What will it take for human-scale mobile manipulators to be happily used in homes?

Charlie Kemp, PhD

Cofounder & Chief Technology Officer

hello robot®

What will it take for human-scale mobile manipulators *to be purchased* and happily used in homes?

Charlie Kemp, PhD

Cofounder & Chief Technology Officer

hello robot®

What will it take for human-scale mobile manipulators to be purchased and happily used in homes?

- The robot has to earn its place
- Safety is paramount
- An example design (Stretch robot)
- People with mobility impairments are promising early adopters

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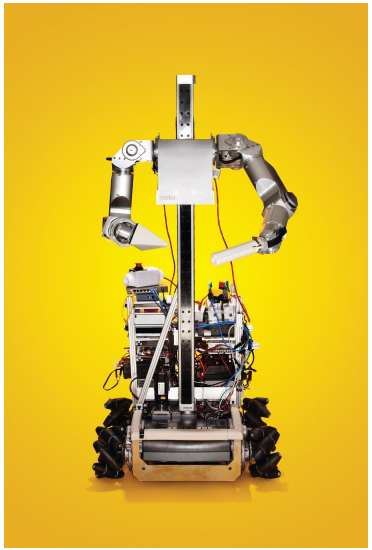
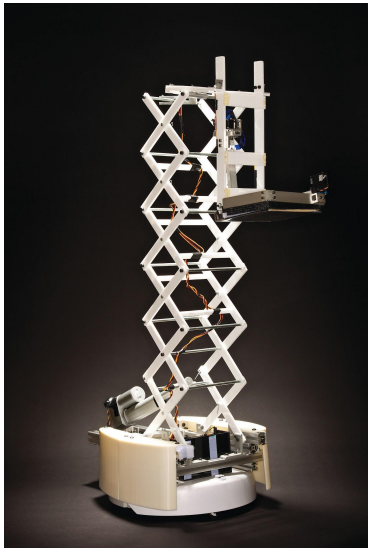
Stretch 3 from Hello Robot

I've focused on in-home assistive mobile manipulation since 2006

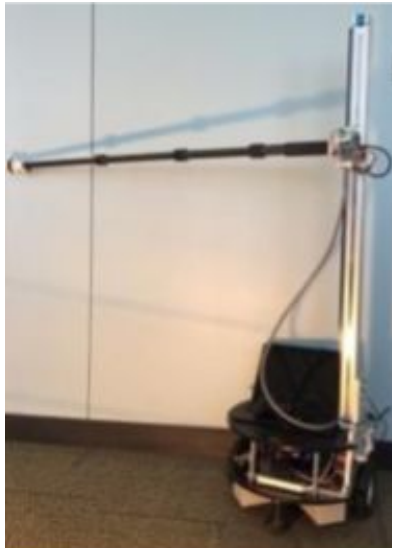
EL-E (2008)



Cody (2009)



Dusty (2010)



Early Prototype for Stretch (2016)

Commercialized by Hello Robot

Cody and Dusty Photos by Josh Meister

Georgia Tech

The Robotics Institute
RI | Seminar | **October 31, 2008**

Robotics Institute Seminar, October 31, 2008

Time and Place | Seminar Abstract | Speaker Biography | Speaker Appointments

Autonomous Mobile Manipulation for the Motor Impaired

Charlie Kemp
Georgia Tech

[Seminar Announcement]

[Original Video of my Talk (Adobe Flash FLV format)]

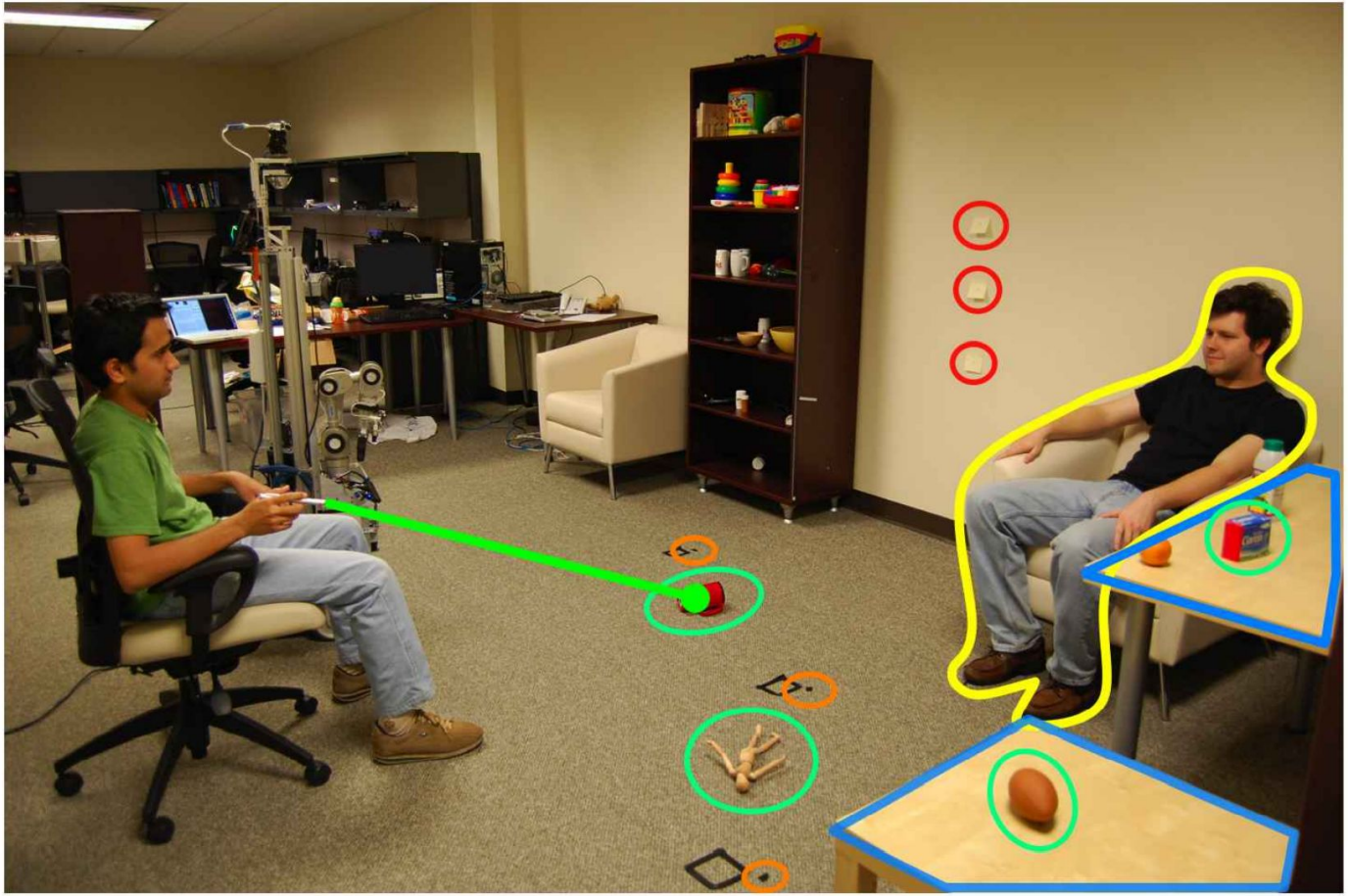
[New YouTube Version]

Stretch's Ancestor

EL-E from 2008

- Statically stable
- Small footprint
- Cameras high
- Reach floor and countertops

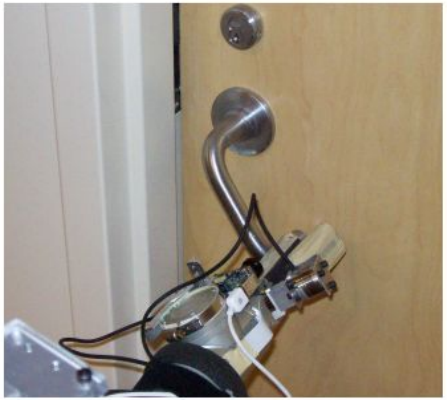
A Point-and-Click Interface for the Real World: Laser Designation of Objects for Mobile Manipulation, Charles C. Kemp, Cressel Anderson, Hai Nguyen, Alex Trevor, and Zhe Xu, 3rd ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2008

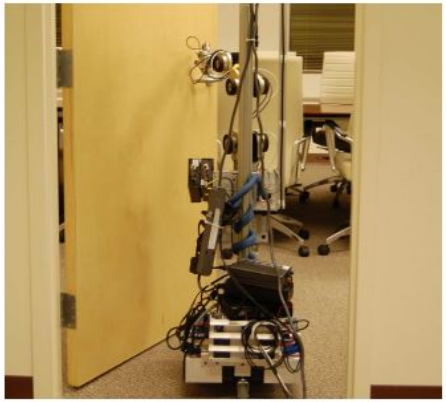


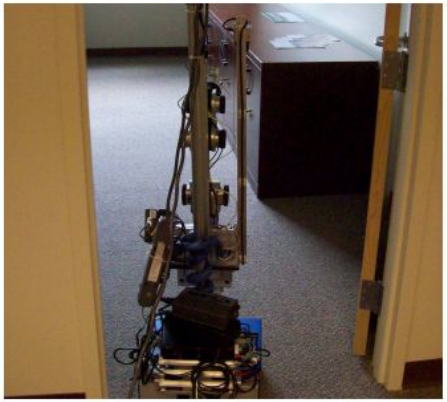
A Clickable World: Behavior Selection Through Pointing and Context for Mobile Manipulation, Hai Nguyen, Advait Jain, Cressel Anderson, and Charles C. Kemp, IEEE/RJS International Conference on Intelligent Robots and Systems (IROS), 2008.

