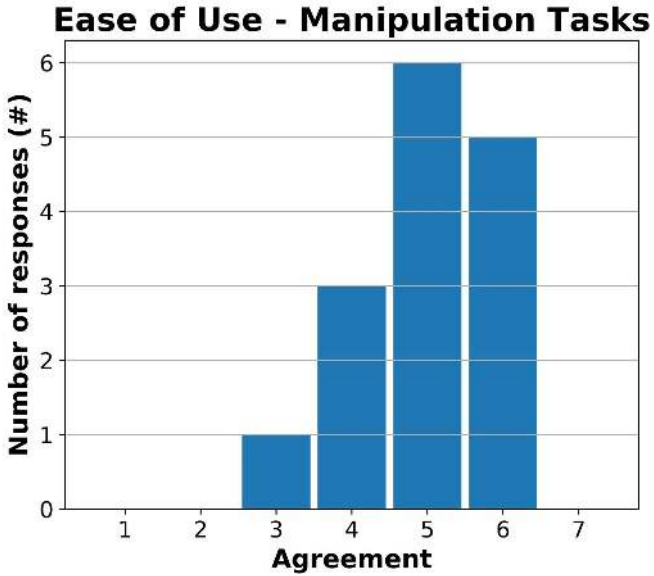
Wilcoxon signed-rank test vs neutral:
W=120, p=.000258



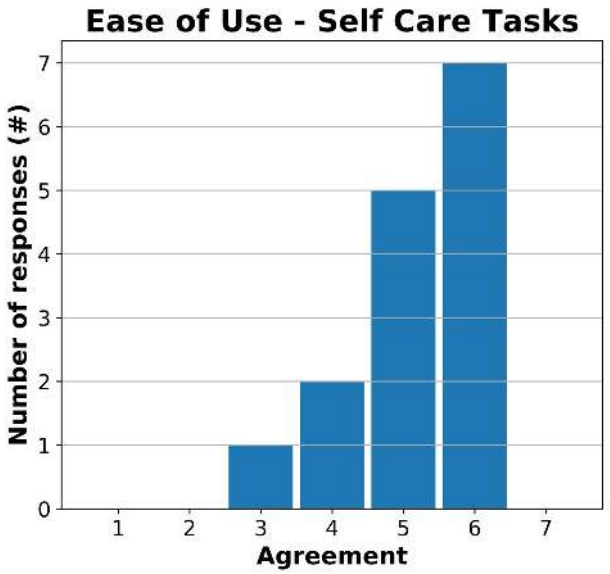
Wilcoxon signed-rank test vs neutral:
W=105, p=.000402

1: Strongly Disagree
2: Disagree
3: Somewhat Disagree
4: Neither Agree nor Disagree
5: Somewhat Agree
6: Agree
7: Strongly Agree

Perceived Ease of Use



Wilcoxon signed-rank test vs neutral:
W=74, p=.00264



Wilcoxon signed-rank test vs neutral:
W=87.5, p=.00142

1: Strongly Disagree
2: Disagree
3: Somewhat Disagree
4: Neither Agree nor Disagree
5: Somewhat Agree
6: Agree
7: Strongly Agree

Limitations

- Slow operation
- Errors
- Depth perception

Limitations

- Slow operation
- Errors
- Depth perception
- **The robot**

Two Problems

- Willow Garage shut down in 2014
- PR2 was impractical
  - $400,000
  - 227 kg (~500 lb)
  - 67 cm wide (~2.2 ft)

Photo from Willow Garage

2002

2010

2008

?

2017

Hourglass photo from https://commons.wikimedia.org/wiki/File:Wooden_hourglass_3.jpg

Fetch
Cost: ~$100,000
Footprint Width: 51cm (20”)
Weight: 113 kg (250 lb)

PAL Tiago
Cost: $58,485 (base model)
Footprint Width: 54cm (21”)
Weight: 70 kg (154 lb)

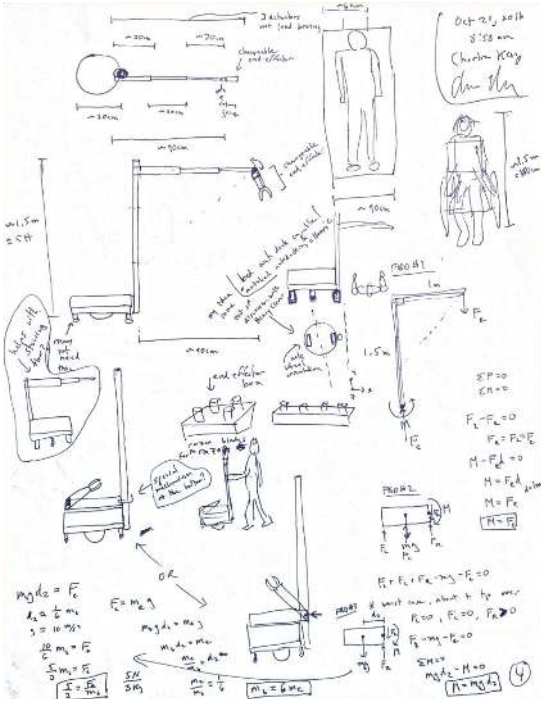
Toyota HSR
Cost: not commercially available
Footprint Width: 43cm (17”)
Weight: 37 kg (82 lb)

Photos from https://fetchrobotics.com/fetch-mobile-manipulator/, https://pal-robotics.com/robots/tiago/, https://global.toyota/en/download/8725328

Frustration Leads to Invention

Minimize the actuator requirements while maximizing the capabilities.

- **affordable**
- compact
- lightweight
- humancentric
- capable



My Initial Georgia Tech Notes
October 2016

[The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments](), Charles C. Kemp, Aaron Edsinger, Henry M. Clever, Blaine Matulevich, preprint on arxiv.org, 2021.