Georgia Tech



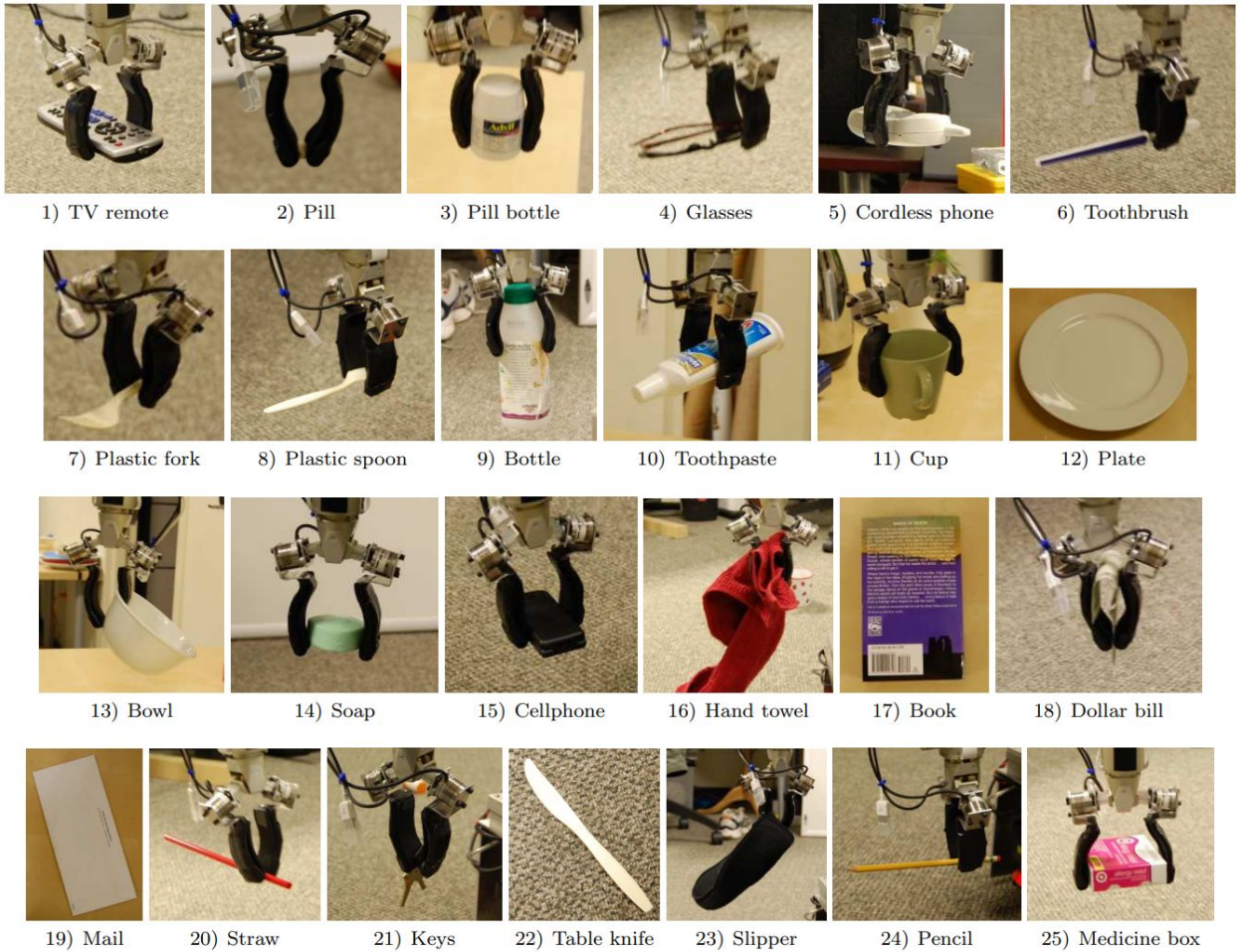







Behaviors for Robust Door Opening and Doorway Traversal with a Force-Sensing Mobile Manipulator, Advait Jain and Charles C. Kemp, RSS Manipulation Workshop: Intelligence in Human Environments, 2008.

Georgia Tech



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

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

Oct 31, 2008 is almost 17 years ago!
Why aren’t people benefiting today?

“For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.”

Richard P. Feynman, "Appendix F – Personal Observations on Reliability of Shuttle", NASA,1986.

https://en.wikipedia.org/wiki/Rogers_Commission_Report#Role_of_Richard_Feynman
https://en.wikipedia.org/wiki/Richard_Feynman#/media/File:Richard_Feynman_Nobel.jpg

The Robot Has to Earn Its Place

- Homes are personal spaces
- They often contain what people value most
  - Family members and guests **of all ages and abilities**
  - Pets
  - Sentimental objects
- People have limited time, space and patience

Image from https://en.wikipedia.org/wiki/House#/media/File:Noto_Emoji_v2.034_1f3e0.svg

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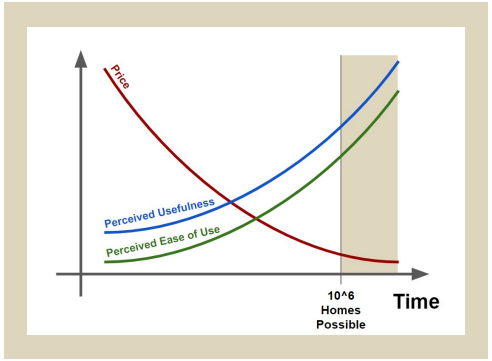
A Simple Model of Technology Adoption



Why will human-scale mobile manipulators eventually be in millions of homes?

Perceived Usefulness

Perceived Ease of Use

Photo from https://ahs.illinois.edu/rogers

Prof. Wendy Rogers introduced me to this model back in 2010 when we began collaborating on home robots.

https://en.wikipedia.org/wiki/Technology_acceptance_model

Georgia Tech

Why will human-scale mobile manipulators eventually be in millions of homes?

Perceived Usefulness

Perceived Ease of Use

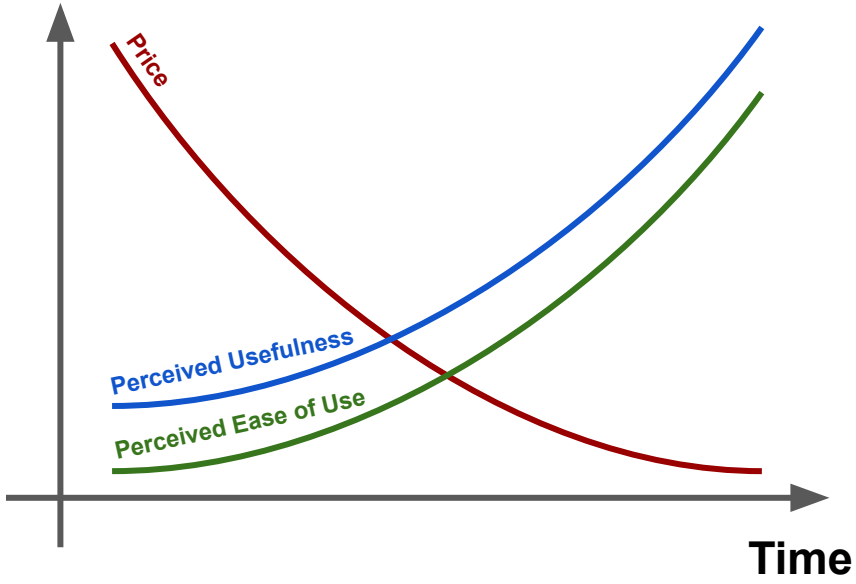
Price

Why will human-scale mobile manipulators eventually be in millions of homes?

Perceived Usefulness

Perceived Ease of Use

Price

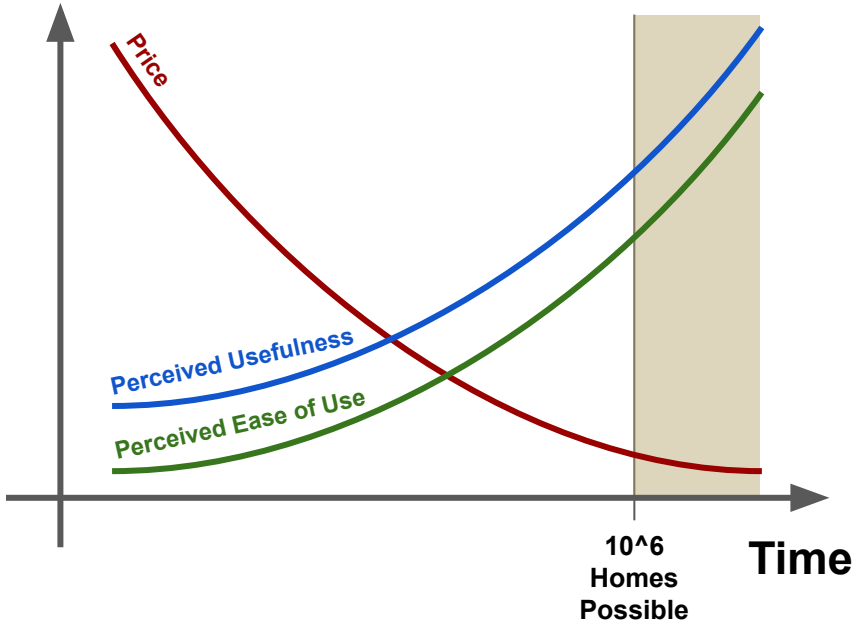


Why will human-scale mobile manipulators eventually be in millions of homes?