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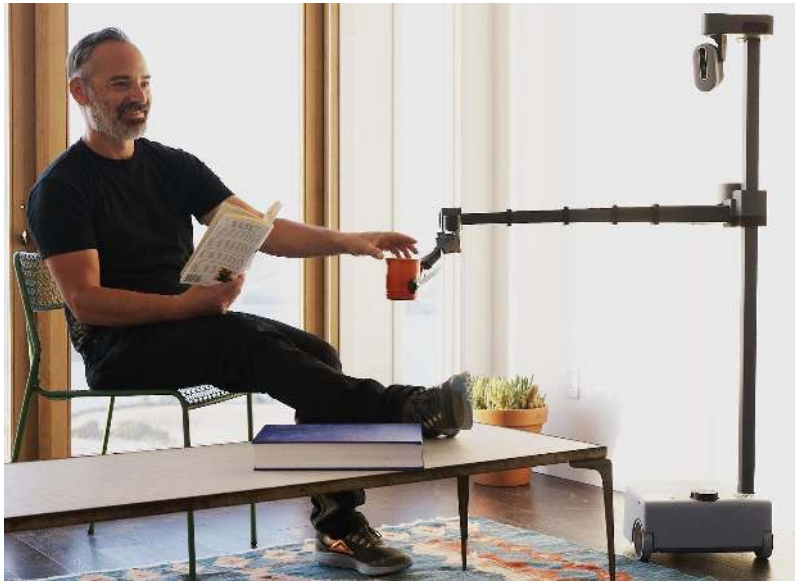
Georgia Tech's Prototype
March 2017

Hello Robot's Product - A Robot for Research
July 2020



2016	2017		2018	2019	2020

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Founding Team

Aaron Edsinger, Founder & CEO

- Founder Meka Robotics and Redwood Robotics
- Former Director of Robotics, Google
- PhD MIT CSAIL
- Built Meka and Redwood Robotics and sold to Google
- World expert on design for robot manipulation

Charlie Kemp, Founder & CTO

- Associate Professor, Georgia Tech
- Founder & Director of the Healthcare Robotics Lab
- PhD MIT CSAIL
- World expert on assistive mobile manipulation

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Hello Robot’s Founding Advisors

Henry & Jane Evans

Vincent Dureau

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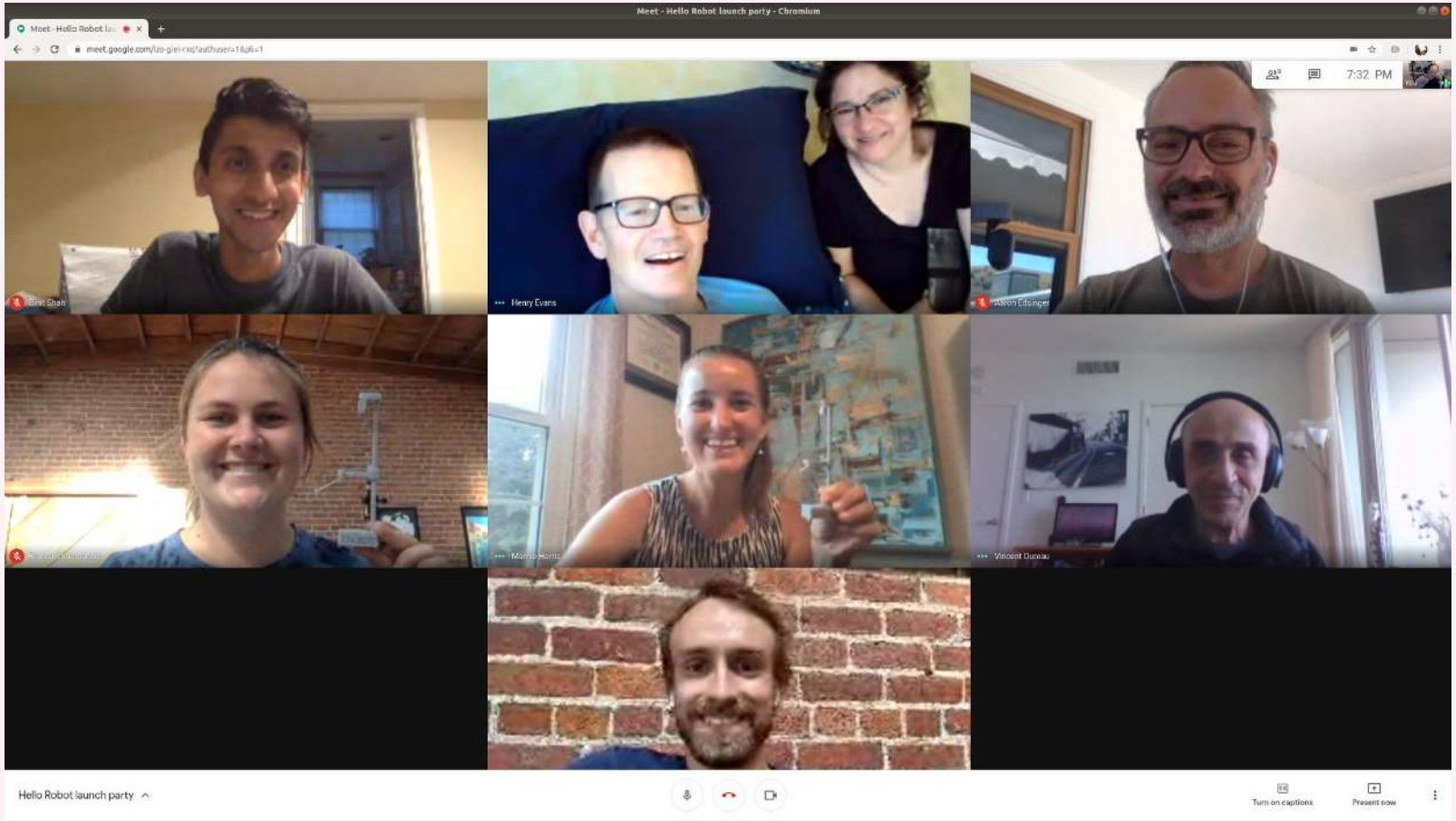
Launch Party, July 2020



hello robot

3 years
8 versions
tested in Charlie’s home

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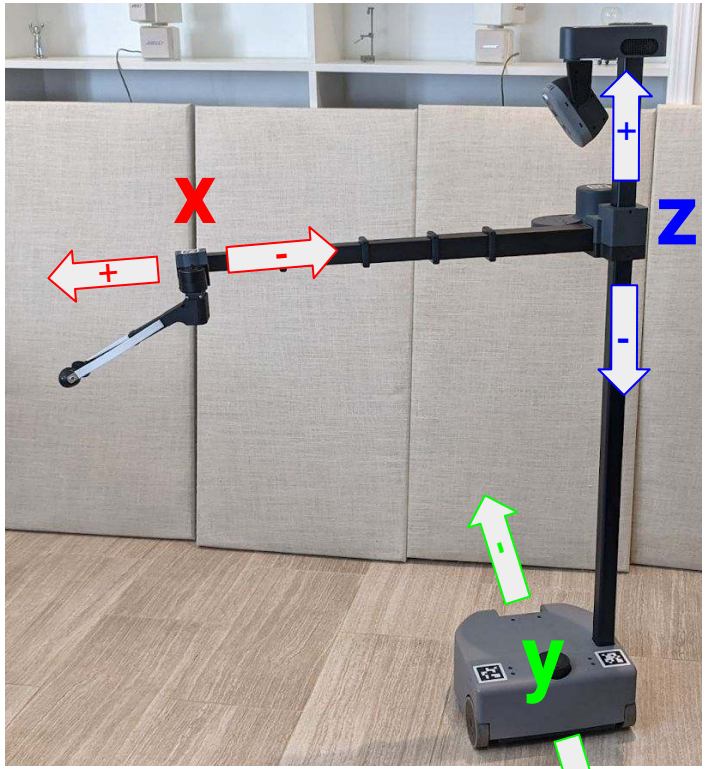
Two Modes of Operation