Perceived Usefulness

Perceived Ease of Use

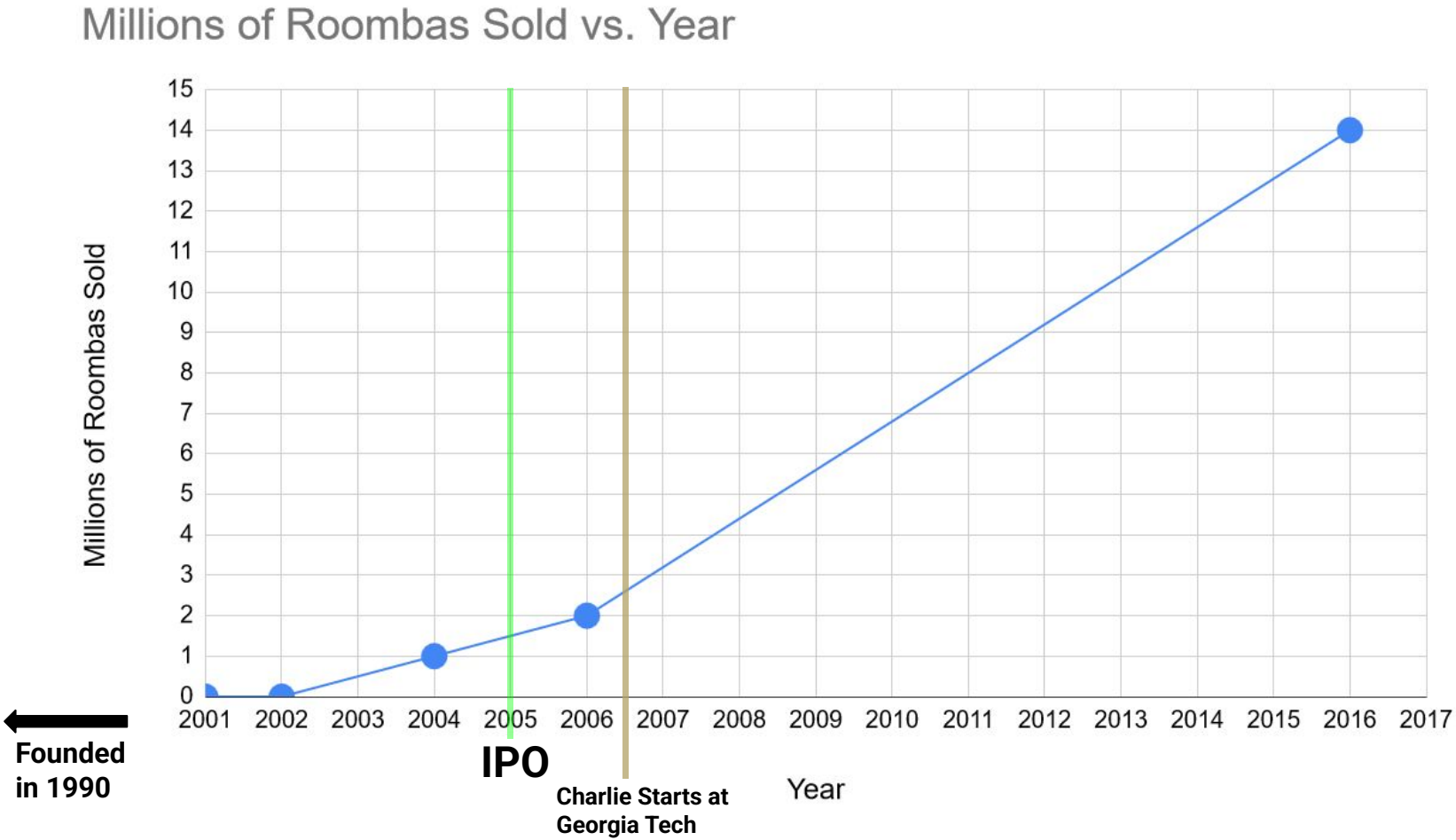
Price



Adoption of Home Robots has Happened Before

The first Roomba from 2002.

23 years ago!


Millions of Roombas Sold vs. Year
Millions of Roombas Sold
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year
Founded in 1990
IPO
Charlie Starts at Georgia Tech

Why is the Roomba in millions of homes?

- **Perceived Usefulness** - Autonomously cleans floors
- **Perceived Ease of Use** - Small, safe, easy to move
- **Price** - $200 at launch (~$350 in 2025 dollars)

Rod Brooks has emphasized the importance of a low price. iRobot wanted a person to be comfortable buying a Roomba without permission from a life partner.

Photo from https://www.edge.org/memberbio/rodney_a_brooks

Safety is Paramount

Homes often contain what we value most

- Family members and guests **of all ages and abilities**
- Pets
- Sentimental objects

Image from https://en.wikipedia.org/wiki/House#/media/File:Noto_Emoji_v2.034_1f3e0.svg

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Human Scale Has Safety Implications

- Human scale enables human-compatible perception and manipulation
- Tends to result in robots that are
  - Larger
  - Stronger
  - Heavier

Image from https://en.wikipedia.org/wiki/House#/media/File:Noto_Emoji_v2.034_1f3e0.svg

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:(

Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

20% complete

For more information about this issue and possible fixes, visit https://www.windows.com/stopcode

If you call a support person, give them this info:

Stop code: CRITICAL_PROCESS_DIED

Have you ever?

Had a device run out of batteries unexpectedly (e.g., phone, laptop)?

Had a computer fail unexpectedly (e.g., blue screen of death)?

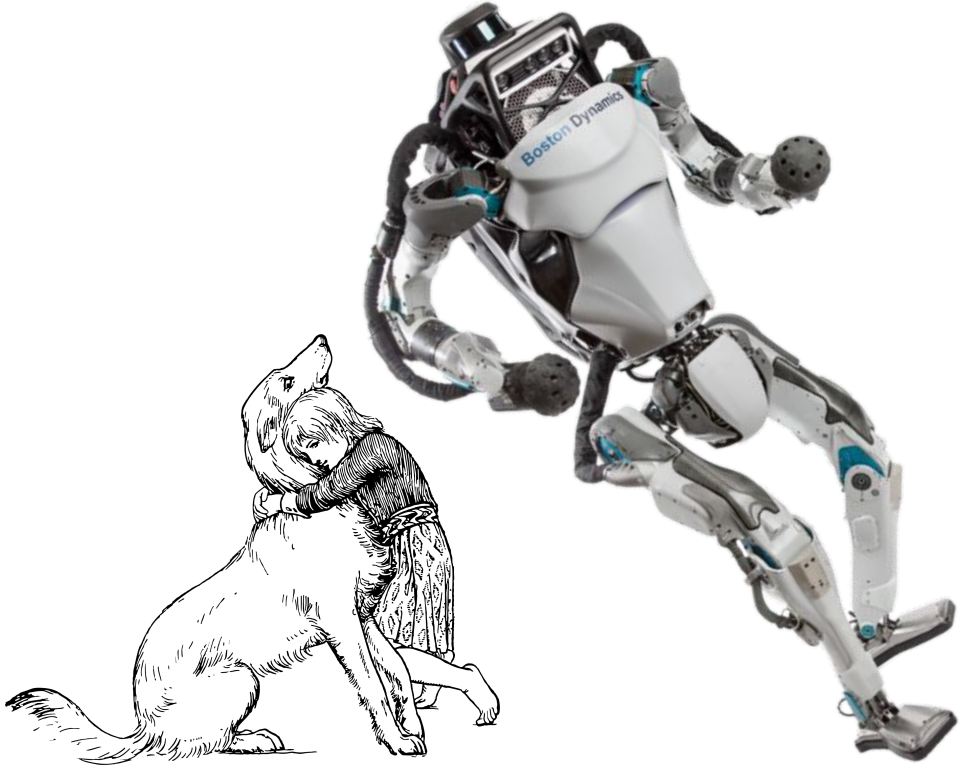
Had a kid or pet do something unexpected around you?

Been careful around an older adult due to concerns about them falling?

Stumbled in your own home?

Image in previous slide from: https://en.wikipedia.org/wiki/Screen_of_death

It Just Takes One Fall



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

A Tale of Two Minor Tragedies

Image from https://www.amazon.com/Luminarc-Beer-Glass-16-Ounce-Free/dp/B01LX3YKFB?th=1

A Tale of Two Minor Tragedies

The Design 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, IEEE International Conference on Robotics and Automation (ICRA), 2022. [4-min video presentation]

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Photo from Willow Garage

The Core Design Problem

Smaller

Lighter Weight

Lower Cost

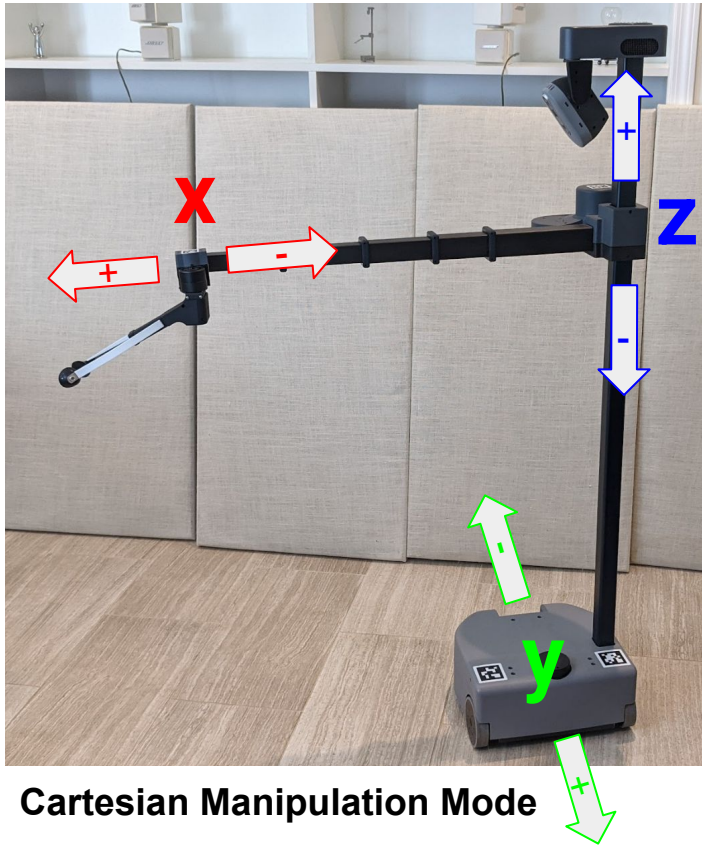
Shorter Reach

Lower Force

Less Dexterity

The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments, Charles C. Kemp, Aaron Edsinger, Henry M. Clever and Blaine Matulevich, IEEE International Conference on Robotics and Automation (ICRA), 2022. [4-min video presentation]

Manipulation Depends on the Mobile Base



Cartesian Manipulation Mode

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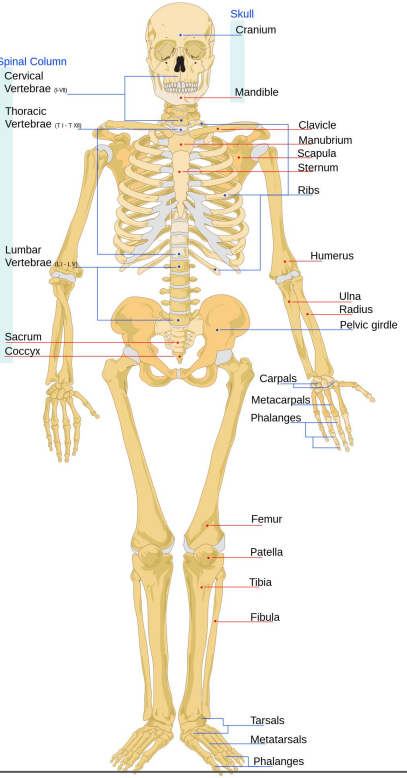
Humanoids Look Useful and Easy to Use

but practical considerations limit adoption in homes



More degrees of freedom

Higher center of mass

Not statically stable

Higher cost & more failure points

More energy transferred when it falls

Greater fall risk & awkward when off

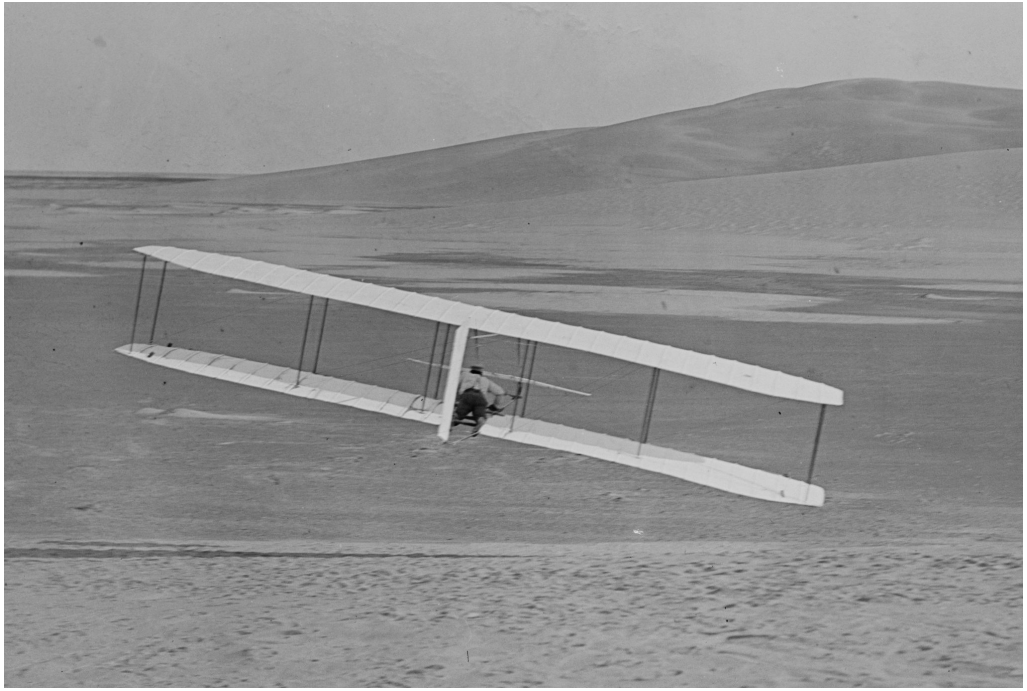
Charles C. Kemp, Paul Fitzpatrick, Hirohisa Hirukawa, Kazuhito Yokoi, Kensuke Harada, and Yoshio Matsumoto. "Humanoids.", Springer Handbook of Robotics, Springer-Verlag, edited by Bruno Siciliano, Oussama Khatib, and Torsten Kröger, 2008, pp. 1307-1333.

image from https://upload.wikimedia.org/wikipedia/commons/thumb/c/ca/Human_skeleton_front_en.svg/1060px-Human_skeleton_front_en.svg.png

Biological Inspiration Can Be Misleading

Edward Purkis Frost's ornithopter from 1902

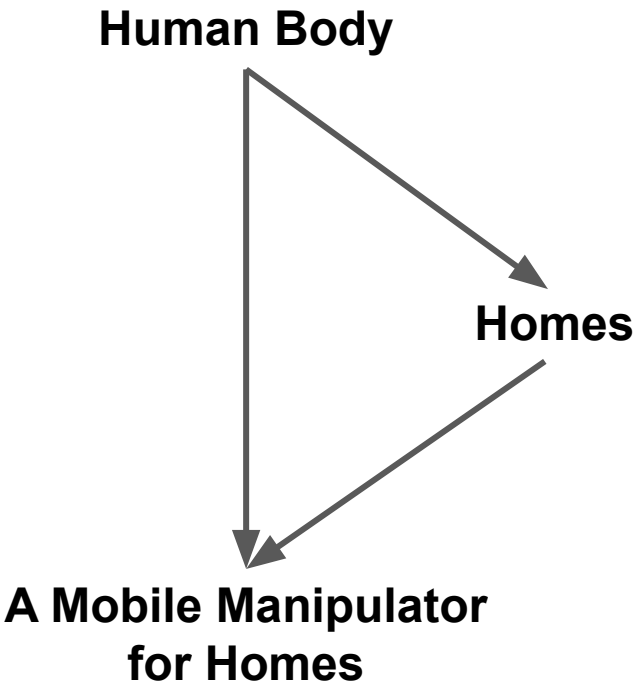
E. P. Frost appears to have been a respected member of the Royal Aeronautical Society, since he was its president from 1908 to 1911.



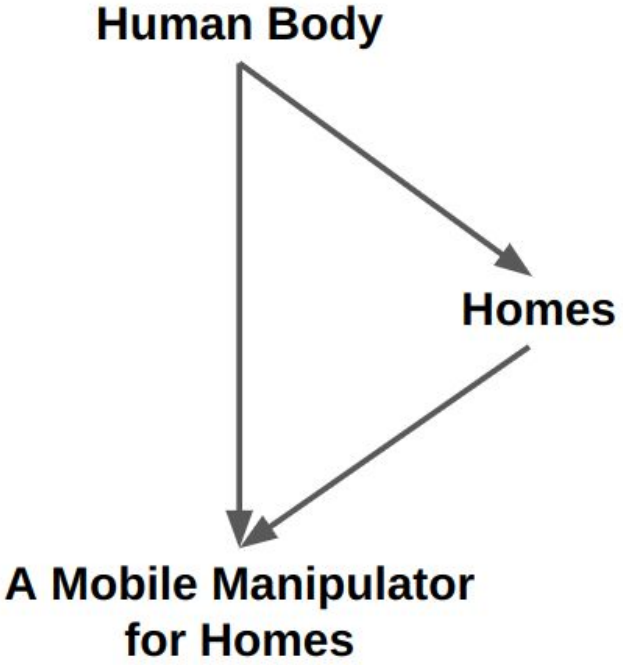
Wright Glider from 1902

Sources:
https://www.onverticality.com/blog/e-p-frost-ornithopters
https://en.wikipedia.org/wiki/Edward_Purkis_Frost
https://upload.wikimedia.org/wikipedia/commons/2/23/1902_Wright_glider_turns.jpeg
https://en.wikipedia.org/wiki/Wright_brothers

A Home Robot's Body Depends on the Human Body



A Home Robot's Body Depends on the Human Body

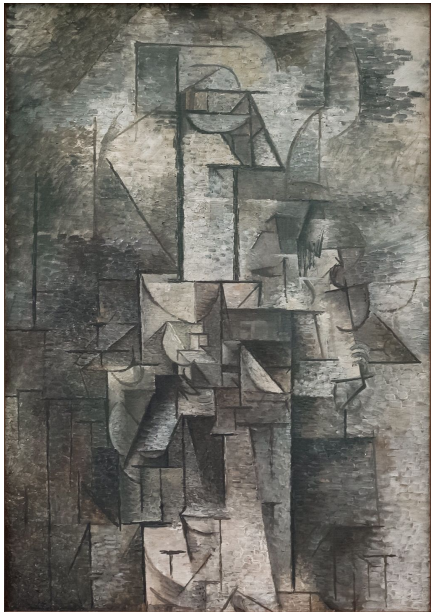


Humanoid Robot

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

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

< 50th Percentile Hip Width

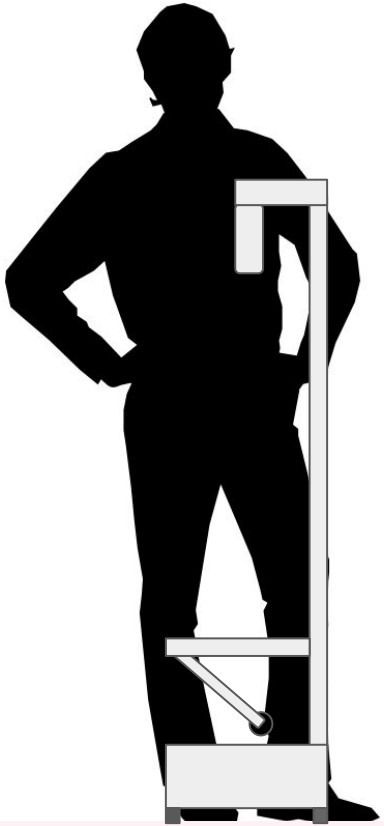
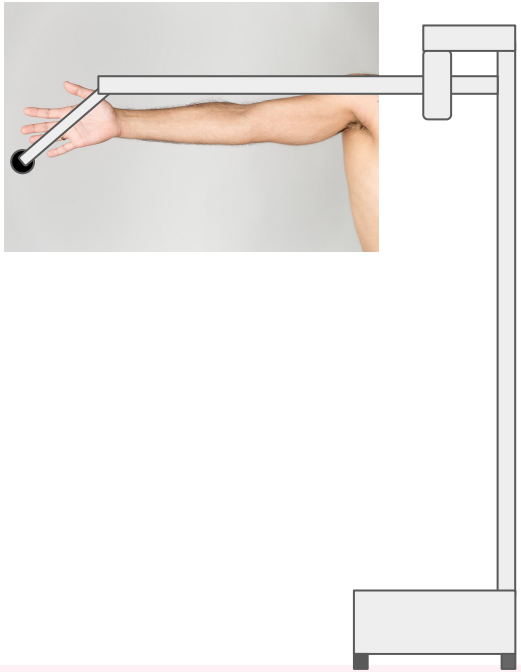