Manipulation Mode
(Cartesian Manipulator)

Navigation Mode
(Differential Drive Mobile Robot)

Arm & Tool Stow into the Footprint

Manipulation Depends on the Mobile Base



Manipulation Mode
(Cartesian Manipulator)

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Robotic Cubism

- Dimensions matched to human environments
- The human form deconstructed and reassembled

La Femme au Violon - Pablo Picasso, 1911

“In Cubist artwork, objects are analyzed, broken up and reassembled in an abstracted form”
- https://en.wikipedia.org/wiki/Cubism

The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments,
Charles C. Kemp, Aaron Edsinger, Henry M. Clever, Blaine Matulevich, preprint on arxiv.org, 2021.

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< 50th Percentile Hip Width

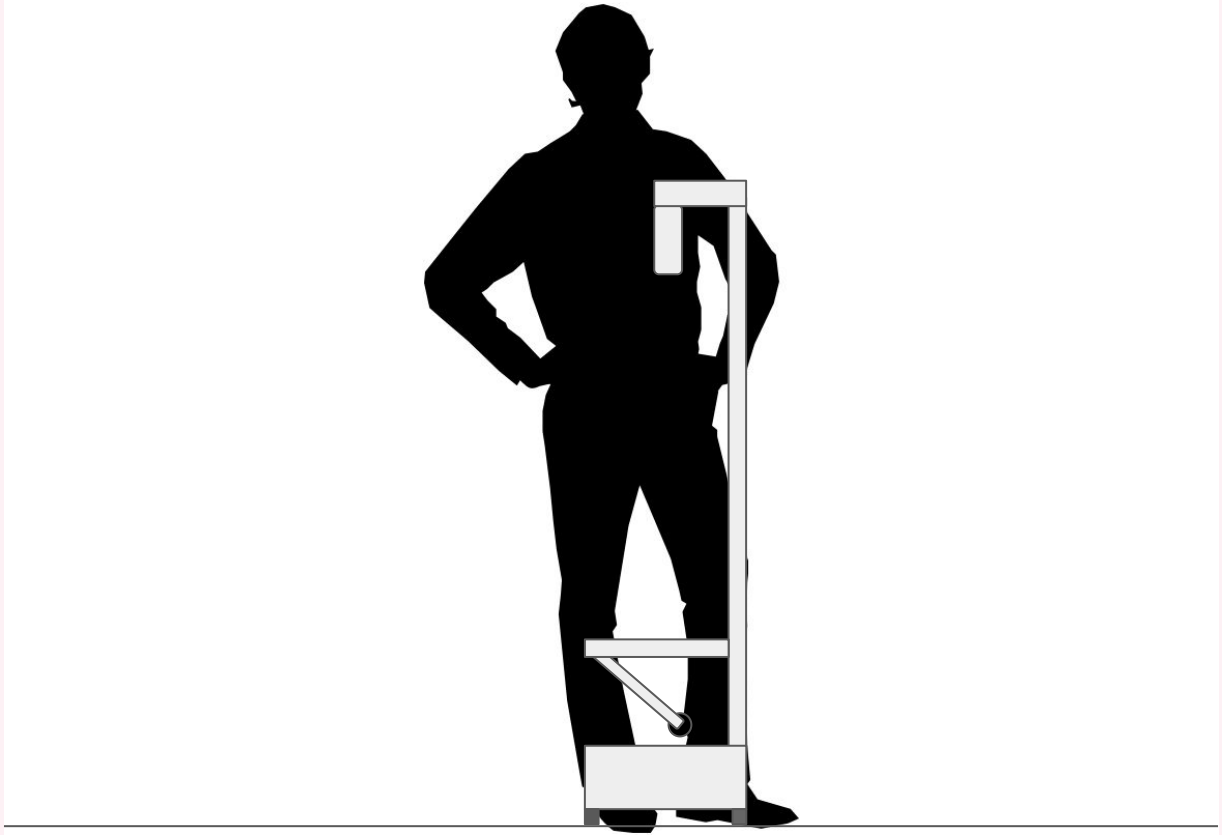

Image: https://openclipart.org/detail/260142/arms-akimbo-male

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50th Percentile Arm Length

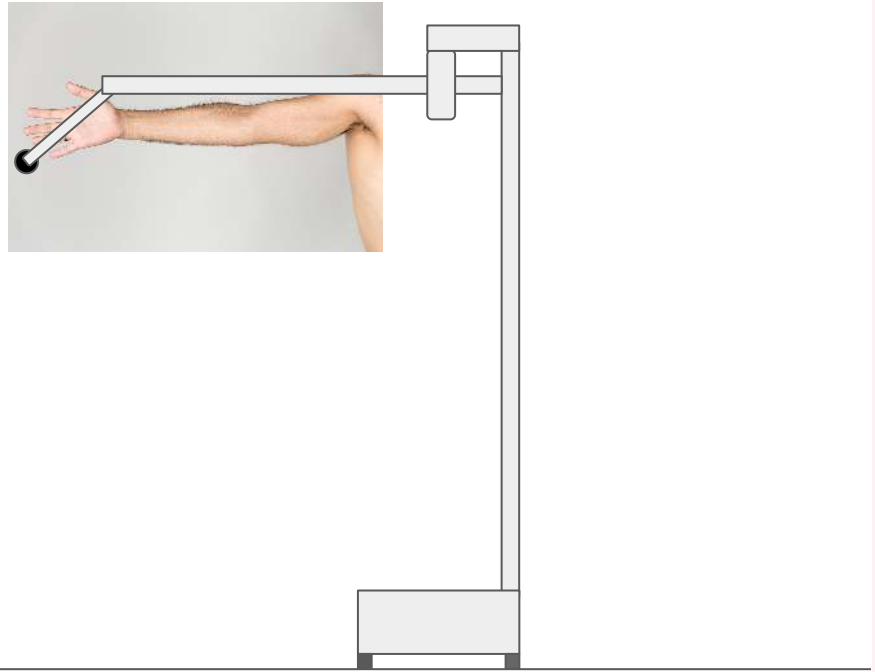

Image: https://en.wikipedia.org/wiki/Arm#/media/File:Extended_arm.jpg

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Reaches 36” Countertops

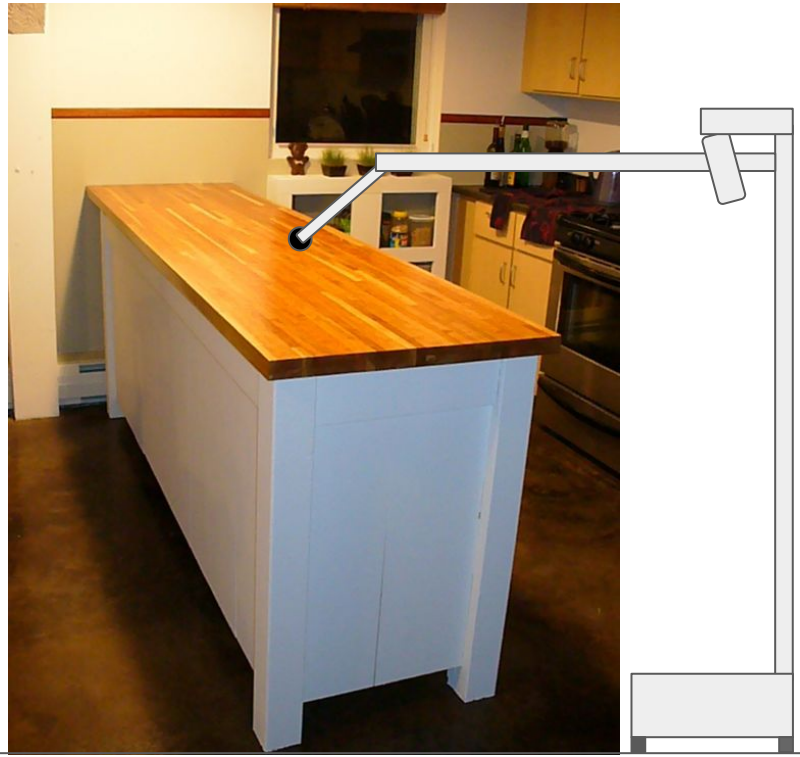

Image: https://commons.wikimedia.org/wiki/File:Butcher_block_counter_top.jpg

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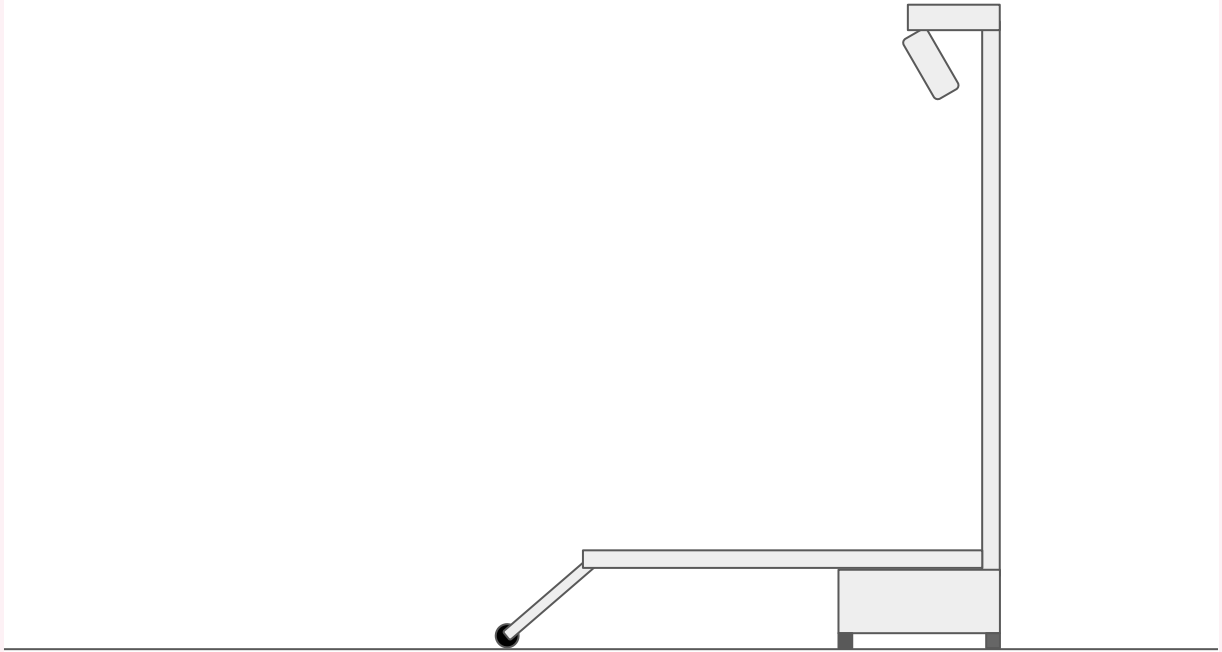
Reaches the Floor



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95th Percentile Shoulder Height for Wheelchair Users