Image: https://en.wikipedia.org/wiki/Arm#/media/File:Extended_arm.jpg

50th Percentile Arm Length



Reaches the Floor

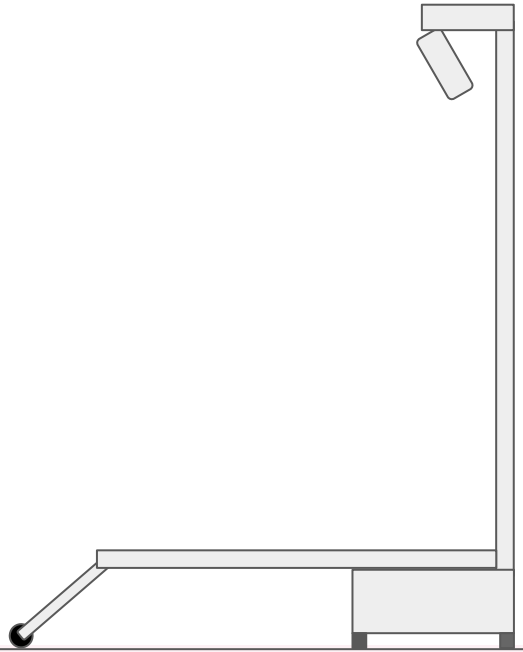
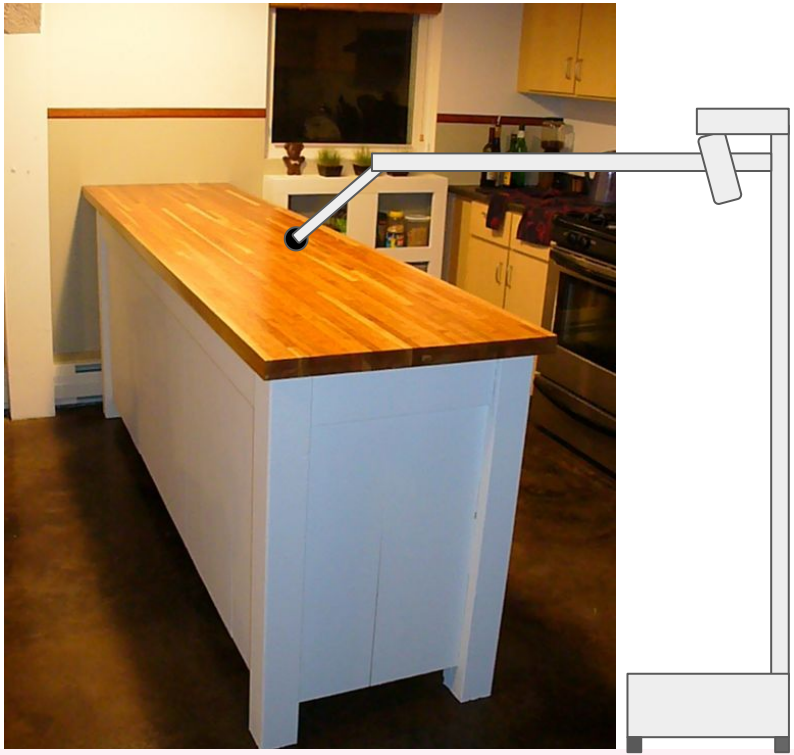


Image: https://commons.wikimedia.org/wiki/File:Butcher_block_counter_top.jpg

Reaches 36” Countertops



The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments, Charles C. Kemp, Aaron Edsinger, Henry M. Clever and Blaine Matulevich, IEEE International Conference on Robotics and Automation (ICRA), 2022. [4-min video presentation]

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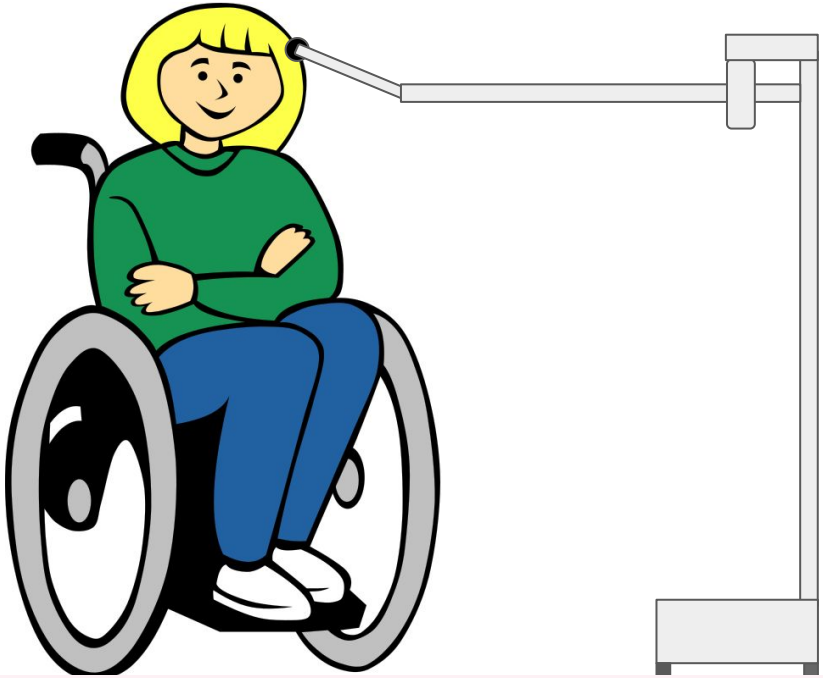
Reaches Above 95th Percentile Eye Height for Wheelchair Users (1.33 m)



Edward Steinfeld, Jordana Maisel, and Dave Feathers. *Standards and anthropometry for wheeled mobility*. Center for Inclusive Design and Environmental Access, School of Architecture and Planning, University at Buffalo, July, 2005.

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

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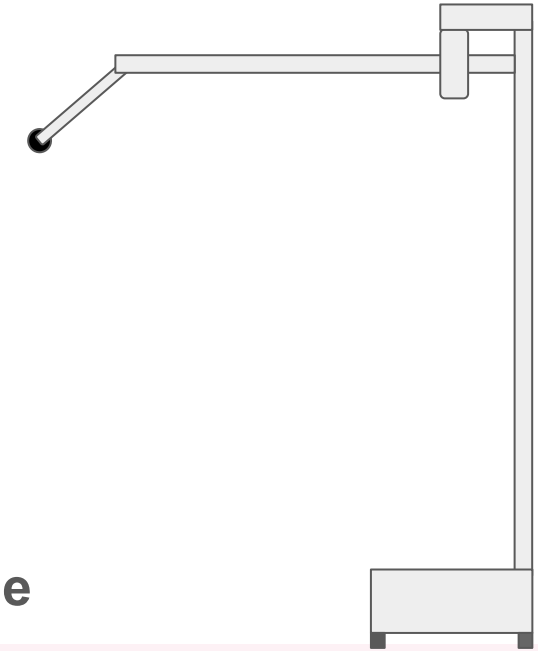
Image: https://en.wikipedia.org/wiki/Arm#/media/File:Extended_arm.jpg

Low Center of Mass

lightweight arm



heavy mobile base

The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments, Charles C. Kemp, Aaron Edsinger, Henry M. Clever and Blaine Matulevich, IEEE International Conference on Robotics and Automation (ICRA), 2022. [4-min video presentation]

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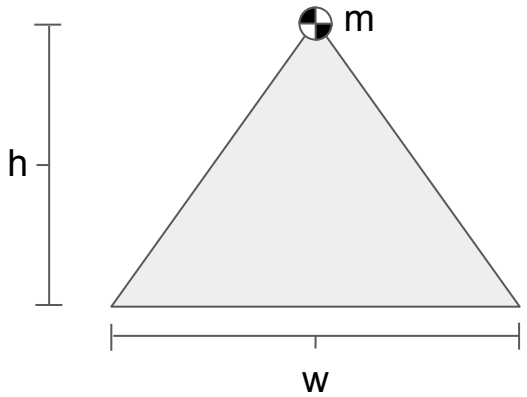
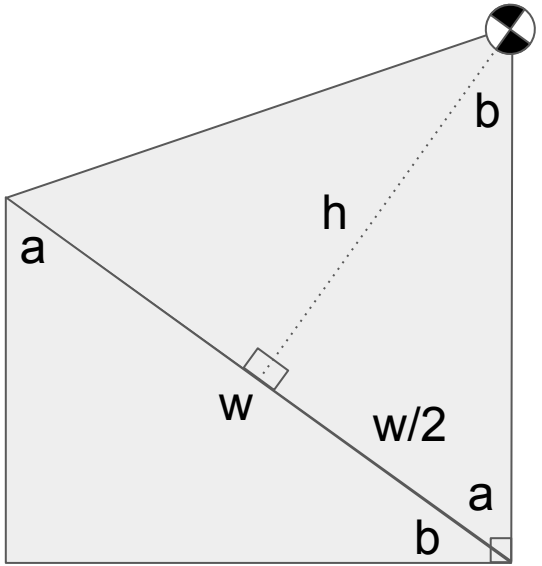
Gravitational Potential Energy as a Measure of Ease of Use

- U = mgh
  - U : gravitational potential energy
  - m : mass of the robot
  - g : gravitational acceleration (9.8 m/s^2)
  - h : height of the center of mass
  - SI unit : joule
- Fall risk
  - mgh models the energy transferred when the robot falls
- Difficulty moving the robot manually
  - m indicates how hard it would be to lift manually
- Robot's base width
  - h is proportional to w, the width of the robot's base required for static stability on a sloped surface



https://en.wikipedia.org/wiki/Gravitational_energy



h is proportional to the minimum width, w, of the robot's base of support for static stability on a slope with angle b

$$h \propto w$$

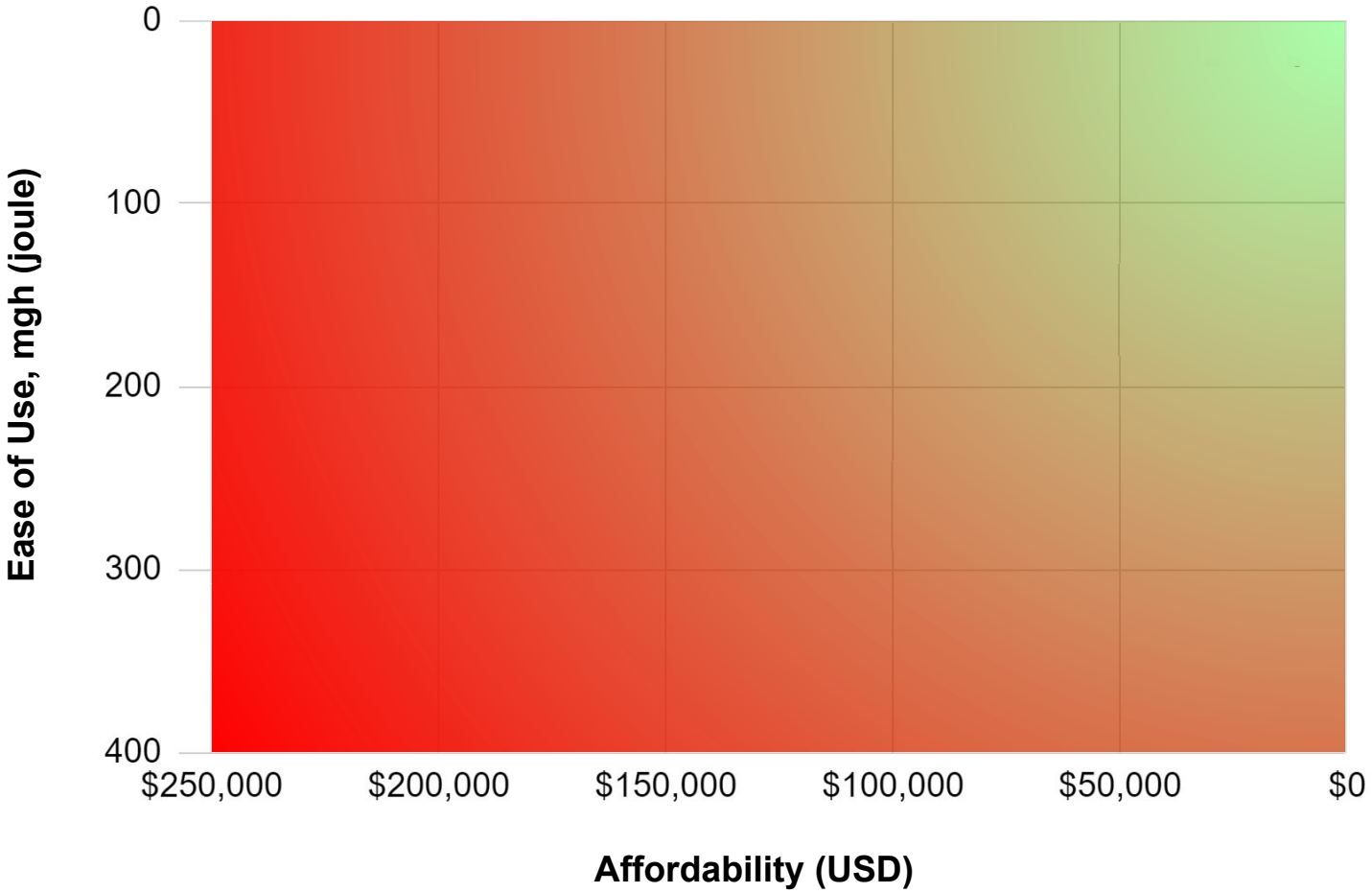
$$\frac{\frac{w}{2}}{h} = \tan(b)$$

$$h = \frac{w}{2\tan(b)}$$

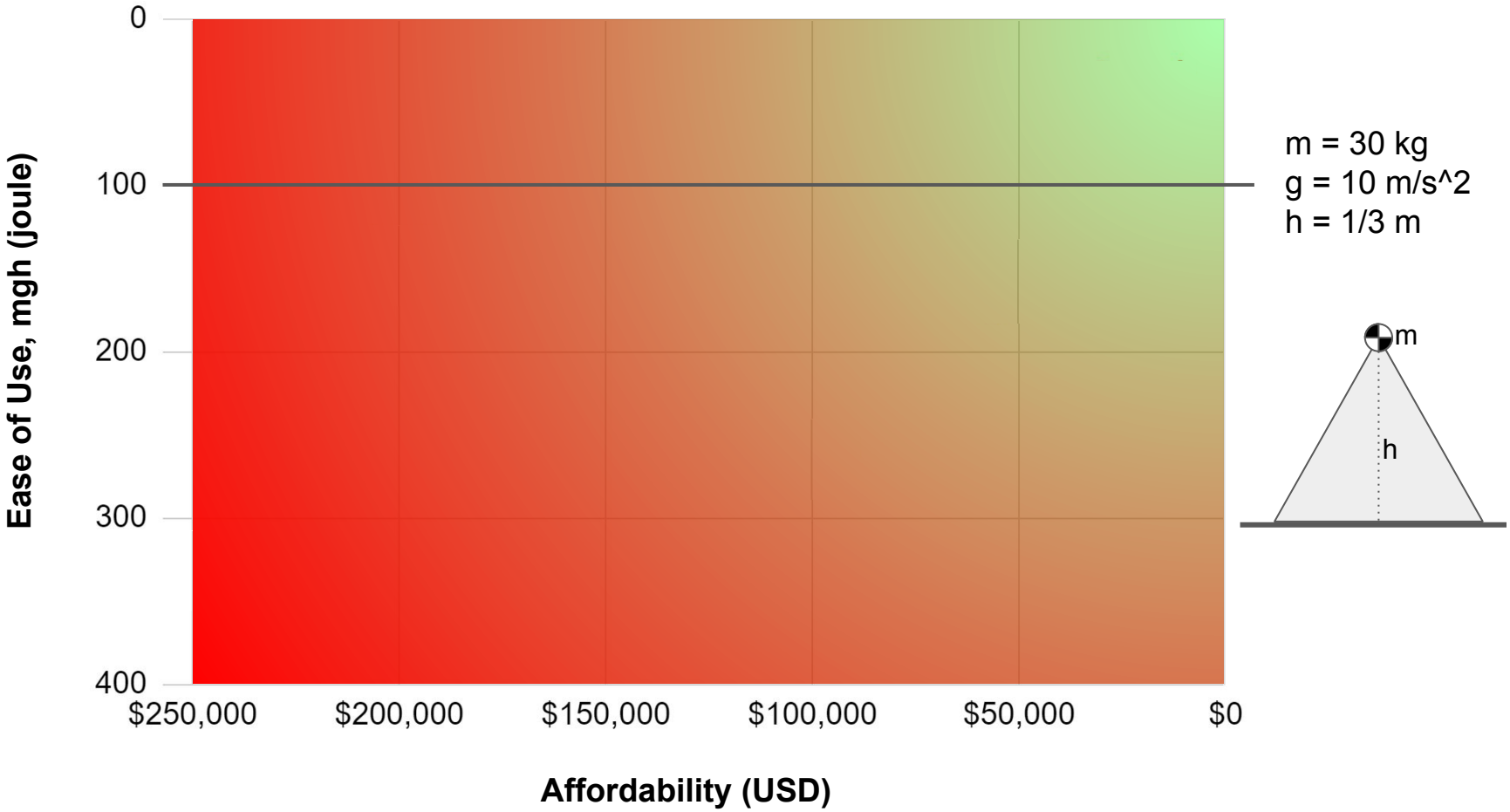
Where

b : maximum slope before tipping
w : minimum base width before tipping

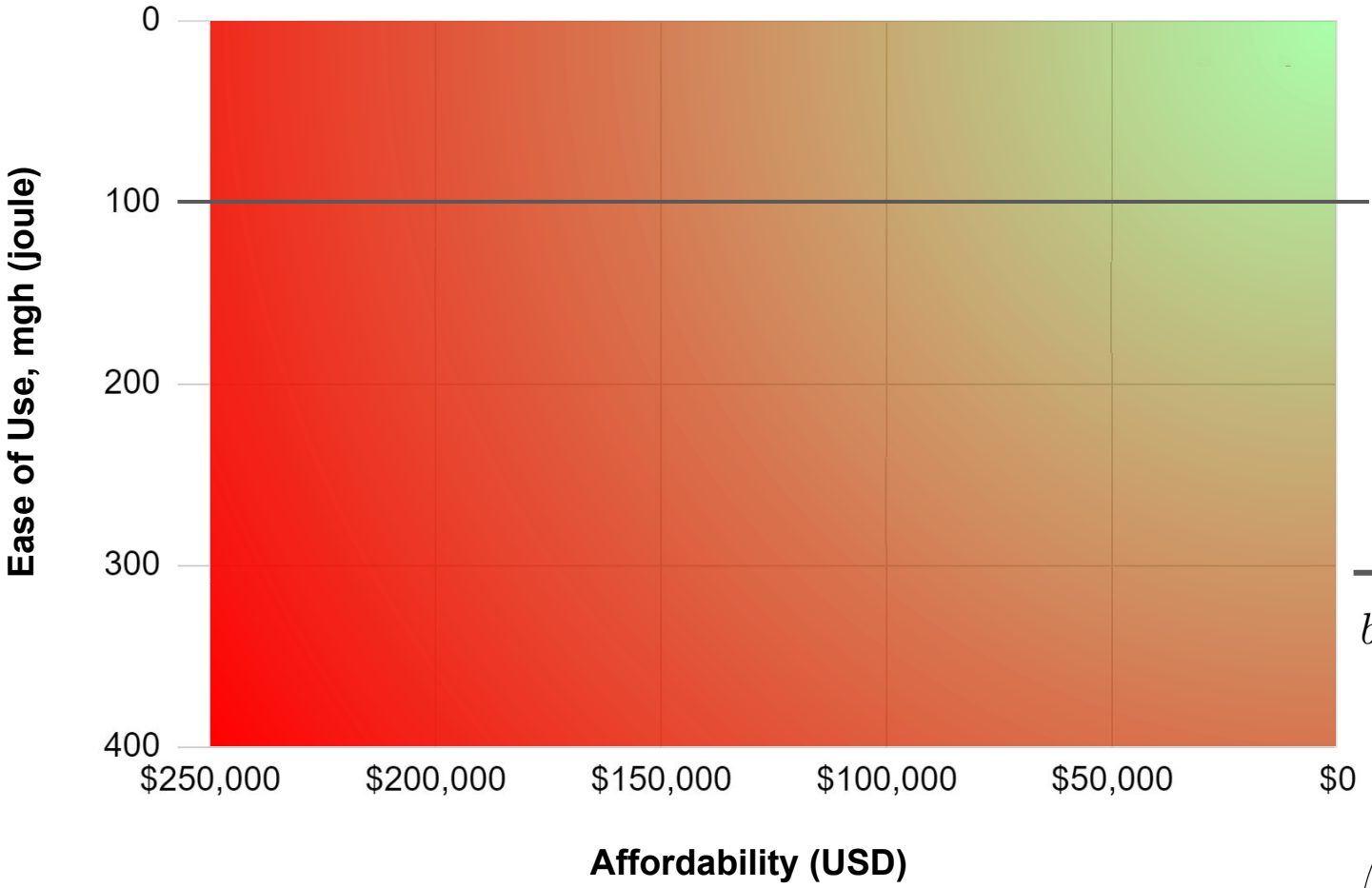
Useful Human-scale Mobile Manipulators



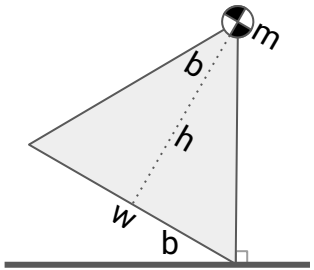
Useful Human-scale Mobile Manipulators



Useful Human-scale Mobile Manipulators

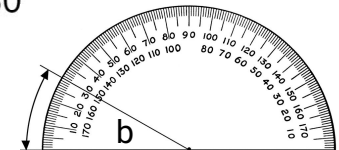


m = 30 kg
g = 10 m/s^2
h = 1/3 m



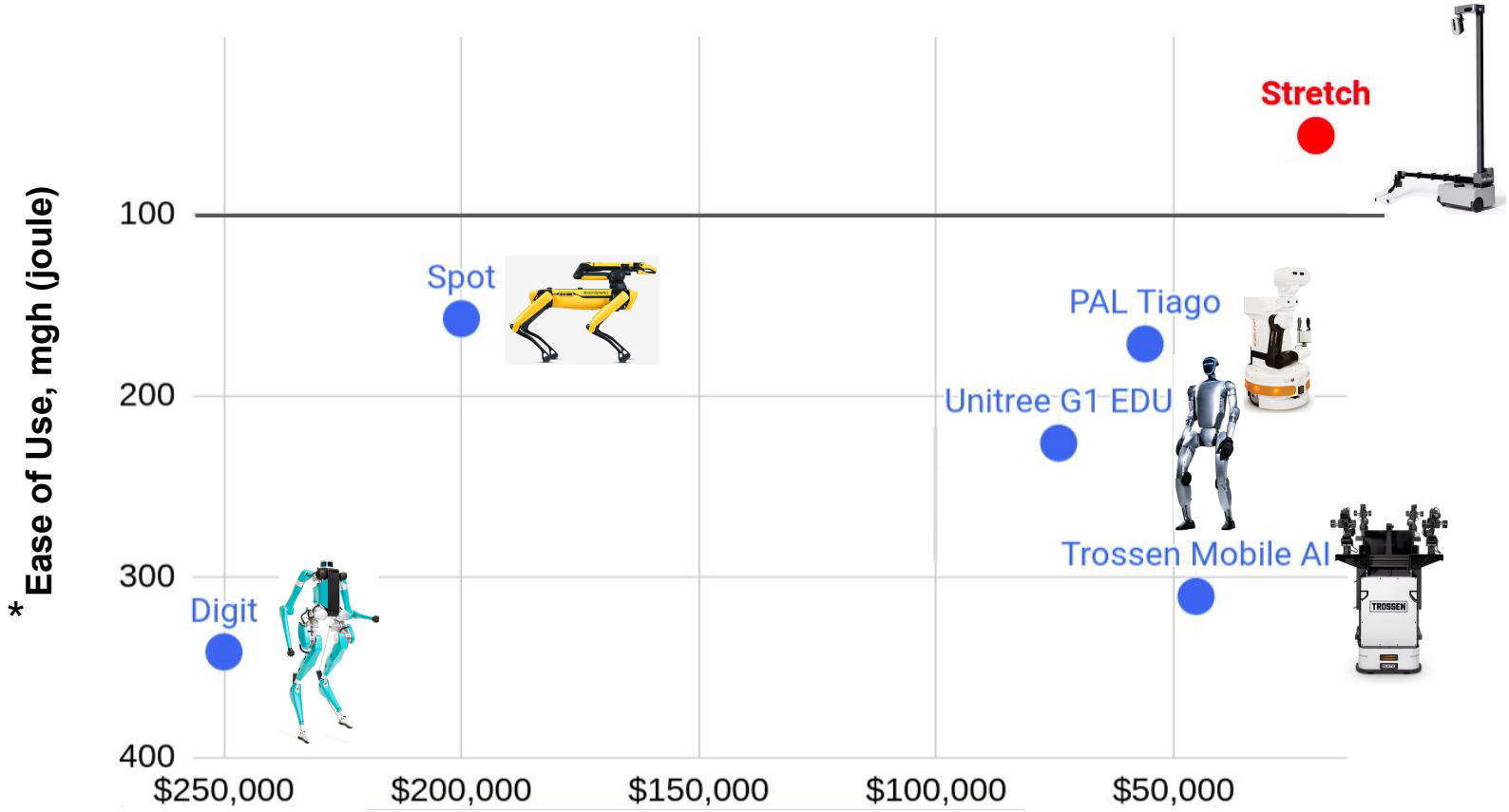
$$b = \arctan\left(\frac{w}{2h}\right)$$

w = 0.4 m
b = 31 deg



https://etc.usf.edu/clipart/42000/42005/pro_30_42005.htm

Useful Human-scale Mobile Manipulators



* *I estimated mgh based on published masses and dimensions with arms and lifts lowered. There could be significant errors.*

images from:
https://hello-robot.com
https://www.trossenrobotics.com/mobile-ai
https://fetchrobotics.com/fetch-mobile-manipulator/
https://robotsguide.com/robots/digit https://pal-robotics.com/robots/tiago/
https://robostore.com/products/unitree-g1-edu-ultimate-a-robotic-humanoid?variant=42169805275206
https://arstechnica.com/gadgets/2021/02/boston-dynamics-robot-dog-gets-an-arm-attachment-self-charging-capabilities/

24.5 kg (54 lb)

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

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Easy to Transport to Real Homes

three robots in a hatchback