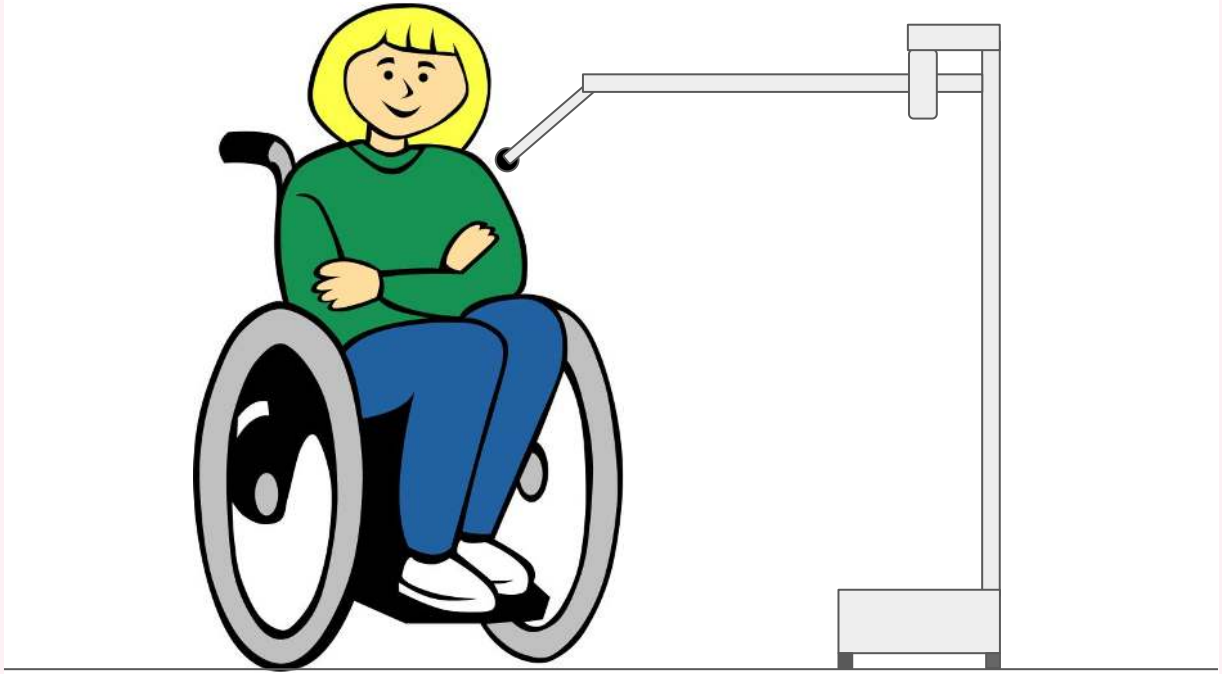

Image: https://openclipart.org/detail/510/girl-in-wheelchair

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23 kg (51 lb)

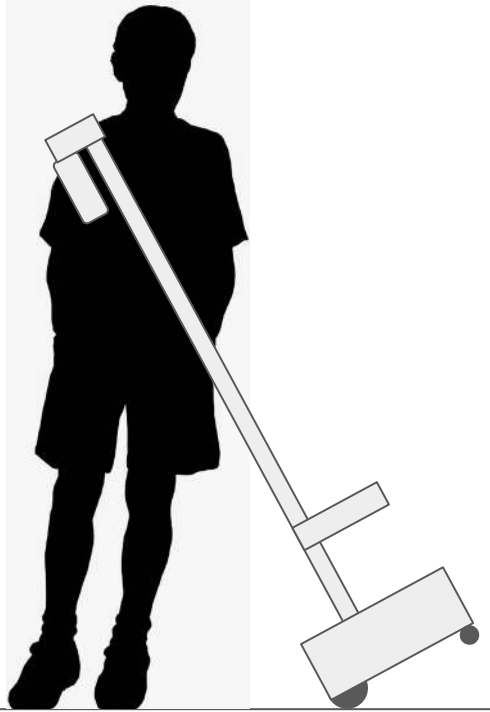

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Image: https://www.seekpng.com/ipng/u2q8y3i1o0r5a9o0_beautiful-silhouettes-of-children-boy-silhouette-transparent-background/

Image from https://sites.gatech.edu/robotic-caregivers/ .


amp air

A Capable Robot

https://www.youtube.com/c/HelloRobot/videos

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Teleoperated Home Examples

https://www.youtube.com/c/HelloRobot/videos

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Teleoperated Workplace Examples

Shelf Picking

Inspection with a Camera

https://www.youtube.com/c/HelloRobot/videos

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Teleoperated Examples with the Dexterous Wrist






https://www.youtube.com/c/HelloRobot/videos

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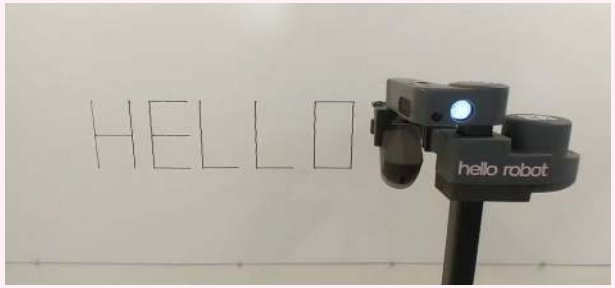
Autonomous Examples



https://forum.hello-robot.com/t/autonomy-video-details

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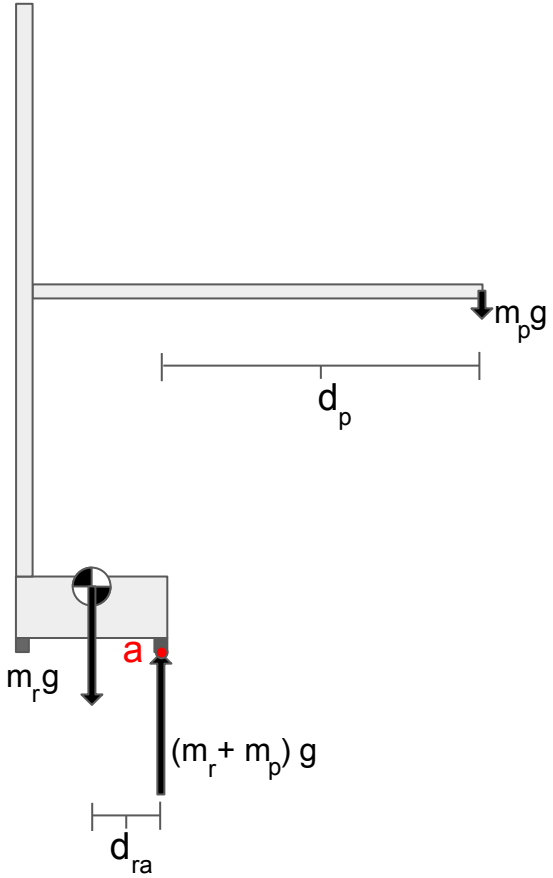
Tipping from Payload



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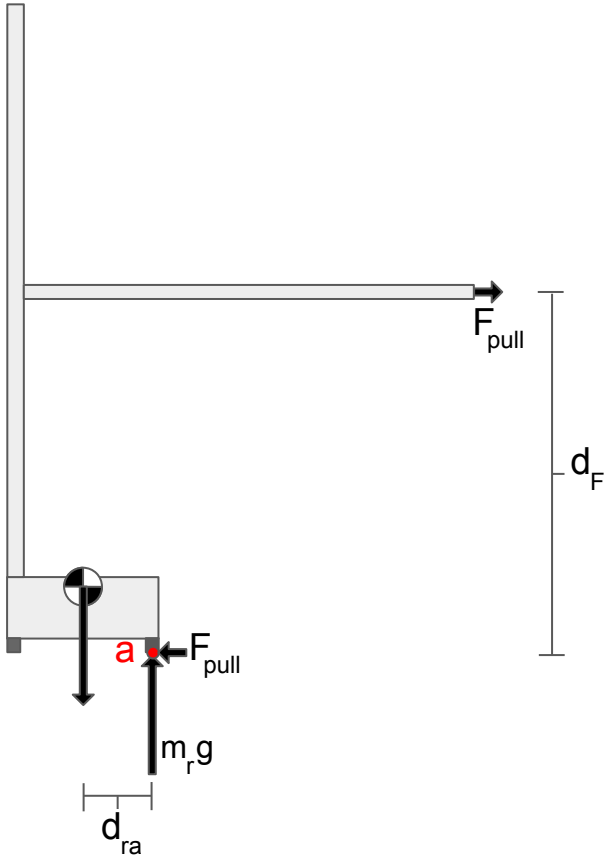
Tipping from Pulling



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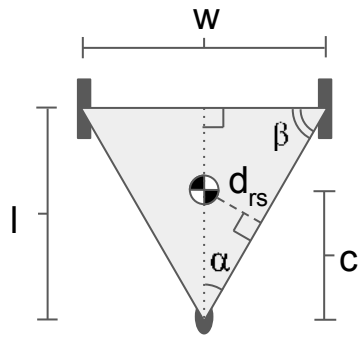
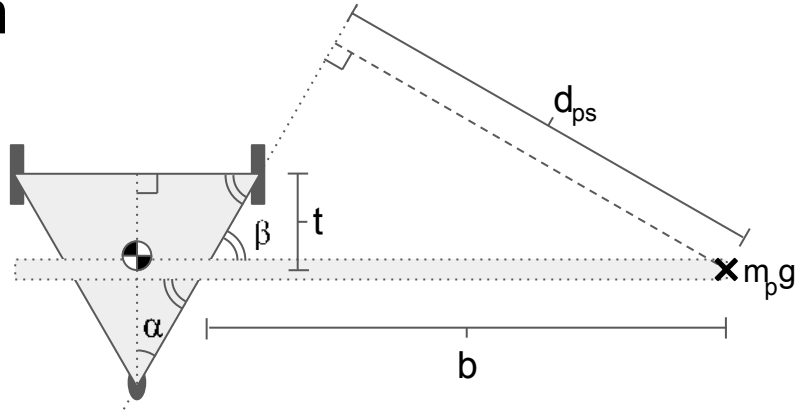
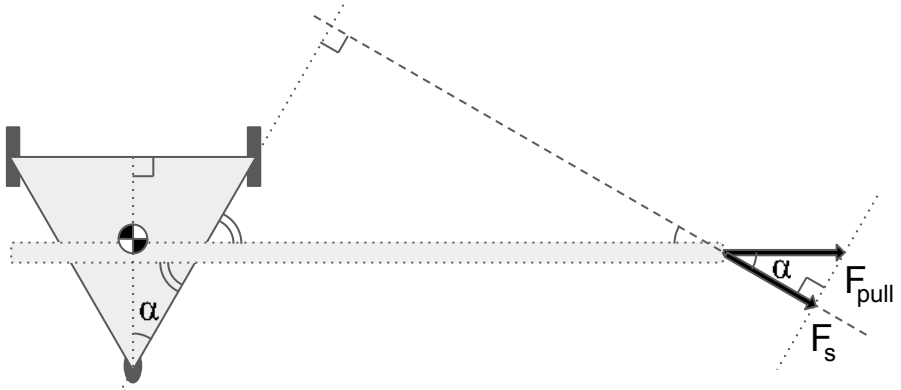
Triangular Support Polygon



Moment Arm (d_{rs}) for the Robot's Center of Mass



Moment Arm (d_{ps}) for the Payload



Tipping Component (F_s) of the Pulling Force

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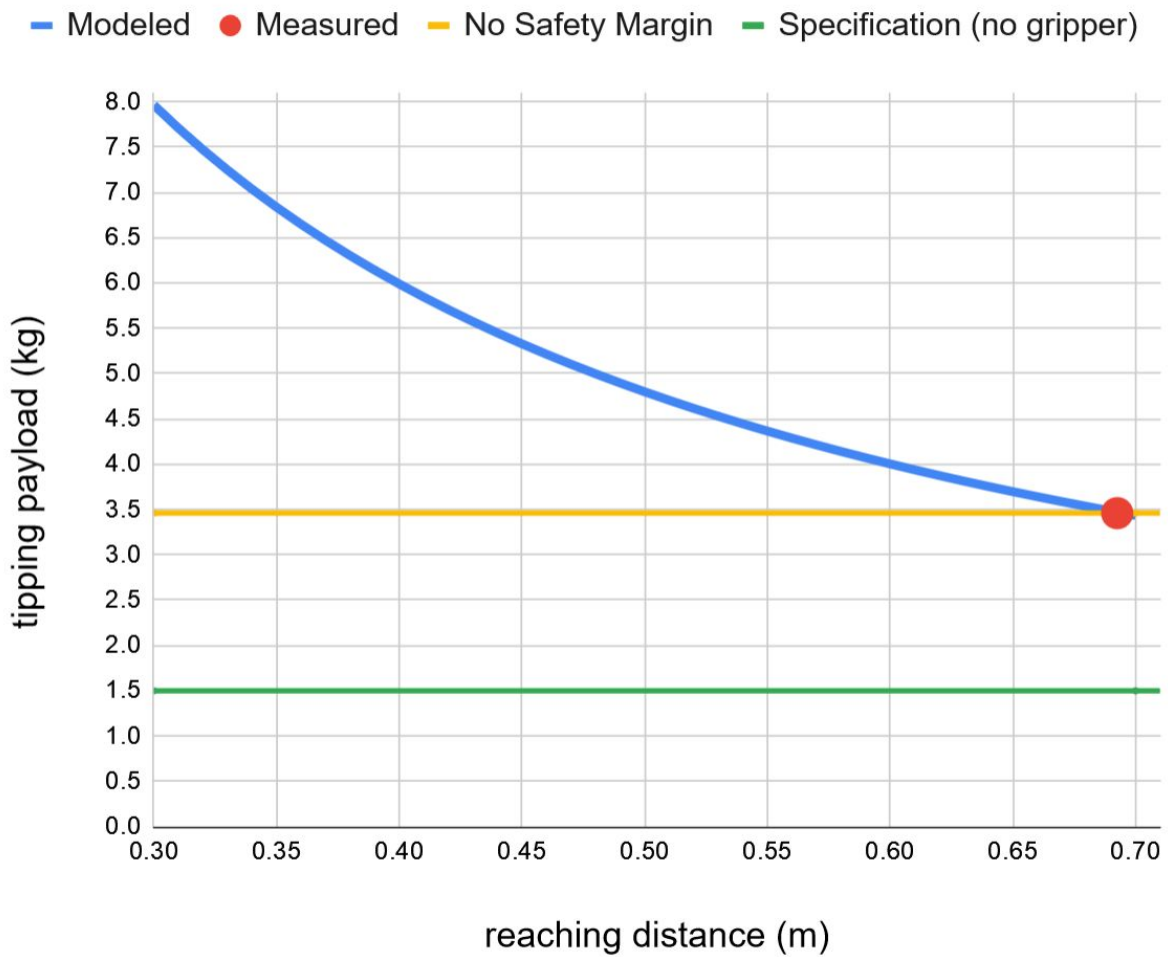
Maximum Payload with Gripper