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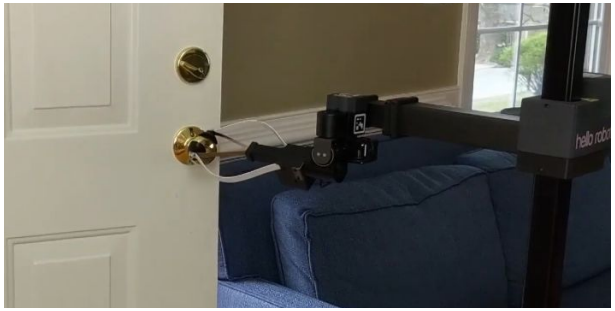
Is Stretch capable?

Early Teleoperated Examples

performed in 2020, except for door opening in 2021



https://www.youtube.com/c/HelloRobot/videos
https://github.com/hello-robot

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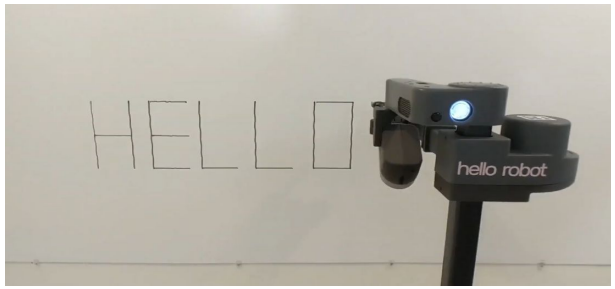
Early Autonomous Examples (2020)

from June & July of 2020



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

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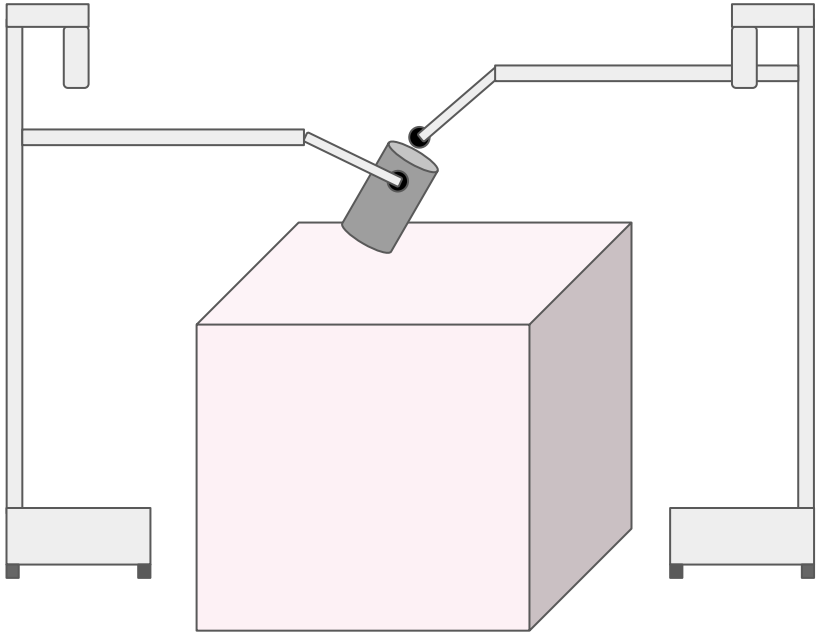
What about bimanual manipulation?

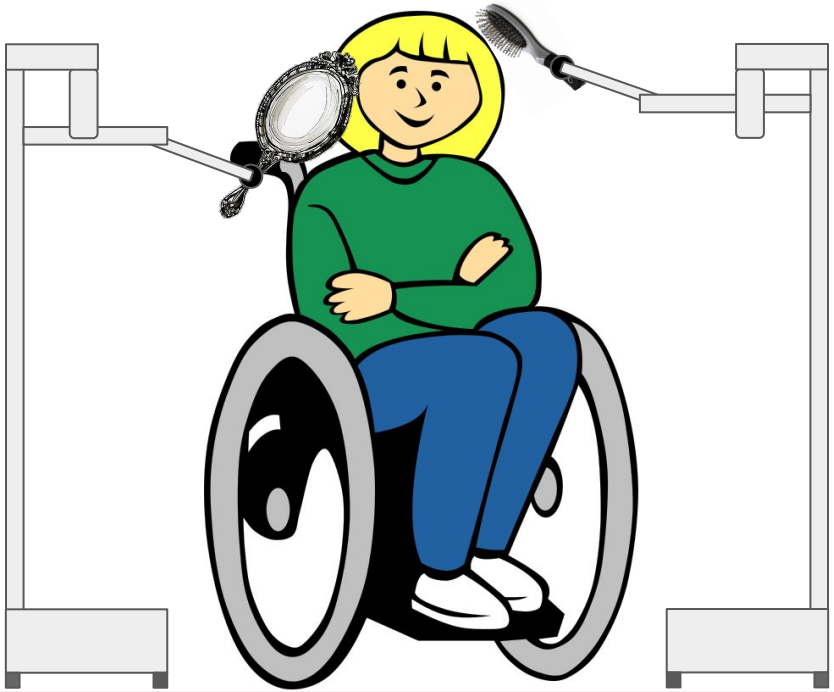
Two Stretch Robots Can Function as One

- Simplifies adoption
  - Start with one robot, which is very capable!
  - Monolithic two-armed robots are inherently bigger and more complex
- Simplifies deployment
  - Easier to move two small compact robots
- Increases versatility
  - Variable distance between the arms
  - Objects in between the arms



Two Robots with a Person Between Them?

this might be more effective than a humanoid form



Images from
https://openclipart.org/detail/510/girl-in-wheelchair
https://upload.wikimedia.org/wikipedia/commons/a/ae/Hairbrush_with_metal_bristles.jpg
https://upload.wikimedia.org/wikipedia/commons/5/51/Hand_mirror.jpg

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Teleoperated
4x Speedup

The Robot Has to Earn Its Place

- Useful enough?
- Easy enough to use?
- Safe enough?