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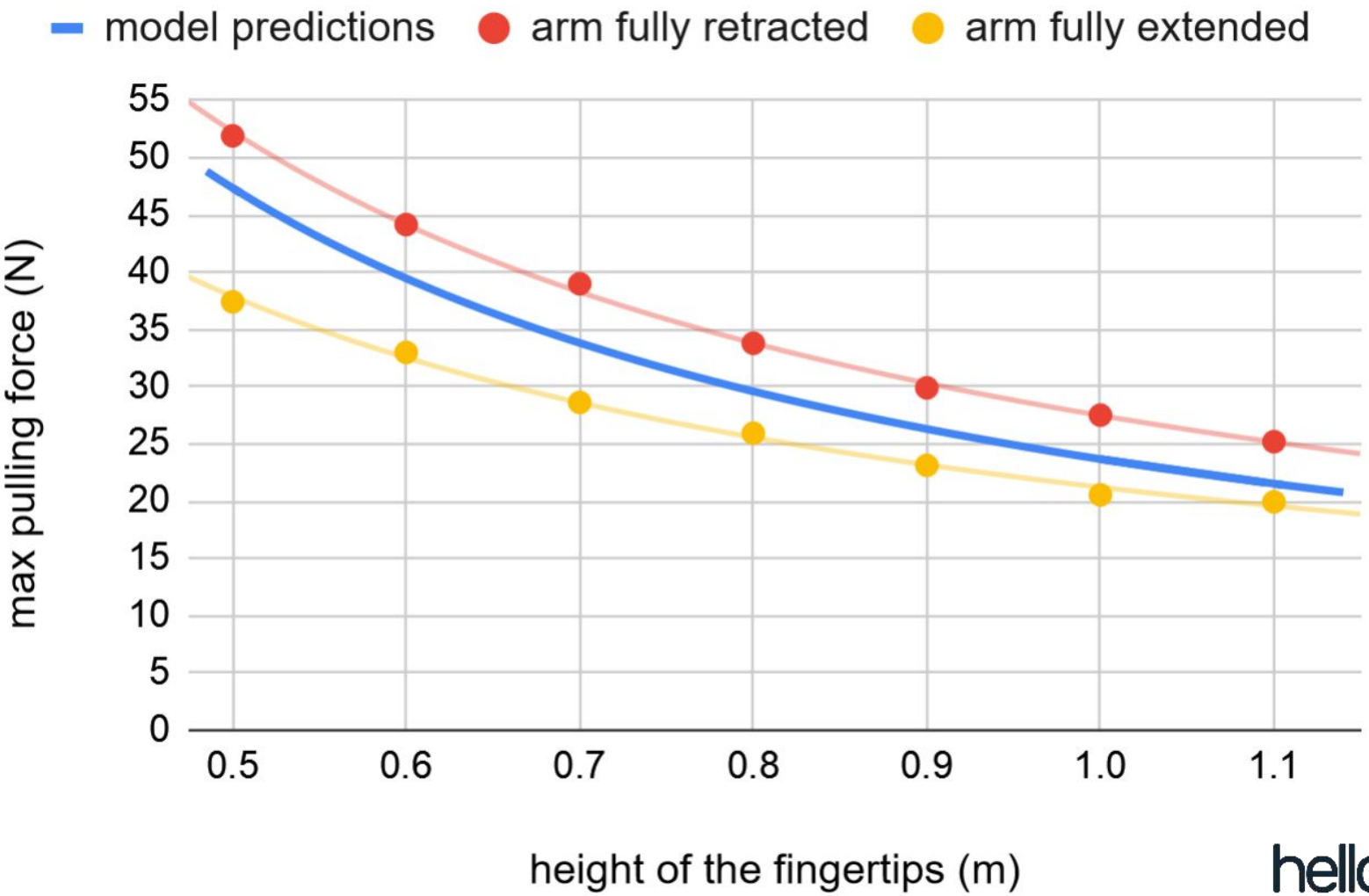
model predictions
arm fully retracted
arm fully extended
max pulling force (N)
55
50
45
40
35
30
25
20
15
10
5
0
0.5
0.6
0.7
0.8
0.9
1.0
1.1
height of the fingertips (m)

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Moving Forward as a Community

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Successful Launch in July 2020

IEEE SPECTRUM Topics Reports Blogs Multimedia

Automaton | Robotics | Home Robots

14 Jul 2020 | 4:01 GMT

Ex-Googler's Startup Comes Out of Stealth With Beautifully Simple, Clever Robot Design

Hello Robot's Stretch wants to reinvent how mobile manipulators perform tasks in home environments

By **Evan Ackerman and Erico Guizzo**

Photo: Hello Robot

Hello Robot, founded by former Google robotics director Aaron Edsinger and Georgia Tech professor Charlie Kemp, is introducing Stretch, a mobile manipulator that weighs only 23 kg and costs less than $20,000.

SVR Silicon Valley Robotics

supporting the innovation and commerc

Hello Robot wins Innovation Award in SVR 'Good Robot' Industry Awards

Posted on December 14, 2020 by Andra Keay

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Tech

Research robot helps with housework and other news

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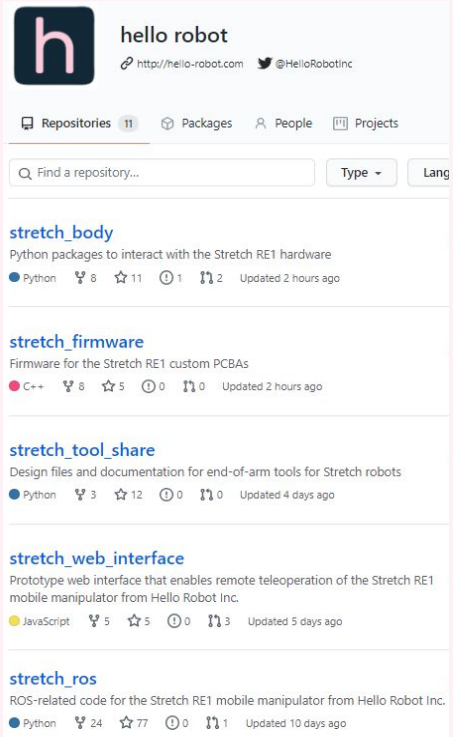
Transparency & Openness

Simple Pricing
hello-robot.com

Open Source & Open Development
github.com/hello-robot

Open Hardware Accessories
github.com/hello-robot/stretch_tool_share

Open Forum
forum.hello-robot.com



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www.hello-robot.com

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A Win for Inclusive Design

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8X Teleoperaton

Assistive Robotics at the University of Washington

21 people, **including 3 people with disabilities**, remotely operated Stretch

Cabrera, Maria E., Tapomayukh Bhattacharjee, Kavi Dey, and Maya Cakmak. "An Exploration of Accessible Remote Tele-operation for Assistive Mobile Manipulators in the Home." In *2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN)*, pp. 1202-1209. IEEE, 2021.

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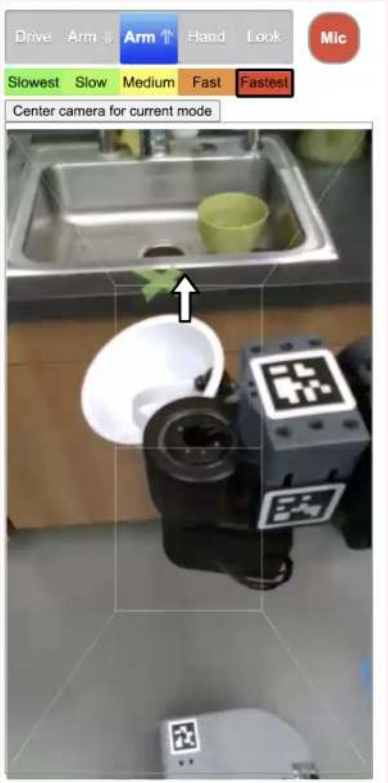
Assistant Professor
UMass Lowell

Tapo Bhattacharjee
Assistant Professor
Cornell University

Kavi Dey
Research Intern
Seattle Academy

Maya Cakmak
Associate Professor
University of Washington



[UW's open source web interface](), which significantly improved [Hello Robot's original version]().

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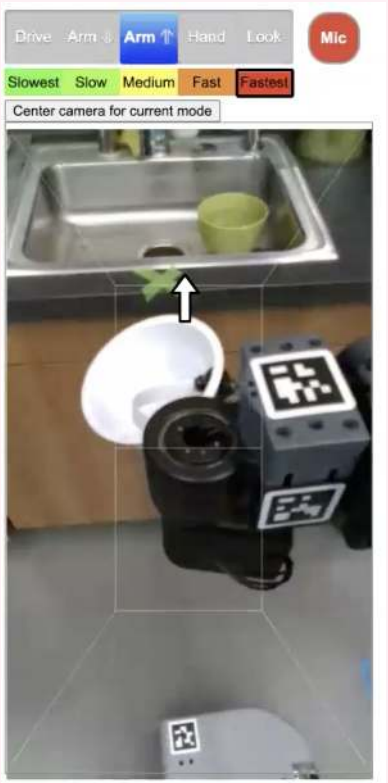

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Occupational Therapy Doctoral Project

Pacific University Oregon

Vy Nguyen

Henry & Jane Evans

Maya Cakmak

Kavi Dey

Tapo Bhattacharjee

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Harshal Mahajan Travis Kadylak Wendy Rogers Megan Bayles

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Elliston Franks

Charlie Kemp

Blaine Matulevich

Binit Shah

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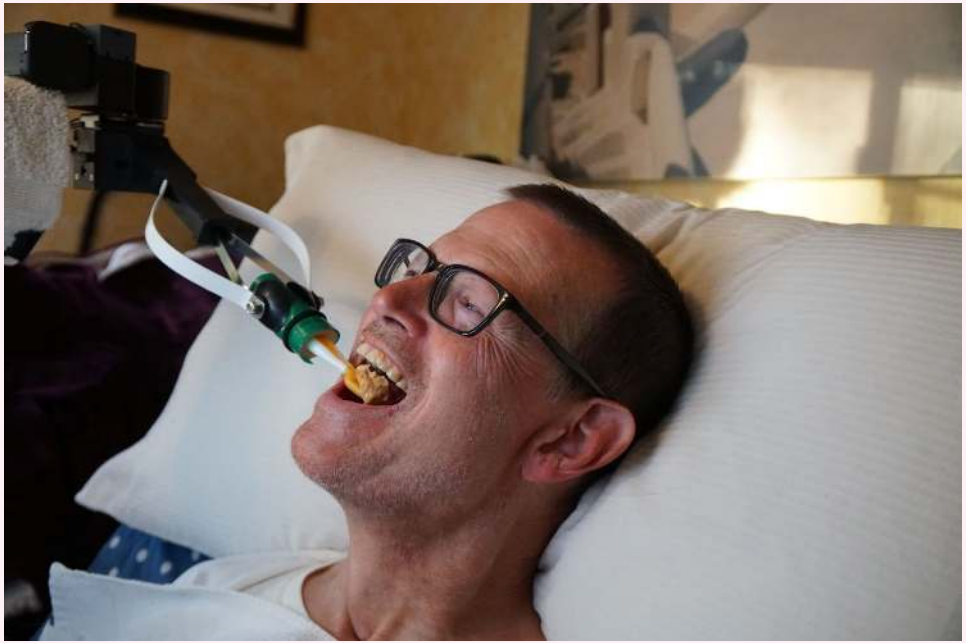
Stretch Provides Meaningful Assistance



https://forum.hello-robot.com/t/summer-research-on-in-home-use-by-henry-evans

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Stretch Provides Meaningful Assistance

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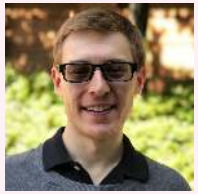
AI-CARING : New NSF AI Institute

AI CARING



- Hello Robot is an official industry partner
- Participating Institutions with Stretch
  - Umass Lowell
  - CMU
  - Georgia Tech
- Already an affiliated class at Georgia Tech
  - Robotic Caregivers: From Dreams to Reality
  - Project-based class using 3 Stretch robots
  - Taught by Prof. Kemp using open materials
- New classes related to AI-CARING
  - This class at Umass Lowell!
  - New class at CMU (spring 2022)
    - Robotic Caregivers and Intelligent Physical Collaboration
    - taught by Prof. Zackory Erickson

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AI-CARING : New NSF AI Institute

AI CARING

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Questions, Answers and Discussion