Image from https://en.wikipedia.org/wiki/House#/media/File:Noto_Emoji_v2.034_1f3e0.svg

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Stretch is Used by an Amazing Community

People with Mobility Impairments are Promising Early Adopters

- High-value tasks are technically achievable
- Supervision and direct control have advantages
- Robots have benefits over human assistance

Image from https://en.wikipedia.org/wiki/House#/media/File:Noto_Emoji_v2.034_1f3e0.svg

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Best Paper Award at HRI 2024

“HAT (Head-Worn Assistive Teleoperation), an inertial-based wearable integrated into any head-worn garment. We evaluate HAT through a **7-day in-home study**”

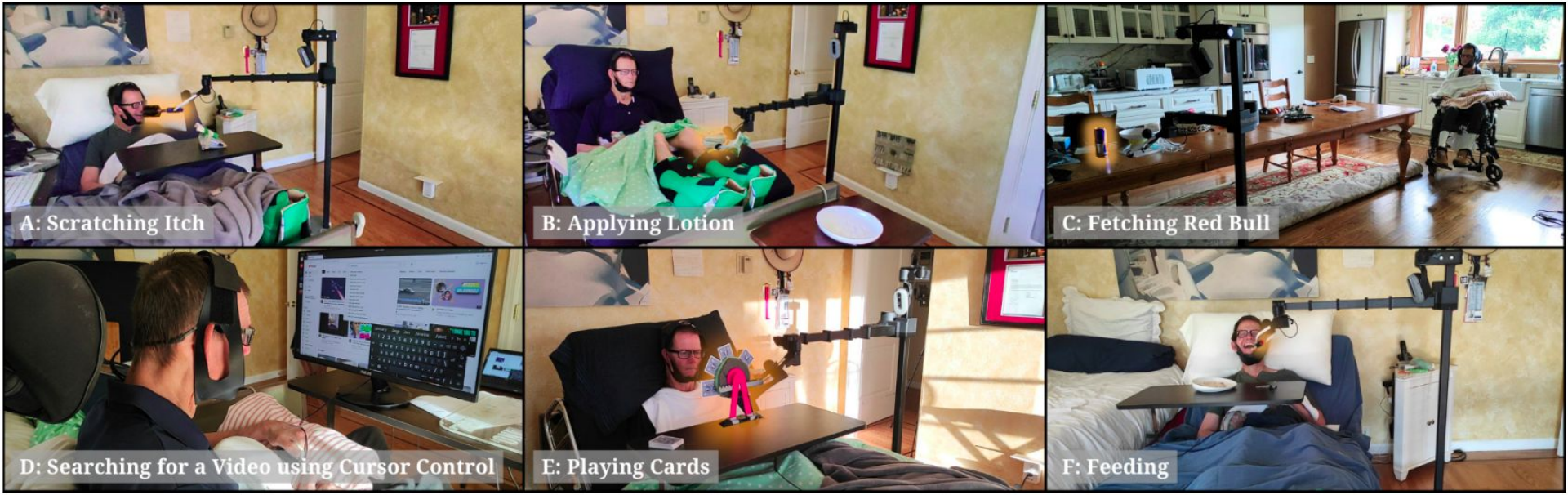


Figure 3: A subset of the tasks conducted during the study. Pertinent objects and tools are highlighted in orange.

Padmanabha, Akhil, Janavi Gupta, Chen Chen, Jehan Yang, Vy Nguyen, Douglas J. Weber, Carmel Majidi, and **Zackory Erickson**. "Independence in the home: A wearable interface for a person with quadriplegia to teleoperate a mobile manipulator." In Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction, pp. 542-551. 2024.

Assistive Robotics at the University of Washington

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

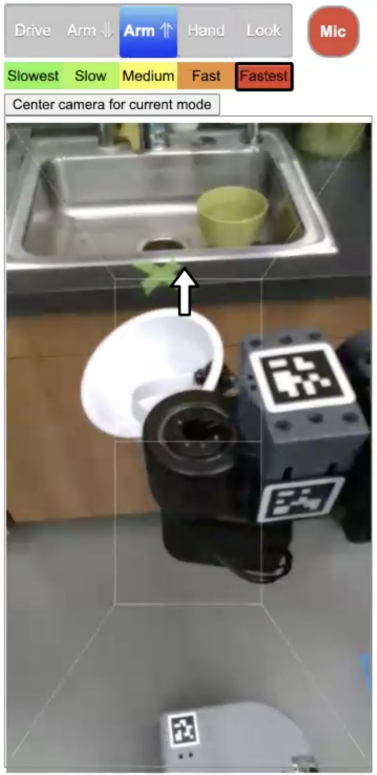
Cabrera, Maria E., Tapomayukh Bhattacharjee, Kavi Dey, and Maya Cakmak. "An Exploration of Accessible Remote Tele-operation for Assistive Mobile Manipulators in the Home." In *2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN)*, pp. 1202-1209. IEEE, 2021.

Maru Cabrera
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 initial open source web interface, which significantly improved Hello Robot's original version.

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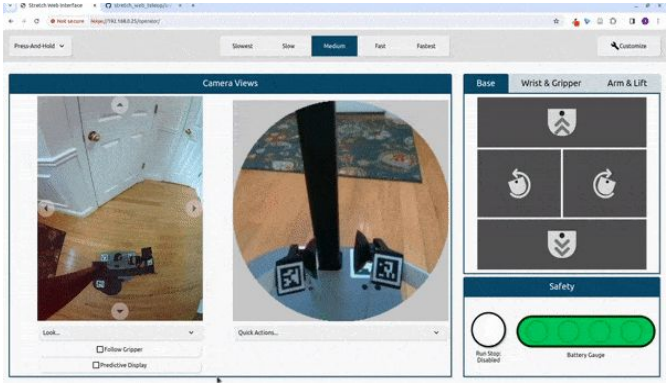
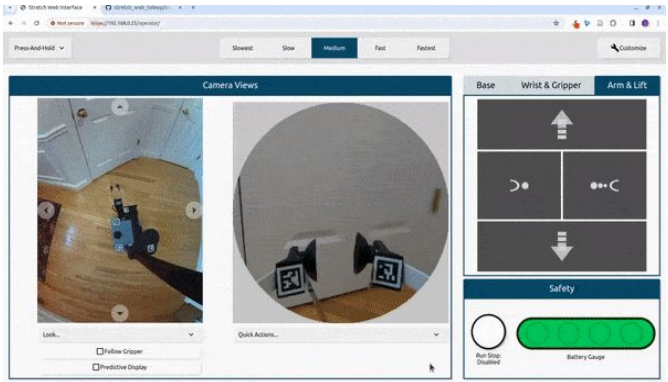
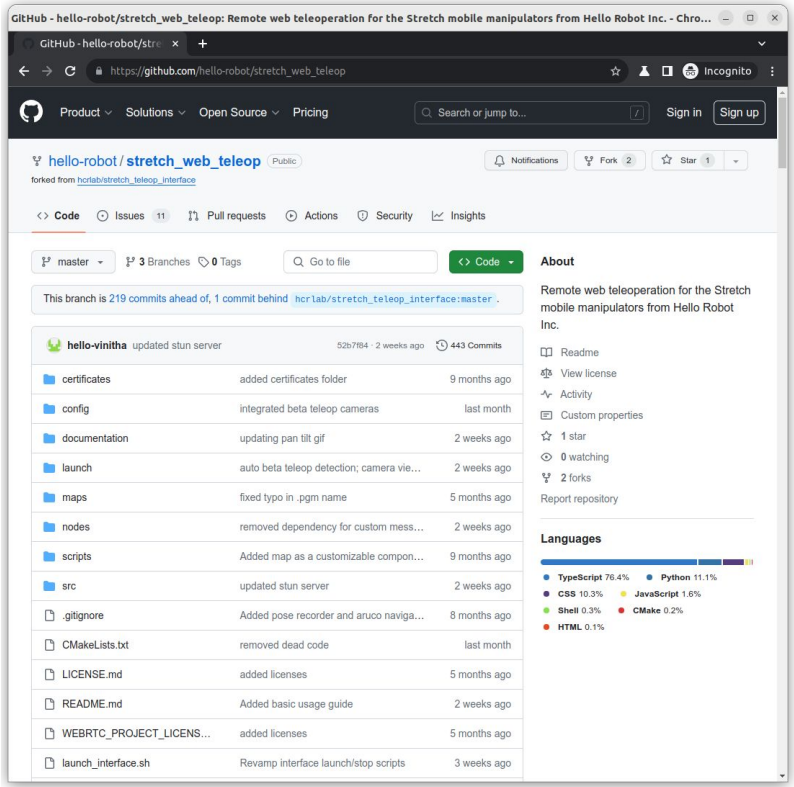
Stretch Comes with an Open Source Accessible Web Interface Pre-installed and Tested

Web Teleop development was led by Vinitha Ranganeni and Prof. Maya Cakmak in collaboration with the Robots for Humanity project

https://github.com/hello-robot/stretch_web_teleop





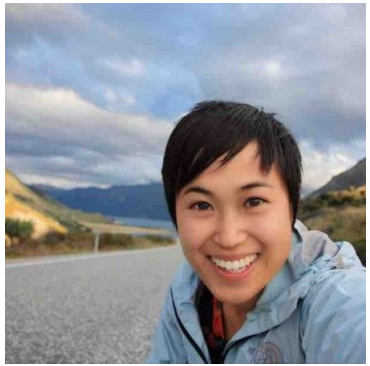


Vinitha Ranganeni, Developing Accessible Teleoperation Interfaces for Assistive Robots With Stakeholders, University of Washington, ProQuest Dissertations & Theses, 2024. 31301580.


Remote Teleop (4x)

The Power of a Community with an Open Platform

Henry & Jane Evans
Robots for Humanity leads



Dr. Vy Nguyen
Hello Robot lead

Prof. Wendy Rogers
UIUC lead

Prof. Maya Cakmak
UW lead

Dr. Vinitha Ranganeni
Web Teleop lead


When we mounted a tablet
with my image on Stretch


From giving Jane a rose to feeding myself
small, soft bites of food

Home Robots Can Enhance Life in Unexpected Ways

Photo by Peter Adams

What will it take for human-scale mobile manipulators to be purchased and happily used in homes?

- The robot has to earn its place
- Safety is paramount
- An example design (Stretch robot)
- People with mobility impairments are promising early adopters

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Stretch 3 from Hello Robot

Join the Amazing Community Using Stretch!

What will it take for human-scale mobile manipulators to be purchased and happily used in homes?

- The robot has to earn its place
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- An example design (Stretch robot)
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Stretch 3 from Hello Robot